R&D programmes for clean coal technologies

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Preface

This report has been produced by IEA Clean Coal Centre and is based on a survey and analysis of published literature, and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own, and are not necessarily shared by those who supplied the information, nor by our member countries.

IEA Clean Coal Centre is an organisation set up under the auspices of the International Energy Agency (IEA) which was itself founded in 1974 by member countries of the Organisation for Economic Co-operation and Development (OECD). The purpose of the IEA is to explore means by which countries interested in minimising their dependence on imported oil can co-operate. In the field of Research, Development and Demonstration over fifty individual projects have been established in partnership between member countries of the IEA.

IEA Clean Coal Centre began in 1975 and has contracting parties and sponsors from: Australia, Austria, Canada, China, the European Commission, Germany, India, Italy, Japan, New Zealand, Poland, Russia, South Africa, Thailand, the UK and the USA. The Service provides information and assessments on all aspects of coal from supply and transport, through markets and end-use technologies, to environmental issues and waste utilisation.

Abstract

Coal is an important energy source for the power industry due to its low cost and wide distribution. Improving coal's environmental performance is key to its future role in the energy mix, especially as emissions regulations are becoming stricter and standards are now being introduced for previously unregulated pollutants, crucially for CO_2. This report examines the policies that drive research, development and demonstration (RD&D) of clean coal technologies (CCTs) and CO_2 capture in the power generating industry for Australia, China, the European Union, India, Japan, Republic of Korea, South Africa and the USA. Domestic energy resources, political environments, market policies and mechanisms, and the level of collaboration amongst national entities can all shape the approaches that a country takes to developing CCTs. Each country chapter begins with a discussion of their energy, coal and climate policies as these can have a major influence on their coal RD&D programmes. It then moves on to describe RD&D policy and any specific CCT and CCS initiatives and programmes. Roadmaps for the development of CCT and CCS are included, where available. The amount the national government spends on RD&D and, where possible, on CCT and CCS is addressed. International collaboration on RD&D is outlined, followed by a brief description of the major national government-funded demonstration and development CCT projects. Finally, the national research organisations carrying out CCT and CCS research are briefly described.

Acronyms and abbreviations

A$	Australian dollar
ACALET	ACA Low Emissions Technologies Ltd
ANLEC R&D	Australian National Low Emissions Coal R&D Ltd
ARPA-E	Advanced Research Projects Agency-Energy (USA)
BCIA	Brown Coal Innovation Australia
BHEL	Bharat Heavy Electricals Ltd (India)
CAS	Chinese Academy of Sciences
CCPI	Clean Coal Power Initiative (USA)
CCS	carbon capture and storage
CCT	clean coal technology
CCUS	carbon capture, utilisation and storage
CRIEPI	Central Research Institute of Electric Power Industry (Japan)
CSIR	Council for Scientific and Industrial Research (South Africa)
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
CURC	Coal Utilization Research Council (USA)
DOE	Department of Energy (USA)
€	euro
EC	European Commission
EERA	European Energy Research Alliance
EIA	Energy Information Administration (USA)
EII	European Industrial Initiative
EOR	enhanced oil recovery
EPRI	Electric Power Research Institute (USA)
EU	European Union
FP7	Seventh Framework Programme (European Union)
FY	fiscal year
FYP	Five-Year Plan
GDP	gross domestic product
GHG	greenhouse gas
IEA	International Energy Agency
IEA CCC	IEA Clean Coal Centre
IEP	integrated energy plan (South Africa)
IEP	integrated energy policy (India)
IGCC	integrated gasification combined cycle
IGFC	integrated gasification fuel cell
IRP	integrated resource plan (South Africa)
JCOAL	Japan Clean Energy Center
J-POWER	Electric Power Development Co (Japan)
KEPCO	Korean Electric Power Corp
KEPRI	KEPCO Research Institute (Republic of Korea)
KETEP	Korea Institute of Energy Technology Evaluation and Planning
KRW	Korean won
LHV	lower heating value
LNG	liquefied natural gas
METI	Ministry of Economy, Trade and Industry (Japan)
MHI	Mitsubishi Heavy Industries (Japan)
MOST	Ministry of Science and Technology (China)

MOTIE	Ministry of Trade, Industry and Energy (Republic of Korea)
Mt	million (10^6) tonnes
NAPCC	National Action Plan for Climate Change
NDRC	National Development and Reform Commission (China)
NEDO	New Energy and Industrial Technology Development Organisation (Japan)
NETL	National Energy Technology Laboratory (USA)
NPP	National Perspective Plan (for R&D in the Power Sector)
NSFC	National Natural Science Foundation of China
OECD	Organisation for Economic Co-operation and Development
R	rand (South Africa)
R&D	research and development
RD&D	research, development and demonstration
RMB	reminbi (China)
Rs	rupee (India)
RSoP	Research Scheme on Power
SANEDI	South African National Energy Development Institute
SET	Strategic Energy Technology
UCG	underground coal gasification
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
US$	United States (American) dollar
USA	United States of America
USC	ultra-supercritical

Exchange rates

Indicative exchange rates (end July 2014)

Australia	US$1 = A$1.07	A$1 = US$0.94
China	US$1 = RMB6.18	RMB1 = US$0.16
EU	US$1 = €0.75	€1 = US$1.34
India	US$1 = Rs60.21	Rs1 = US$0.02
Japan	US$1 = 102.11 yen	1 yen = US$0.01
South Africa	US$1 = R10.59	R1 = US$0.09
South Korea	US$1 = KRW1026.56	KRW1 = US$0.001

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1 Introduction

Coal is an important source of energy for the world, particularly for power generation. It is the world's most abundant and widely distributed fossil fuel. Demand for coal has risen rapidly in the last decade, exceeding the demand for gas, oil, nuclear and renewable energy sources. Various projections suggest that this trend is likely to continue. The latest *World Energy Outlook 2013*, for example, forecasts a 17% increase in global coal demand from 2011 to 2035, with two-thirds of the growth occurring by 2020. This is for a scenario based on the continuation of existing policies and the implementation of policies that have been announced by governments but are yet to be given effect. Most of the coal demand will occur in emerging economies, predominantly India, China and Southeast Asia. Coal use, though, is expected to decline in the Organisation for Economic Co-operation and Development (OECD) countries. Globally coal is expected to remain the leading source of electricity generation, although its share is predicted to fall from 41% to 33% in 2035. The power sector will account for around 63% of total coal use in the period to 2035. Global installed generating capacity is likely to grow by over 70%, from 5649 GW in 2012 to about 9760 GW in 2035, after some 1940 GW of generating capacity is retired. About 60% of retirements will be in OECD countries, where about two-thirds of the coal fleet is already over 30 years old (IEA, 2013a).

Pollutants, such as nitrogen oxides, sulphur oxides, particulates, mercury and carbon dioxide, are formed when coal is combusted in a power plant boiler. Over 40 countries have set limits on the amounts of nitrogen oxides, sulphur oxides and particulates that can be emitted because of environmental and health concerns. These limits are becoming increasingly stringent, and restrictions are being introduced on pollutants that were not previously regulated. China and some other countries have recently introduced limits on mercury emissions, and the Canadian Government now requires all new coal-fired power plants built after 1 July 2015 to emit no more than 420 tCO_2 per GWh of power produced. The US Environmental Protection Agency has proposed CO_2 emission limits for new coal- and gas-fired power plants. Carbon taxes have also been introduced in a number of countries.

The energy sector is the largest source of anthropogenic carbon dioxide emissions, the main contributor to climate change. It was responsible for about two-thirds of global greenhouse gas (GHG) emissions, with electricity generation as the largest contributor. In 2011, the electricity and heat sector emitted 13.1 tCO_2 or 42% of global CO_2 emissions from fuel combustion, with coal-fired power production contributing 9.4 $GtCO_2$ (IEA, 2013b). The aim of limiting the average rise in global temperature to between 2 and 3ºC means it will be necessary to halve (from current levels) CO_2 emissions by 2050. However, in the *World Energy Outlook 2013*, energy-related CO_2 emissions are predicted to rise by 20% from 2011 to 2035, reaching 37.2 Gt under the scenario discussed above, with emissions from coal accounting for 15.7 $GtCO_2$ (IEA, 2013a). Hence the development and deployment of clean coal technologies (CCTs) and the capture and storage of CO_2 will play a key role in preventing the atmospheric concentration of CO_2 from reaching an unacceptable level. It will also alleviate other environmental impacts of coal-fired power generation.

This report examines the policies that drive research, development and demonstration (RD&D) of clean coal technologies (CCTs) and CO_2 capture in the power generating industry for selected countries. CCTs are advanced systems for converting coal to power with low environmental impact and high efficiency. Improving the efficiency of power generation is one way of lowering CO_2 emissions. CCTs encompass a wide array of technologies. These include modern pulverised coal combustion with high temperature, high pressure steam cycles and high efficiency flue gas clean-up systems, and advanced ultra-supercritical power plants that are currently under development. The other main clean coal systems are those based on fluidised bed combustion, and those that use coal gasification together with a combined cycle gas turbine that burns the product gas (integrated gasification combined cycle (IGCC) power plants).

Carbon capture and storage (CCS) is the set of technologies that will reduce CO_2 emissions much further than the use of CCTs alone. CCS is required if significant reductions of CO_2 (>90%) from coal-fired power plants are to be obtained. The technologies include pre-combustion systems where the CO_2 is removed from the coal gasification gas before it is combusted in the combined cycle gas turbine (IGCC power plants) and post-combustion methods where the CO_2 is separated from the flue gas (pulverised coal combustion plants). Another technology is oxyfuel (or oxycoal) combustion, where coal is combusted in an oxygen/recycled flue gas mixture instead of air. After the removal of condensate from the CO_2-rich gas, the ~98% pure CO_2 is sent for storage. However, the high cost and energy requirements of current CO_2 capture processes are major barriers to their use. Only the capture element of CCS will be covered as the transport and storage of CO_2 is outside the scope of the report. Carbon mitigation technologies suitable for emerging economies are discussed in the IEA Clean Coal Centre (IEA CCC) report by Minchener (2012a). Estimates of the potential CO_2 emissions savings through thermal efficiency improvement measures and replacement with new plants of higher efficiency (CCTs) for China, India, South Africa, the USA and UK are given in Henderson and Baruya (2012). The areas where R&D is needed before clean coal and CO_2 capture technologies can be deployed are addressed in CIAB (2008) and Kather and others (2008). The IEA CCC has also published a series of reports on the prospects of coal and CCT in various countries, including the Philippines, Kazakhstan, Ukraine, Malaysia, Thailand, Vietnam, Russia, Czech Republic, Poland and Turkey, countries not covered in this report.

The report covers both developed countries and emerging economies, which can face a different set of challenges in the development and deployment of CCTs. Domestic energy resources, political environments, market policies and mechanisms, and the level of collaboration amongst national entities can all shape the approaches that a country takes to developing CCTs. Each country chapter begins with a discussion of their energy, coal and climate policies as these can have a major influence on their RD&D programmes. It then moves on to describe R&D policy and any specific CCT and CCS initiatives and programmes. Roadmaps for the development of CCT and CCS are included, where available. The purpose of roadmaps is to provide the strategic decisions and steps necessary to achieve technologies for meeting long-term goals. The amount the national government spends on RD&D and, where possible, on CCT and CCS is then addressed. International funding sources for major coal investment projects are covered in the IEA CCC report by Hill (2006). International collaboration on RD&D is outlined, followed by a brief description of the major national government-funded demonstration and development CCT projects. Demonstration projects which involve international participation are covered in the country where the project is based. Finally, the national research organisations carrying out CCT and CCS research are described. University research on CCT and CCS is excluded.

2 Australia

Australia is rich in mineral resources, including coal, oil, natural gas and uranium, and has abundant renewable energy sources. It is the ninth largest energy producer in the world and a significant fossil fuel exporter – over 70% of its total energy production is exported (Bureau of Resources and Energy Economics, 2013). The energy sector is a major contributor to Australia's economy, contributing between 16% and 17% of current GDP (IEA, 2012a). Earnings from energy exports were around A$77 billion in 2011–12, accounting for 34% of the total value of Australia's commodity exports. Coal is the largest energy exporter earner, with a value of around A$48 billion in 2011–12, followed by crude oil and LNG (Bureau of Resources and Energy Economics, 2013). In 2010, Australia was the largest global exporter of coal (292.6 Mt), with about 27% of the world market. However, in 2011 it was overtaken by Indonesia. In 2012, Australia exported 301.5 Mt. Australia is currently the world's fifth largest coal producer (420.7 Mt in 2012), exporting about 72% (301.5 Mt) of its production (IEA, 2013c). The thermal coal (159.2 Mt) is exported principally to Japan, China, South Korea and Taiwan.

In 2010–11, coal accounted for 59% of Australia's primary energy production, in energy content terms, followed by uranium (20%) and gas (13%). Crude oil and LPG represented a further 6%, and renewables 2%. The majority of Australia's electricity is produced using coal, which accounted for 69% of total electricity generation in 2011–12, some 47% from black coal and 22% from brown coal. This is because coal is a relatively low cost energy source in Australia. It also reflects the abundance of coal reserves along the eastern seaboard, where the majority of electricity is generated and consumed. Gas accounted for 20%, and renewable energy sources, mainly hydroelectricity, wind and bioenergy, for the remaining 11% of the electricity generation mix in 2011–12 (Bureau of Resources and Energy Economics, 2013). For the year leading up to March 2012, coal-fired electricity generation emitted around 155 $MtCO_2$, which is about 30% of Australia's man-made GHG emissions in this period (Hannan, 2013). Overall, Australia was the world's 15th biggest CO_2 emitter from fuel combustion in 2011, releasing 396.8 $MtCO_2$, of which 198.8 $MtCO_2$ came from coal. Electricity production (252.6 TWh) generated 207.8 $MtCO_2$ or 823 gCO_2/kWh (IEA, 2013b). Coal-fired electricity generation accounted for 173.3 TWh (IEA, 2013c). In 2010, coal-fired power generation emitted 1000 gCO_2/kWh (IEA, 2012c).

2.1 Energy policy

The Australian Government published an ***Energy White Paper*** at the end of 2012 that builds on past energy reforms and the government's Clean Energy Future (climate change) plan. It sets out the Australian Government's strategic policy framework for further development of its energy sector over the next four years that will:

- provide accessible, reliable and competitively priced energy for all Australians;
- enhance Australia's domestic and export growth potential; and
- deliver clean and sustainable energy.

Australia's energy policy is being revised by the new government, elected in September 2013. The new Energy White Paper will set out an approach to reduce cost pressures on households and businesses, improve Australia's international competitiveness, and help increase exports and economic prosperity (*see* http://ewp.industry.gov.au/). There appears to be less emphasis on clean and sustainable energy delivery, although measures to encourage the deployment of renewable energy, as well as low emission technologies that would allow Australia to continue to utilise its coal and gas resources will be considered. The white paper is due to be published at the end of 2014.

The following discussion outlines the current energy policy set out in the 2012 Energy White Paper. Four priority areas for future action were identified in the paper, one of which is the enhancement of clean energy transformation (Department of Resources, Energy and Tourism, 2012). The key mechanisms to drive the transformation to cleaner energy had already been put in place through the Clean Energy Future plan and earlier commitments by the Australian Government. Additional key areas for action were specified to overcome the potential market gaps or barriers to the up-take of clean energy technologies. These included the implementation of clean energy programmes to ensure continued support for innovation and commercialisation.

The 2012 Energy White Paper projected a significant reshaping of the energy mix with renewable energy accounting for at least 20% of electricity generation by 2020, rising to around 40% by 2035 and potentially to over 50% by 2050. By 2050, over 80% of Australia's conventional fossil fuel power generation could be replaced by coal- and gas-based CCS systems and other clean energy technologies. The Australian Treasury forecast that fossil fuel power plants with CCS could provide between 26 and 32% of total electricity generation by 2050 (Department of Resources, Energy and Tourism, 2012; IEA, 2012a). Consequently energy RD&D, including CCT and CCS, will be important in order to achieve these targets. It would be difficult to meet the clean energy targets without successfully commercialising CCS technologies. The projected energy mix is likely to change under the new government – it has already diluted the renewable energy target.

Australia's clean energy transformation was to have been driven by the Government's ***Clean Energy Future*** plan, which committed Australia to a 5% reduction in GHG emissions below 2000 levels by 2020 (irrespective of what other countries do) and by up to 15% or 25%, depending on the scale of global action (Australian Government, 2011). These targets would require cutting expected pollution by at least 23% in 2020. The Government had further set a new 2050 target to reduce emissions by 80% compared with 2000 levels. These targets are a major challenge for Australia given its reliance on coal, and the importance of coal exports to its economy. The new government has committed to keep the 5% reduction below 2000 levels by 2020 target.

One purpose of the Clean Energy Future plan was to bring all previously existing clean energy policies together and strengthen them by introducing new policies. Major elements of the plan relating to the energy sector commenced on 1 July 2012. These included the introduction of a carbon pricing mechanism (which is now being repealed), encouraging innovation in clean energy through the establishment of a

Clean Energy Finance Corporation and a Renewable Energy Agency, and improving energy efficiency. The objective of the A$10 billion Clean Energy Finance Corporation is to overcome capital market barriers hindering the financing, commercialisation and deployment of renewable energy, low emission and energy efficiency technologies. It excludes CCS as this is supported in other programmes such as the CCS Flagships (discussed later).

Most of the initiatives in the Clean Energy Future plan will be closed by the new government. The 2014–15 Budget (*see* www.budget.gov.au/2014-15/index.htm) discontinues funding of the Clean Energy Finance Corporation and Renewable Energy Agency, and these organisations (amongst others) will be dismantled. The budget still has to be approved by the Senate, where the government does not have a majority.

The new government's response to climate change and emissions reduction is called the ***Direct Action Plan***. Much of the detail still remains to be developed. The centrepiece is an ***Emissions Reduction Fund***, which will provide incentives for emission reduction activities (*see* www.environment.gov.au/climate-change/emissions-reduction-fund). A bill has been introduced to implement the fund. The Government plans to invest A$2.55 billion in the fund over 10 years from 1 July 2014, but expects to spend A$1.14 billion of the amount over the next four years (Australian Government, 2014a). Funding for all government programmes related to climate change has been reduced for the next 4 years in the 2014–15 Budget.

2.2 Coal and CCS initiatives and programmes

Low pollution technologies are a key factor in Australia's current energy and climate policies and consequently, are an important driver for research and deployment of CCTs and CCS. Thus the focus of coal R&D is on environmentally sustainable uses, such as low emissions power generation. This includes IGCC with CCS, pre- and post-combustion CO_2 capture, and oxyfuel combustion.

A number of initiatives and programmes have been implemented by the Australian and State Governments to encourage the development and deployment of low emission technologies and CCS. For example, the Victorian government has provided over A$430 million since 2005 for R&D, pilot-scale and pre-commercial demonstration projects, through the Energy Technology Innovation Strategy in order to drive advances in low emission technologies. The New South Wales Government has a A$100 million Coal Innovation NSW Fund whose main purpose is to support RD&D of low emissions coal technologies for commercial application. Details about some of the State government initiatives can be found on the website www.zeroCO2.no/projects/countries/australia, although some of the information is out-of-date. The emphasis here will be on the Australian Government initiatives. Earlier initiatives are covered in the IEA CCC report by Henderson and Mills (2009). Many of these initiatives and programmes have been renamed over the years and the funds transferred.

In 2008, the Australian Government created the ***National Low Emissions Coal Council*** (under the National Low Emissions Coal Initiative) primarily to develop a national low emissions coal strategy

(National Low Emissions Coal Council, 2009). The strategy was delivered to the Minister for Resources and Energy in 2009, and an update paper was produced in 2010 to reflect recent climate change and CCS activities (National Low Emissions Coal Council, 2010). One of the outcomes of the strategy was to set priorities for establishing a national research programme. It identified a need to focus on applied R&D to support the CCS demonstration projects, and to increase total R&D funding. Funded jointly by the Australian coal industry and the Australian Government, the Australian National Low Emissions Coal R&D Ltd (ANLEC R&D) was established to manage the Council's A$150 million R&D investments (*see* Section 2.3). In March 2011, the Council was superseded by the ***National Carbon Capture and Storage Council*** (National CCS Council), which has now been disbanded. This body oversaw the implementation of the national low emissions coal strategy, and advised the Government on the accelerated development and deployment of CCS in Australia. It included representatives of the coal, oil and gas industry, Australian and State Governments, and the research community. A roadmap for the development and deployment of CCS in Australia was completed by the Council in May 2013. The 2004 CCS roadmap is described in Henderson and Mills (2009).

The ***National Low Emissions Coal Initiative*** (formerly known as the National Clean Coal Fund) was established by the Australian Government in 2008 to accelerate the development and deployment of low emission coal technologies and CO_2 transport and storage infrastructure to enable major cuts in GHG emissions from coal usage to be made over time, whilst enhancing energy security and maintaining the contribution of coal to Australia's economic growth. It is supported by the National Low Emissions Coal Fund, with the Australian Government providing more than A$280 million over 8 years (until June 2015). The Callide oxyfuel project, the Loy Yang and Tarong post-combustion CO_2 capture projects (*see* Section 2.5) and ANLEC R&D are all supported under the Initiative. According to the 2012 Energy White Paper, funding for the Initiative is A$370 million (Department of Resources, Energy and Tourism, 2012). The Initiative is being closed, with funding cut by A$16.8 million over 2 years in the 2014–15 Budget. A$96.6 million over 4 years will remain to support the projects (Australian Government, 2014b; www.budget.gov.au/2014-15/content/bp2/html/bp2_expense-17.htm).

In May 2009, the Australian Government announced the establishment of the ***Clean Energy Initiative*** to support the growth of clean energy generation and new technologies, to reduce carbon emissions, and to stimulate the economy. The budget was initially A$4.5 billion, later increased to A$5.1 billion. The Initiative included A$2.1 billion for CCS (including the National Low Emissions Coal Initiative and the CCS Flagships programme). Components of the Initiative, such as the CCS Flagships and the Solar Flagships, are now part of the Clean Energy Future package.

The A$1.68 billion ***Carbon Capture and Storage (CCS) Flagships*** programme, announced in May 2009, builds on the National Low Emissions Coal Initiative. It is intended to fast-track the development of CCS by supporting the construction and demonstration of 2 to 4 large-scale integrated CCS projects in Australia in partnership with private industry. Two of the short-listed projects, both of which were IGCC power plants with CCS, have either been withdrawn (ZeroGen project) or amended (Wandoan power project to just CO_2 storage). The ZeroGen project in Queensland was completed and wound-up due to concerns about its economic viability and as a suitable CO_2 storage site could not be found. The selected South West CO_2 Geosequestration Hub and CarbonNet projects are described in Section 2.5. In the latest 2014–15 Budget, funding for the Flagships has been reduced by A$459.3 million over three years from 2017–18 (including A$263.3 million in 2018–19 and A$33.1 million in 2019–20), reflecting the new government's CCS policy. No new projects will be funded, but funding of $191.7 million over seven years remains to support the existing projects (*see* www.budget.gov.au/2014-15/content/bp2/html/bp2_expense-17.htm).

The Australian Government, using A$45 million from the National Low Emissions Coal Initiative, is jointly funding the A$90 million ***Advanced Lignite Demonstration Program*** with the Victorian Government. This initiative, announced on 3 August 2012, funds pre-commercial demonstration-scale projects that reduce the GHG emissions intensity of brown coal (lignite). Brown coal upgrading must form part of the project. Details about the three chosen projects can be found at www.energyandresources.vic.gov.au/energy/innovation-and-research/etis/advanced-lignite-demonstration-program. One of the projects involves a A$25 million grant for the development of a A$119 million demonstration briquetting plant and cogeneration unit at the Loy Yang A power plant.

The Australian bituminous coal producers are providing funding to support the pre-commercial demonstration of low emissions coal technologies, including CCS. The ***Coal21 Fund*** (*see* www.minerals.org.au/resources/coal/climate_change_technology/coal21 and www.acalet.com.au), established in 2006, is funded entirely by a voluntary levy. It builds on the ***COAL21 Partnership***, which was formed in 2003, and included representatives from the coal and electricity industries, unions, Commonwealth and State Governments and the research community. The main outcome of this partnership was the COAL21 Action Plan, launched in 2004, which provided a blueprint for accelerating the demonstration and deployment of technologies that will reduce GHG emissions from coal-based electricity generation. The Coal21 Fund is managed by ACA Low Emissions Technology Ltd (ACALET). To date, A$250 million has been committed to projects, with a further A$46 million under consideration. Supported projects include the Callide Oxyfuel Project (*see* Section 2.5), ANLEC R&D and several state-based CO_2 storage basin exploration activities

2.3 RD&D funding

Most of the R&D in the Australian energy sector is undertaken by private businesses, with expenditure on energy R&D by Australian businesses representing around 14% of total business R&D expenditure in 2010–11. Despite a fall in 2011, business spending on energy R&D increased at an average rate of 28% a year from 2000–01 to 2010–11, reaching A$2.6 billion in 2010–11. This includes R&D related to energy resources (such as exploration for and mining of coal, uranium, oil, gas and geothermal energy), to preparing and transforming energy resources (for example, preparing oil and coal and using them to generate electricity) and for other aspects of energy (including renewable energy, energy distribution and storage, energy efficiency, and waste management). The oil and gas extraction industry had the largest R&D expenditure in 2009–10, with business spending of A$1.3 billion. This was followed by the coal mining industry with A$591 million of R&D expenditure (Bureau of Resources and Energy Economics, 2013).

In 2012, the Government (Australian and States) invested 0.0324% of its GDP in energy RD&D (A$502.591 million), down from 0.0409% in 2011. It spent A$49.2 million (US$50.9 million, both in 2012 prices) on coal RD&D in 2011 or about 0.0033% of its GDP. This was an increase over the budget in 2010, but less than that for 2009 (*see* Table 1). The budget for 2012 is even lower at A$11.399 million (US$11.8 million) or 0.00074% of GDP (IEA, 2013d). Coal production, preparation and transport generally consume the largest percentage of the coal budget. This reflects the importance of the coal mining industry and the large part coal exports play in Australia's economy.

Table 1 Australian RD&D budgets for coal and CCS (IEA, 2013d)

		2008	2009	2010	2011
Total RD&D in million A$ (million US$, in 2012 prices and exchange rates, where US$1 = A$0.966 in 2012)	Coal production, preparation and transport	12.202 (12.631)	105.081 (108.78)	6.089 (6.303)	–
	Coal combustion (including IGCC)	5.206 (5.389)	1.605 (1.661)	0	–
	Coal conversion (excluding IGCC)	2.45 (2.536)	5.071 (5.249)	4.306 (4.458)	0.021 (0.022)
	Other coal	12.098 (12.524)	5.525 (5.719)	2.883 (2.984)	–
	Total coal	31.957 (33.082)	117.282 (121.41)	13.278 (13.745)	49.176 (50.907)
	CO_2 capture/separation	–	30.59 (31.667)	48.255 (49.953)	20.764 (21.495)
	CO_2 transport	–	19.144 (19.818)	75.381 (78.034)	–
	CO_2 storage	–	19.144 (19.818)	73.641 (76.233)	61.921 (64.1)
	Unallocated CO_2	0.032 (0.033)	0	0	110.563 (114.454)
	Total CCS	0.032 (0.033)	68.878 (71.302)	197.277 (204.22)	193.248 (200.05)

Note: all data refers to the financial year, for example 2012 refers to July 2011 to June 2012

The importance the Government attaches to CCS RD&D is seen in the increased expenditure on RD&D, with the budget more than doubling (65% increase) in 2010 (*see* Table 1). In 2012, the budget had further risen to A$240.35 million (US$248.81 million) or about 0.0155% of GDP. Part of the CCS budget includes research on CO_2 capture from coal-fired power plants. The RD&D budget for coal and CCS together has risen each year to a total of A$251.749 million (US$260.61 million) in 2012, around 0.0162% of GDP. However, this is likely to change with the election of the new Government and its budget cuts for CCS research and deployment, announced in May 2014.

Two organisations supporting R&D programmes and projects are the Australian National Low Emissions Coal R&D Ltd (ANLEC R&D) and Brown Coal Innovation Australia (BCIA). ***ANLEC R&D*** (*see* www.anlecrd.com.au) was established by the National Low Emission Coal Council to support, enable and accelerate CCS demonstration in Australia. Its primary objective is to reduce the investment risk in early demonstration of low emissions coal-fired power generation. ANLEC R&D is funded by the Australian Government through the Clean Energy Initiative and ACALET (that is, the black coal industry) through the COAL21 initiative. A$150 million will be invested over six years in RD&D on low emissions coal technologies for power generation. This focus is driven by the recognition that early projects must succeed for low emissions coal technologies to help achieve substantial reductions in CO_2 emissions, while meeting growing energy demand. ANLEC R&D will accelerate the feedback between the early demonstration projects and applied technology R&D, thereby mitigating risk and accelerating the technology development cycle. Project costs are expected to have a minimum 1:1 in matching contribution. The seven key programme areas are alternatives and fundamental, brown coal, carbon transport and storage, IGCC, oxyfuel, post-combustion capture, and techno-economic analysis.

In its third year of operation, ANLEC R&D has provided several science and technology reports in the programme areas that include brown coal, post-combustion carbon capture, black coal IGCC, oxyfuel combustion, oxy-circulating fluidised bed combustion and CO_2 storage. The scoping studies provide targets and milestones for the development of the technologies and are available on the ANLEC R&D and Global CCS Institute websites.

Brown Coal Innovation Australia (BCIA), founded in late 2009 and funded for 4 years, is a not-for-profit company that co-invests in brown coal innovation and emission reduction R&D programmes and projects (*see* www.bcinnovation.com.au). Its members include the State Government of Victoria (a founding member), ANLEC R&D, CSIRO, Australian companies and universities, and JCOAL (from Japan). More than A$3.5 million is available in its third (2013) competitive funding round for projects that will lead to a sustainable low emissions future for brown coal-fired power generation. This compares to A$8.3 million awarded in 2011 to ten R&D programmes. The current projects cover low cost, low emission (improved efficiency) brown coal power generation (including direct injection coal engines), chemical looping combustion, CO_2 capture, and alternate uses of brown coal (including low emission production of chemicals and fuels). BCIA also serves as the brown coal node for ANLEC R&D activities. In addition, it has a number of partnerships and strategic alliances with national and international organisations in the brown coal innovation sectors, and key Australian and State Government agencies.

2.4 International collaboration

The Australian Government cooperates with a number of countries and the European Commission to foster clean energy RD&D. For example, it has allocated A$20 million to support a range of activities and projects under the ***Australia-China Joint Coordination Group on Clean Coal Technology*** that are specifically focused on the development, application and transfer of low emission coal technology (Department of Resources, Energy and Tourism, 2012). The Joint Coordination Group (JCG) was established in 2008 and is co-chaired by Australia's Department of Resources, Energy and Tourism (now the Department of Industry) and China's National Energy Administration. Ongoing projects include an Australia-China post-combustion capture project (A$12 million), a post combustion capture technology advancement (PCC-3) project (A$2.4 million), and the Australia-China JCG Partnership Fund (A$1.1 million) (Hannan, 2013).

The ***Global CCS Institute*** (*see* www.globalccsinstitute.com) was established by the Australian Government in early 2009 with funding from the National Low Emission Coal Initiative. The aim is to facilitate the development, demonstration and deployment of CCS worldwide. The Institute also fosters the sharing of knowledge across international boundaries, envisaging that the exchange of information will reduce costs and enhance public awareness. It currently has around 370 members from more than 40 countries, including national governments, global corporations, small companies, environmental non-government organisations, research bodies and universities. A Five-Year Strategy Plan, covering 2013–17, outlines the Institute's strategic objectives. Its primary source of funding is now from membership fees.

2.5 Demonstration and pilot projects

Post-combustion capture, pre-combustion capture (including IGCC) and oxyfuel were identified as priority technology options for CO_2 mitigation. The National Low Emissions Coal Council recommended that these options should be pursued through collaborative R&D (National Low Emissions Coal Council, 2009, 2010). This is reflected in the national RD&D programmes, and the demonstration projects that are partially funded by the Australian Government.

Callide oxyfuel project

The A$200 million project (*see* www.callideoxyfuel.com) involves retrofitting oxyfuel technology on a 30 MWe coal-fired boiler and a cryogenic CO_2 capture plant (70 tCO_2/d) at CS Energy's Callide A power station near Biloela, Qld. The project aims to demonstrate the complete and integrated process of oxyfuel combustion of pulverised coal, oxygen production, plus CO_2 capture, processing, liquefaction, transport and geological storage. The liquid CO_2 will be transported by road tanker to the injection point for storage in depleted gas fields. The demonstration project is a joint venture between CS Energy, the Australian Coal Association, Glencore Xstrata Coal, Schlumberger and Japanese participants J-POWER, Mitsui and IHI, with JCOAL providing technical support. The Australian, Queensland and Japanese governments are all providing financial support. The demonstration phase of the project started in December 2012, following the initial commissioning of oxyfiring in March 2012. Additional funding (A$27 million) is being provided by the Australian Government (A$13 million), ACALET, J-POWER, Mitsui, IHI and the Japanese Government to extend the demonstration phase to November 2014 to allow the project to achieve 10,000 operating hours.

CarbonNet project

The project is exploring the potential for establishing a large-scale CCS network. Around 1–5 $MtCO_2$/y would be captured from multiple CO_2 capture projects in the Latrobe Valley in Victoria, transported via a shared pipeline and injected into underground offshore storage sites in the Gippsland Basin. Over 90% of Victoria's electricity is generated from coal-fired power plants in the Latrobe Valley. The project, established in 2009, is managed by the Victorian Department of State Development, Business and Innovation, and funded by the Australian and Victorian State governments (*see* www.energyandresources.vic.gov.au/energy/carbon-capture-and-storage/the-carbonnet-project). It is one of the two CCS Flagship projects under the Clean Energy Initiative.

CO2CRC UNO Mk 3 project

This 3-year A$4.2 million project is demonstrating the UNO Mk 3 system (*see* www.co2crc.com.au/research/uno_mk3_process.html and http://www.gdfsuezau.com/about-us/asset/Hazelwood) at the GDF Suez Hazelwood brown coal-fired power plant in Victoria (CO2CRC, 2013a). UNO Mk 3 uses a potassium carbonate solvent to capture CO_2 from flue gas. The pilot plant, commissioned in late 2012, was built with funding from the Victorian State Government through BCIA, and CO2CRC partners, including the Australian Government, with the support of GDF Suez Australian Energy. It captures 1 t/d of CO_2, and will operate to 2014. The next step is a projected 50 tCO_2/d plant. Other CO_2 projects operating at the plant include the International Power carbon capture plant (*see below*).

Delta CCS demonstration project

The goal of this project (*see* www.newgencoal.com.au/active-projects/delta-pcc.html and www.resources.nsw.gov.au/coal-innovation/research-projects/nsw-carbon-capture-and-storage-demonstration-project) is to demonstrate integrated post-combustion capture, transport and permanent geological storage of CO_2 from a coal-fired power plant. A post-combustion module will be retrofitted at the Delta Electricity's Point Vales power plant to capture up to 100,000 tCO_2/y for geological storage in New South Wales. The project commenced in 2010, and is planned to be operational by 2015. It is funded by the Australian Government (through the National Low Emissions Coal Initiative), ACALET (Coal21 Fund), and the NSW State Government (through Coal Innovation NSW). A geological storage site is currently being identified, before a detailed engineering study for the post-combustion capture plant is carried out.

The project builds upon a pilot-scale CCS project (utilising aqueous ammonia to capture CO_2) by Delta at the Munmorah power plant. The pilot plant has been moved to the Point Vales plant. Planned trials include the utilisation of solar thermal energy for CO_2 liquid solvent regeneration, evaluation of solid sorbents for CO_2 capture in real flue gases, and the impact of flue gas impurities (Feron, 2012).

Loy Yang projects

A mobile pilot plant for capturing up to 1000 tCO_2/y from flue gas using an amine-based system was installed at the brown coal-fired Loy Yang A power plant in 2008 (Feron, 2012). The project was funded by the Victorian State Government (through the Energy Technology Innovation Strategy programme), BCIA, Loy Yang Power and CSIRO. It formed part of the Latrobe Valley Post Combustion Capture Project (Hooper, 2009). The pilot plant is currently testing a range of solvents for capturing CO_2. The BCIA 2011 funding round provided a A$1.5 million grant to integrate SO_2 and CO_2 removal in a single column (BCIA, 2011).

Another pilot CO_2 capture facility will be built at the Loy Yang power plant that will be capable of operating around the clock (BCIA, 2014). The collaboration project between CSIRO and IHI Corporation in

Japan entails a 2 y evaluation of two advanced liquid absorbents, two advanced process designs and an advanced gas/liquid contractor. The combination of these three aspects is expected to result in a 40% reduction in the absorbent energy requirements compared to a standard amine post-combustion process. A 0.5 tCO_2/d pilot plant will be designed and manufactured by IHI in Japan, before being installed at the Loy Yang plant. BCIA has provided a A$650,000 grant.

International Power carbon capture plant

A post-combustion capture plant is operating at the GDF Suez Hazelwood power plant (formerly International Power Hazelwood). The 25 tCO_2/d plant, which began operating in 2009, captures CO_2 from the flue gas using an ammonia solvent. The captured CO_2 is then mixed with the ash water to form saleable calcium carbonate (International Power, 2012). The project was partly funded by the Australian and Victorian State Governments as part of the Latrobe Valley Post Combustion Capture Project.

South West CO_2 Geosequestration Hub project

The hub (a CCS Flagship project) plans to transport CO_2 captured from various industrial sources, including a coal-based urea plant, alumina production and power generation, via a pipeline network and inject it into an underground onshore storage site in Western Australia (*see* www.dmp.wa.gov.au/documents/South_West_Hub.pdf; www.globalccsinstitute.com/project/south-west-co2-geosequestration-hub-formerly-collie-south-west-hub). The Australian and Western Australian governments, amongst others, are funding the project.

Tarong post-combustion carbon capture project

CSIRO, in collaboration with Stanwell Corp, has installed a pilot plant to capture 100 kg/h (1000 t/y) of CO_2 from a flue gas slipstream at the Tarong power station near Kingaroy, Qld. The pilot plant was officially opened in December 2010. The A$5 million project received funding from the Australian Government as part of the Asia-Pacific Partnership on Clean Development and Climate. Initial operation of the facility utilising MEA as the solvent finished in 2011. Work with concentrated piperazine, with funding from ANLEC R&D, was completed in April 2013 (Huang and others, 2013).

2.6 Research organisations

This section covers two research organisations that carry out research on CCT and CCS and are partly funded by the Australian Government.

Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC)

The CO2CRC (*see* www.co2crc.com.au) is a collaborative research organisation focused on the RD&D of technologies for CO_2 capture and storage from large stationary sources. It is a joint venture with participants from government (state, national and international), research organisations, industry and universities. Funding comes from the Commonwealth Government Cooperative Research Centres Programme, other Australian and State Government programmes, and CO2CRC participants (including industry). On 2 August 2013, the CO2CRC announced that it had signed an agreement with the Australian Government concerning A$51.6 million of funding from the Education Infrastructure Fund as part of the

Clean Energy Future package (CO2CRC, 2013b). The investment will support R&D related to the CCS Flagships and CCS deployment. CO2CRC's research portfolio includes work on pre- and post-combustion CO_2 capture (such as solvent, membrane, adsorbent and cryogenic/hydrate separation technologies). CO2CRC also works with, and advises, industry and the government on CO_2 capture studies and pilot projects.

CSIRO

The Commonwealth Scientific and Industrial Research Organisation (CSIRO, *see* www.csiro.au) is Australia's national science agency which supports R&D through 11 national Flagship programmes, one of which is the Energy Transformed Flagship. CSIRO is working with ANLEC R&D, State Governments and universities to develop a national research programme for low emission technologies. Its Energy Technology Division is researching coal gasification for low emission power generation with the aim of improving performance, reducing costs and increasing its adoption at a commercial scale. It includes research on the fundamentals of coal gasification, syngas cleaning, processing and membrane-based gas separation, and post-combustion CO_2 capture and storage. Pilot post-combustion capture facilities are operating at the Loy Yang and Tarong power plants (*see* Section 2.5). A pilot plant has also been constructed at the Huaneng Changchun power station in China. The post-combustion CO_2 research links with the Australian Government's CCS Flagships programme. Research is also being carried out on technologies to increase the efficiency and safety of underground coal mining while lowering fugitive emissions, coal preparation, liquid fuels, coal-fired diesel engines and direct carbon fuel cells. Funding cuts of A$111.4 over the next 4 years (outlined in the 2014–15 Budget – *see* www.budget.gov.au/2014-15/content/bp2/html/bp2_expense-17.htm) are likely to affect some of these research projects.

3 China

China is the world's most populous country with the second largest economy. It is the biggest energy consumer, with coal playing a crucial role in meeting its energy needs – about 70% of primary energy consumption is from coal. China is the largest producer and consumer of coal in the world, accounting for just over half of 2012 global coal consumption. In this year, China produced some 3549.1 Mt of coal and consumed about 3665.9 Mt (IEA, 2013c). Despite its ample resources (third largest behind the USA and Russia), China is currently the world's biggest coal importer, overtaking Japan in 2011. About 288.8 Mt were imported in 2012, with over 60% coming from just two countries, namely Indonesia (40%) and Australia (21%). The amount of imported coal reflects the bottlenecks in transporting domestic coal to the end user. About half of China's coal reserves are in the provinces of Shanxi and Inner Mongolia in northern China (where the majority of the state-owned coal mines are based), whereas the major consumers are in the East.

More than half of China's coal is consumed in power and heat generation. Power generation capacity has grown very rapidly, over 200% in the ten years to the end of 2010. Total installed capacity was 963 GWe in 2010, with fossil fuels contributing 73% (707 GWe). Only ~20 GWe came from gas- and oil-fired power plants, with the rest generated from coal (Minchener, 2012b). This shows the dominance of coal-fired power generation in China. Power generation from coal is still rising, and is expected to continue to grow, because of China's large coal reserves, even as other cleaner fuels increase market share. In 2012 alone, coal plant with a net capacity of 80 GW was installed (IEA, 2013b).

China's high and rising energy demand, underpinned by fossil fuels, has resulted in China becoming the world's largest emitter of CO_2 – 8 $GtCO_2$ from fossil fuel combustion in 2011 or about a quarter of global emissions. China overtook the USA in 2007 to become the world's largest emitter of energy-related CO_2, although in cumulative and per-capita terms the USA remains the larger emitter. Chinese CO_2 emissions more than tripled between 1990 and 2011. Since 1990, emissions in the electricity and heat generation sector grew the most, reaching 4.01 $GtCO_2$ in 2011, some 50% of Chinese CO_2 emissions. Coal combustion accounted for 6.62 $GtCO_2$. Electricity generation emitted 764 gCO_2/kWh; some 4754.7 TWh of electricity was generated (IEA, 2013b). In the previous year (2010), 967 gCO_2/kWh came from just coal-fired power generation (IEA, 2012c).

3.1 Economic and energy policies

A product of the planned economy, China operates on the basis of a five-year planning cycle. The State Government's Five-Year Plan (FYP) for National Economic and Social Development sets out the country's economic, social and environmental development, and provides guidelines, policy frameworks and targets to be met. Provincial governments and local organisations provide detailed five year work plans for achieving the designated targets. The relevant authorities of the State Government issue FYPs for specific sectors (such as energy development) that provide guidelines, principles, goals, targets, key tasks and policy measures for the sector's development, in line with the national targets. Although the timescale is nominally five years, many policies and directives flow through from one plan to the next. There is also an ongoing process of review and revision over the 5 y lifetime of the plans.

The current ***12th FYP for National Economic and Social Development*** (covering 2011–15) builds upon the previous 11th FYP, which for the first time addressed environmental issues. The key themes of the 12th FYP are rebalancing the economy, addressing social inequality and protecting the environment (Delegation of the European Union in China, 2011). The Plan gives a high profile to energy, climate change and environmental issues. The need to meet China's increasing energy demand, while simultaneously reducing pollution and ensuring a stable, reliable and clean energy supply, has become an ongoing priority of the government. This is being supported by a significant investment commitment of more than RMB3 trillion in the environmental protection industry over the term of the plan. China will develop seven strategic emerging industries, which include energy conservation and environmental protection, and new energy. The State Government will help the development of these industries by establishing industrial standards and supporting the entry of the main products into the international market.

Important R&D, energy and environmental targets set in the 12th FYP for the period to 2015 include:

- R&D expenditure to account for 2.2% of GDP, with an emphasis on scientific and technological innovation leading to Chinese intellectual property rights;
- energy consumption per unit of GDP to be cut by 16% from 2010 levels;
- CO_2 emissions per unit of GDP to be cut by 17% from 2010 levels;
- non-fossil fuel use to account for 11.4% of primary energy consumption, with a target of 15% for 2020;
- SO_2 and NOx emissions to be cut by 8% and 10%, respectively, from 2010 levels. These include those from coal-fired power generation. New emission standards for coal-fired power plants came into effect in January 2012.

R&D funding in the 12th FYP is set to increase from the previous plan's 1.7% to reach 2.2% of GDP. This includes funds from both the public and private sectors. Consequently, CCT and CCS RD&D projects may benefit from the higher expenditure since these are considered to be priority technologies. Certainly, RD&D of polygeneration (power and chemicals) from coal, coal-based liquid fuels, and synthetic natural gas from coal will continue.

China has ratified the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Since it is classified as a developing country, China has no emission limits under either accord. However, a national target has been set. The CO_2 emission target in the 12th Plan is in line with an earlier pledge to cut CO_2 emissions per unit of gross GDP by 40% to 45% from 2005 levels by 2020 (Minchener, 2011). Measures to achieve this include meeting 15% of the total energy demand with non-fossil fuels and introducing significant energy efficiency improvements.

China has huge resources of renewable energy, and its percentage within the energy mix will increase. However, coal is expected to continue to be the dominant fuel for some time as China is dependent on coal use to drive economic growth. Therefore the development and deployment of CCTs are crucial to promote sustainable development in China. The development of advanced power generation technology improves the efficiency of coal-fired power plants and hence alleviates CO_2 emissions. The 12th FYP includes a commitment to the development of clean and efficient large-capacity coal-fired generating units. The State Council's ***12th FYP for Energy Development***, released in January 2013, outlines the need for the construction of another 300 GW of coal-fired power plants by 2015. Of this number, 70 GW will be combined heat and power projects and 50 GW will use low calorific value coal as the fuel (Lee, 2013). Others will be either 600 or 1000 MWe high efficiency supercritical or USC units. The Energy Development plan also advocates the development of clean and efficient coal power generation.

In October 2012, the Information Office of the State Council published a White Paper on China's ***Energy Policy 2012*** outlining the policy on energy development (State Council, 2012). An important strategic task of the Chinese government is to maintain long-term, stable and sustainable use of energy resources. The policy is concerned with 'giving priority to conservation, relying on domestic resources, encouraging diverse development, protecting the environment, promoting scientific and technological innovation, deepening reform, expanding international cooperation, and improving the people's livelihood' It indicates how some of the goals in the 12th FYP for National Economic and Social Development, such as lowering CO_2 emission per unit of GDP by 17% from 2010 levels, could be met. The White Paper highlights the importance China gives to CCT and CCS in its promotion of the development of clean and efficient thermal power, and energy technology R&D. A need to develop IGCC power generation, and demonstration projects of carbon capture, utilisation and storage (CCUS) is noted. Research into the storage or utilisation of CO_2 is often separated from research into its capture. China is taking steps to ensure that new research policies bring both these actions together. The utilisation of CO_2 for enhanced oil recovery, in the food industry and other uses has direct monetary benefits. Hence the importance China attaches to CO_2 utilisation. Thus China's use of the acronym CCUS in preference to CCS.

The White Paper also states that the government will continue to support large enterprises, R&D institutes, colleges and universities to set up innovation platforms that can conduct independent R&D and make breakthroughs in China's core technologies. China aims to develop its own clean coal and CCS technologies that can be marketed abroad. Because most of China's energy and large-scale industrial companies are state-owned enterprises, the government is able to significantly influence the adoption of certain technologies through its central planning, policies and state budgets.

3.2 RD&D policies for CCT and CCS

The Ministry of Science and Technology (MOST) is responsible for RD&D in China. In 2006, MOST published the ***National Medium- and Long-Term Science and Technology Development*** plan (*see* http://english.gov.cn/2006-02/09/content_183426.htm) that sets out China's direction for R&D over the period 2006 to 2020. The plan included the target of investing 2.5% of GDP in R&D by 2020 (Tan, 2010). Developing technologies related to energy and environmental protection were among the top priorities. These include the development of efficient, clean and near-zero emissions fossil energy and CCUS (Kastmann and others, 2013; Minchener, 2011).

Five-year plans have been set that provide the guidelines, objectives and the general framework for China's science and technology development. The latest ***12th FYP on Science and Technology Development*** (*see* www.most.gov.cn/mostinfo/xinxifenlei/gjkjgh/201107/t20110713_88230.htm) was issued in July 2011 by MOST. The focus for clean coal is on the development of coal gasification, liquefaction, coal-based chemical processing and other clean conversion technologies, and on IGCC, USC and circulating fluidised bed power generation. The development of CCUS and pollutant control technologies for coal-fired power plants are included. International collaboration on research activities, such as energy and the environment, is additionally recommended. The Plan reiterates that R&D expenditure will increase from 1.7% of GDP in 2010 to 2.2% of GDP by 2015, in line with the national target.

The development of the CCTs identified in the Plan are expanded in the ***12th FYP for Clean Coal Technology***, which covers the period 2011–15 and was released by MOST in April 2012 (*see* www.most.gov.cn/fggw/zfwj/zfwj2012/201204/t20120424_93882.htm). The key core technologies for R&D cover:

- coal upgrading;
- high efficiency clean power generation;
- advanced coal conversion (including clean coal-based fuels and polygeneration); and
- high efficiency, low emission coal-fired industrial boilers.

China has large coal reserves but only limited domestic supplies of oil and gas, which cannot meet current and projected future demand. Hence the interest in coal conversion for energy security. The Plan for clean and efficient power generation calls for research to lay the foundation for the demonstration of advanced USC power generation (600 MW unit), supercritical circulating fluidised bed boiler (600 MW unit), USC combustion (600°C/1200 MW), IGCC (including heavy duty gas turbines), and the capture and utilisation of CO_2 from a 30 MW unit (3–5 tCO_2/y). Advanced pollution control technologies include research into selective catalytic reduction of NOx and low NOx burners. An industrial demonstration of an IGCC polygeneration plant generating 400–500 MW of power and 1 million t of liquid fuels or chemicals is planned, but no target date is given.

Various other policies and plans have been issued to facilitate the development of clean energy development, highlighting the importance attached by China to CCT and CCS RD&D. Those covering CCT and CCS include the National Climate Change Programme (June 2007), Scientific and Technological Actions on Climate Change (June 2007), 12th Five Year Work Plan on Controlling Greenhouse Gas Emissions (November 2011), 12th FYP for the Coal Industry (March 2012), 12th FYP for Energy Development (January 2013), Policies and Actions for Addressing Climate Change (the latest issued in 2013) and the National 12th Five Year Special Plan for Carbon Capture, Utilisation and Storage Technology Development (March 2013).

In April 2013, the National Development and Reform Commission (NDRC) issued the ***Climate [2013] Document No. 849 on promoting carbon capture, utilisation and storage pilot demonstration***. The NDRC is an important government organisation, being responsible for China's overall policy/long-term planning, including the development plans within the 12th FYP for National Economic and Social Development. The Document has been sent to all provincial, autonomous regions, special zones, municipal and city governments, as well as to a wide range of ministries and commissions, all state--owned key enterprises and industry associations. Its purpose is to promote CCUS pilot and demonstration projects throughout the thermal power, coal chemical, cement and steel industries (NDRC, 2013) by:

- developing pilot and demonstration projects for the full CCUS technology chain. This includes pre-combustion, post-combustion, oxyfuel combustion and other CO_2 capture pathways;
- developing CCUS demonstration projects and sites;
- exploring and establishing financial incentive mechanisms;
- strengthening strategy and planning for CCUS development;
- promoting CCUS standards and regulation; and
- strengthening capacity building and international collaboration.

This indicates that CO_2 capture projects will be encouraged in the power industry. The Document also states that research institutes should actively engage in pilot and demonstration projects to solve technical issues. Subsequently, the Ministry of Environmental Protection issued a document on environmental impact issues of CCUS (Zhang, 2014).

The RD&D priority actions required for the different CO_2 capture technologies to meet the milestone goals of 2015, 2020 and 2030 are shown in Figure 1. These are the result of a high level stakeholder meeting held in Chongqing in June 2011 to develop a technology roadmap for the development of CCUS technology (Zhang and others, 2013). The NDRC, with assistance from the Asian Development Bank, is compiling a new comprehensive government-endorsed roadmap for CCS, which, in turn, is expected to encourage more demonstration projects in China. The roadmap is set to launch at least two large-scale CCS demonstration projects by 2016, with an installed capacity to capture at least 2 $MtCO_2$/y. It will include plans for all the different capture technologies, and is looking to establish pilots at several different locations. The roadmap is due in April 2014 (Kastmann and others, 2013).

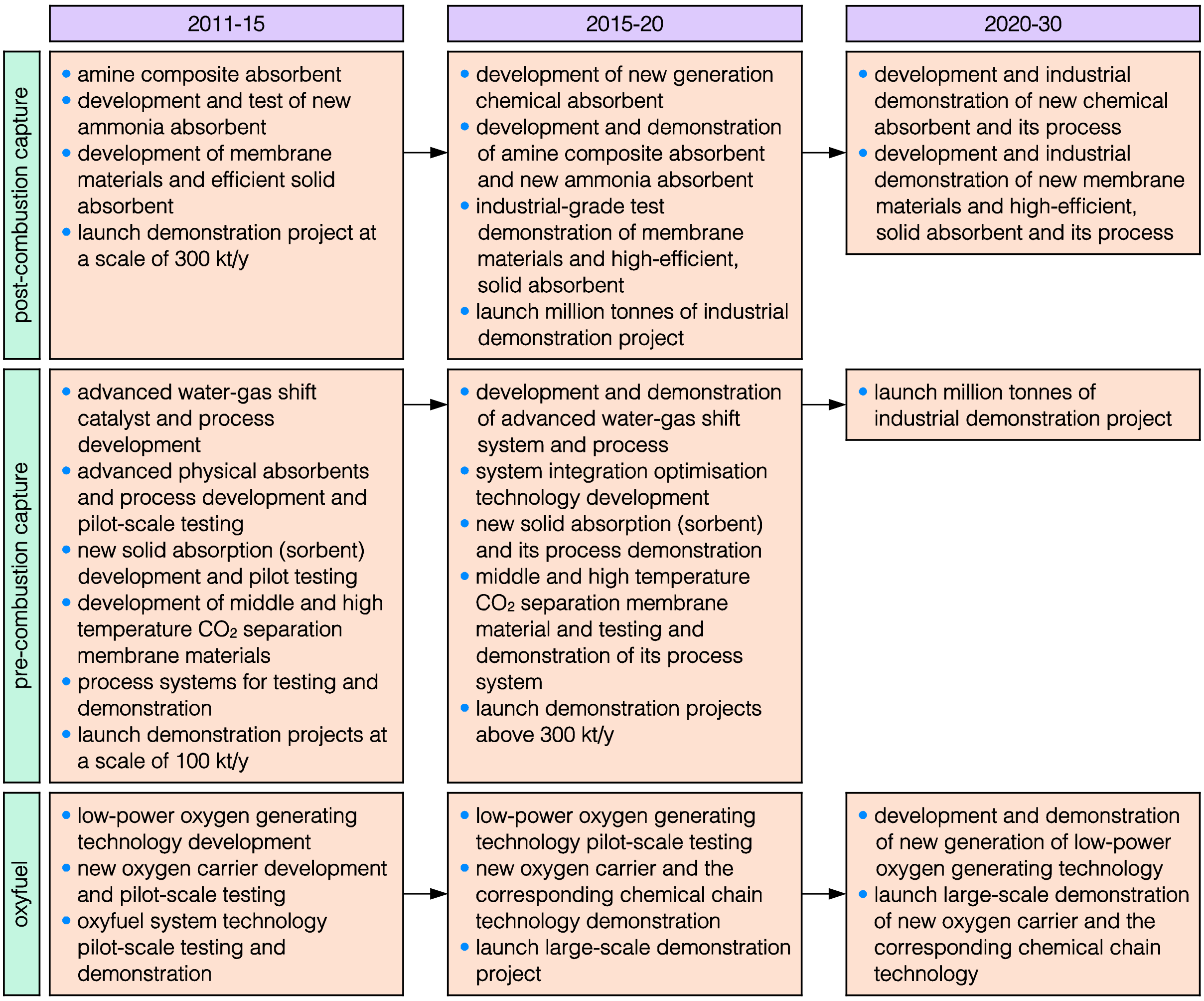

Figure 1 RD&D actions required for CO_2 capture (Zhang and others, 2013)

3.3 RD&D funding

China's R&D investment is linked to its national goals, such as those outlined in the 12th FYP. The energy RD&D budget is allocated first by the Ministry of Finance to MOST, NDRC, the National Natural Science Foundation of China (NSFC) and the Chinese Academy of Sciences (CAS). MOST, NDRC and NSFC then allocate their funds in line with their missions to research institutes (including national laboratories), higher education institutions and enterprises (including non-state owned ones). As well as funding from the Ministry of Finance, CAS can also get contract funds from MOST, NDRC and NSFC. The little amount of money for RD&D received by NDRC principally goes to deployment, demonstration and diffusion (Kempener and others, 2010). In 2012, China spent RMB560.01 billion on science and technology R&D (a 16.7% increase over the previous year), of which RMB261.36 billion came from central government and RMB298.65 billion from provincial and local governments. Some RMB15.79 billion was spent by the government and industry on coal mining and washing, and RMB4.68 billion on power and heat generation R&D (State Statistics Bureau and others, 2013).

The distribution of funds among the many government organisations and its further allocation makes it difficult to obtain figures on the amount the Chinese government is spending on CCT and CCS RD&D. Even within MOST, for example, the funding comes from different departments. Nevertheless, the majority of money for CCT and CCS RD&D is managed by MOST, principally through the National Basic Research Programme (973 Programme), National High-Tech R&D Programme (863 Programme), and the National Key Technology R&D Programme.

The ***863 Programme*** (*see* www.863.gov.cn) was launched in 1986 to stimulate technological research and innovation in areas of strategic importance to China's economic and social development. One of its aims is to develop technologies that could be marketed abroad. Clean coal and CCS technologies supported include IGCC and coal-to-liquid demonstration plants, oxyfuel combustion and chemical looping combustion. The programme has provided seed funding to some 30 gasification research projects, including five IGCC demonstrations. Three of the IGCC demonstrations have been at power plants and two at coal-to-liquids plants (Best and Levina, 2012). There is a significant programme of work on the development of lower cost CO_2 capture technologies, based on adsorption and absorption. There is an integrated project to establish techniques for CO_2 emissions reduction, in conjunction with low NOx combustion, SOx control and multi-pollutant removal (Minchener, 2010, 2011). Funding for CCT research programmes was RMB45 million per year during the 11th FYP (2006–10) (Tan, 2010). RMB300 million (US$43 million) was allocated to CCS from 2008–10 (Best and Levina, 2012). Funding is continuing under the 12th FYP (2011–15).

The ***973 Programme*** (*see* www.973.gov.cn), launched in 1997, supports fundamental research to meet the nation's strategic needs. This includes CCT and CCS, and covers coal gasification and pyrolysis, polygeneration and gas turbines, as well as the use of CO_2 for enhanced oil recovery, CO_2 separation and CO_2 emission mitigation (Minchener, 2010). On average, each project receives RMB20–30 million over the 5 y time span. Each project has to go through a mid-term evaluation after 2 y, and the funding for the next 3 y is then based upon the evaluation (Tan, 2010). In 2011, the budget for the whole 973 Programme was RMB4.5 billion, of which 9.1% (RMB409.5 million) was spent on energy projects and 8.1% (RMB364.5 million) on resources and environmental sciences (MOST, 2013).

The ***National Key Technology R&D Programme***, also known as the Support programme, funds applied R&D projects in fields that include energy and environmental protection. Research and demonstration of oxyfuel combustion with CCS and IGCC with CCUS are included in the programme. Details of CCS projects funded through the programme can be found on the www.ccuschina.org.cn website. These include the Shenhua Erdos CCS and Shengli EOR projects. Projects typically last about three to four years, and are only partly funded by the government.

Another important funding source for basic research is NSFC. It supports, for example, fundamental research on CO_2 storage. The NSFC and Shenhua Group set up the ***Joint Fund of Coal Research***, which mainly supports basic research in coal development and utilisation. Coal utilisation includes basic research into thermal power generation (such as advanced USC pulverised coal-fired generation and USC circulating fluidised bed boilers), clean coal conversion, energy conservation, pollution control (for example, ultrafine particulate control), and related new energy areas. The first 3 y phase (2011–13) has a budget of RMB150 million; the budget for 2013 is about RMB49 million (NSFC, 2013).

At the local level, provincial and municipal governments are also actively involved in funding RD&D. During the past 10 years or so, Chinese local governments' science and technology appropriations have seen a steady increase, and even surpassed those from the State Government in 2008. Shanghai has consistently topped the nation with nearly 5% of its GDP devoted to science and technology RD&D. Local government's science and technology appropriations play an important role in providing matching funds for MOST's key projects. Projects that have received funding from local government include the GreenGen IGCC, Shenyang IGCC and Dongguan IGCC projects (*see* Section 3.5).

In addition to direct funding from the various governments, China is encouraging the private sector to undertake a greater role in RD&D. Tan (2010) outlines some of the policies the State Government has introduced to stimulate private sector funding of RD&D, such as tax policies.

3.4 International collaboration

China collaborates with several countries on CCT and CCS RD&D through membership of international organisations (such as the Global CCS Institute, represented by MOST), bilateral and multilateral agreements, academic co-operation and industrial collaboration. The ***Australia-China Joint Coordination Group on Clean Coal Technology***, for example, focuses on the development, application and transfer of low emissions coal technology (*see* Section 2.4). The US$150 million ***US-China Clean Energy Research Institute*** (*see* www.us-china-cerc.org/index.html), announced in November 2009, conducts joint research on advanced power generation (such as IGCC), clean coal conversion technology, oxyfuel combustion, pre- and post-combustion CO_2 capture, and CO_2 utilisation and storage. Initial five year joint work plans for the US and Chinese participants were signed on 11 January 2011 (Fletcher and Zhang, 2013).

The ***China-UK Near Zero Emissions Coal (NZEC) Initiative*** (*see* www.nzec.info) is being carried out in three phases, the first phase of which has been completed. The goal, following Phase 3, is to have constructed and operated a coal-fired power plant with integral CCS in China by 2015. The Initiative was the result of an agreement between the UK Government and MOST, with funding of up to £3.5 million being provided by the UK Government for Phase 1 (Luo and others, 2009). The European Commission has allocated funding of up to €50 million for the construction and operational phases of the project. Phase 2 has started and is being funded by Norway and the UK (Minchener, 2011). More CCT and CCS collaboration projects are described in Minchener (2010, 2011) and IEA (2009).

3.5 Demonstration and development projects

This section describes the principal CCT and CCS national development and demonstration projects in China concerning the power industry. Most of the CCS demonstration projects are driven by the major state-owned power generating, coal and oil companies, some of which include an international partner.

There is a significant level of research at Chinese universities on CCTs and CCS, usually as part of the national R&D programmes.

National 700°C USC Coal-Fired Power Generation Technology Innovation Consortium

In July 2010, the Chinese government (National Energy Administration, NEA) launched this project with the objective to develop and commercialise advanced USC power generation technology. The 18 members include Chinese power companies, manufacturers, equipment suppliers, steel suppliers and research institutes. There are four technical sub-committees in the national consortium, covering plant design, materials R&D, boiler and turbine. A technology roadmap for the development and testing of the core technologies has been drawn up, with the eventual goal of building and operating a demonstration plant by 2020. Funding for the project comes from NEA and MOST through national research funds, with RMB50 million allocated (Nicol, 2013; Sun and others, 2012).

MOST has set up a related research programme 'Research on advanced boiler's key pipes of ultra-supercritical thermal power units', under the 863 Programme. The consortium of 10 members has received funding of RMB29.5 million (Sun and others, 2012).

35 MWth oxyfuel industrial demonstration project

A 35 MWth oxyfuel combustion boiler is planned by Huazhong University of Science and Technology and other participants at Yingcheng, Hubei Province. About 50,000–100,000 tCO_2/y will be captured and stored in salt mines. The project, which began in May 2011, is funded by the National Key Technology (Support) programme (Best and Levina, 2012; Kastmann and others, 2013; www.ccuschina.org.cn).

Datang Daqing oxyfuel project

China Datang Corp is collaborating with Alstom to build a 350 MW coal-fired heat and power cogeneration plant using Alstom's oxyfuel combustion technology in Daqing, Heilongjiang province (*see* www.globalccsinstitute.com/project/datang-daqing-ccs-project). About 1 $MtCO_2$/y will be captured and stored in a deep saline formation and used for EOR. Pre-feasibility studies for the capture plant are expected to be concluded by 2015.

Dongguan Taiyangzhou IGCC project

Dongguan Taiyangzhou Power Corp is planning to construct an 800 MW IGCC plant with CCS in Dongguan City, Guangdong Province (*see* www.globalccsinstitute.com/project/dongguan-taiyangzhou-igcc-ccs-project). The project, in which the Xinxing Group and Nanjing Harbin Turbine Co are also partners, will capture up to 1 $MtCO_2$/y to be stored in depleted onshore oil and gas reservoirs. It forms part of the Reform and Development Plan for the Pearl River Delta, which is endorsed by the State Council. During 2005 to 2010, the project received financial support for IGCC R&D from the government's National 863 Programme. Start-up is provisionally planned for 2015, but seems optimistic.

Dongying CCS project

This second joint venture of China Datang Corp and Alstom plans to build a 1000 MWe combined heat and power plant in Dongying, Shandong Province. By 2020, some 1 $MtCO_2$/y will be captured using one of

Alstom's CO_2 capture processes (oxyfuel combustion or post-combustion capture with chilled ammonia or advanced amines). The CO_2 will be used for EOR in nearby oil fields (*see* www.cslforum.org/technologyroadmap/china.html).

GreenGen IGCC project

The GreenGen Co was launched in 2005 with support from NDRC, MOST and other Chinese ministries. The consortium consists of China's five largest power companies (under the China Huaneng Group with 51% equity), two of the biggest coal companies, an investment company and the only non-Chinese member, Peabody Energy. The objective is to achieve high efficiency power generation with near-zero emissions. The project is being implemented in three stages. In Stage 1, a 250 MWe IGCC plant (based on a Chinese entrained flow gasifier) was built in Tainjin, south east of Beijing. As well as power generation, the plant also supplies some syngas and heat to local chemical plants. Commercial operation began on 7 December 2012, and the associated GreenGen R&D Centre was opened. Small-scale CO_2 capture is expected to start in 2013 with some of the CO_2 sold to the food and beverage industry. The next two stages will lead to the construction and demonstration of a 400 MWe IGCC system with hydrogen production via coal gasification, power generation from a combined-cycle gas turbine and fuel cells plant (IGFC), and the capture of up to 2 $MtCO_2$/y for use in EOR. The goal is to achieve a 55–60% generation efficiency with more than 80% of the CO_2 being separated and reused by 2020. Financing of the earlier stages of the project was through the GreenGen consortium, government agencies, banks (including the Asian Development Bank) and other sources. The project was approved as part of the National 863 Programme, and is also part of the Tianjin Lingang Industrial Zone Circular Economy Plan. In April 2008, GreenGen and Tianjin officials signed an agreement proposing two further 400 MWe IGCC units (Henderson and Mills, 2009; Jaeger, 2012; Xu, 2013; www.globalccsinstitute.com/project/huaneng-greengen-igcc-project-phase-2).

Haifeng integrated CCS demonstration project

China Resources Power is planning to capture 1 Mt/y of CO_2 from a flue gas slipstream from the planned Unit 3 at its Haifeng power plant (*see* www.globalccsinstitute.com/project/china-resources-power-haifeng-integrated-carbon-capture-and-sequestration-demonstration). The CO_2 will be injected into an offshore saline formation in the northern South China Sea or used for EOR. Construction of the carbon capture facilities is expected to start in February 2016 and be completed by August 2018. A full feasibility study was due to start in May 2014.

Lianyungang IGCC project

This project, under the Energy Power Research Centre of the CAS, consists of a 1200 MW IGCC power plant (with coproduction of fuel and chemicals) built alongside two 1300 MW USC power plants in Lianyungang, Jiangsu province (*see* www.ccuschina.org.cn; www.globalccsinstitute.com/project/lianyungang-igcc-ccs-project). Up to 1 Mt/y of CO_2 would be captured from the syngas and USC flue gas, some of which would be stored in onshore deep saline formations and the rest utilised for EOR or chemical production. Heat integration between the IGCC and USC power plants is being investigated, as well as a solar heat collector to further improve the efficiency of the system. The project is a key feature of the Lianyungang Clean Energy Innovation Industrial Park, set up to promote the development of industrial-scale, low carbon facilities. The feasibility study was due to be completed at the end of 2011, with construction beginning in 2012. The project is currently awaiting approval from NDRC.

Shanghai Shidongkou project

This demonstration project in Shanghai was a result of the successful 3000 t/y pilot-scale capture of CO_2 at the state-owned China Huaneng Group's Gaobeidian power plant, Beijing. Some 120,000 tCO_2/y (99.9% pure) is currently being captured from the flue gas from two 660 MW boilers at the Shanghai Shidongkou No. 2 USC power plant (~4% of total flue gas emissions). An amine-based post-combustion capture process is employed that has been operating since 2010. It is the largest coal-fired power plant post-combustion capture unit in the world, and had a total investment cost of RMB150 million (Best and Levina, 2012). Work continues to optimise plant performance and the capture system, and to test the performance of new CO_2 capture solvents. The second phase of the project will capture CO_2 from an additional two 660 MW USC units (Global CCS Institute, 2013; www.cslforum.org/technologyroadmap/china.html).

Shanxi International Energy Group oxyfuel project

The Shanxi International Energy Group is planning to build a 350 MWe oxyfuel combustion supercritical power plant at Taiyuan, Shanxi province (*see* www.globalccsinstitute.com/project/shanxi-international-energy-group-ccus-project; www.zeroco2.no/projects/shanxi-international-energy-oxyfuel-project). More than 2 $MtCO_2$/y will be captured using Air Products' oxyfuel combustion technology. The captured CO_2 will be utilised and/or stored. Air Products is providing a feasibility study and detailed cost estimates. A final investment decision is expected in 2014. The US Department of Energy and China National Energy Administration have included this project in the US-China Fossil Energy Protocol (Annex II: Clean Fuels) aimed at promoting scientific and technological cooperation.

Sinopec Shengli post-combustion capture and EOR project

Sinopec has begun to expand the CO_2 capture capacity at its Shengli power plant in Dongying, Shangdong province (*see* www.zeroco2.no/projects/sinopec-shengli-pcc; www.globalccsinstitute.com/project/vsinopec-shengli-oil-field-eor-project-phase-2). An integrated pilot plant currently captures 40,000 tCO_2/y. This second phase will retrofit post-combustion control to an existing fluidised bed boiler power plant to capture 1 $MtCO_2$/y, which will be transported by pipeline for EOR in the nearby Shengli oilfield. A commercial deal has already been signed with the Shengli Oilfield Company. A final investment decision is expected in 2013–14, with an operational date of 2017. The project is partly being funded through the Support programme.

Tianjin Beitang Power Plant project

China Guodian Corporation plans to construct a 20,000 t/y CCUS demonstration project at the Tianjin Beitang Power Plant by the end of 2012. A chemical absorption technique will be used to capture CO_2 for utilisation in the food industry (Best and Levina, 2012; www.ccuschina.org.cn).

3.6 Research organisations

This section describes the principal national research organisations. RD&D activities involving international collaboration are covered in Section 3.4.

Administrative Centre for China's Agenda 21 (ACCA21)

ACCA21, which is affiliated to MOST, was established in 1994 to promote the implementation of China's Agenda 21 for sustainable development in the 21st century. One of its functions is to study policies and measures on GHG emission reduction, including strategies for key low carbon technologies such as CCUS. ACCA21 was involved in producing the CCUS technology roadmap, as well as other reports on CCUS (*see* www.acca21.org.cn). It manages national RD&D projects, as well as international collaboration projects, such as the NZEC project.

Chinese Academy of Sciences (CAS)

The CAS (*see* http://english.cas.cn) is the world's largest science and technology research organisation. It advises the Chinese government on science policies and priority areas of research, as well as directing many research institutes and research programmes. One of the major research directions identified in the CAS Development Planning in the 12th FYP period was clean and high efficiency utilisation of low rank coal (CAS, 2012).The ***Institute of Coal Chemistry*** (*see* http://english.sxicc.cas.cn) principally conducts basic and applied research and commercialises new technologies in energy and the environment, advanced materials and green chemistry. Its ***Pulverized Coal Gasification Engineering Research Centre*** is involved in developing coal gasification technologies and equipment for commercialisation. The Centre has implemented numerous State-level R&D projects. The ***Institute of Engineering Thermophysics*** (*see* http://english.iet.cas.cn) carries out basic and applied research into IGCC/cogeneration, circulating fluidised bed, advanced energy power systems and other topics. Some of the projects are funded under the National 973 and 863 programmes. Research undertaken at the ***Institute of Process Engineering*** (*see* http://english.ipe.cas.cn) includes fluidised beds (such as fluidised bed gasification technology for caking coal), coal topping, decoupling combustion and unconventional green processes. It includes research into CO_2 capture using ionic liquids, pollution control and waste product utilisation.

Energy Research Institute

The Energy Research Institute (*see* www.eri.org.cn), which is part of NDRC, conducts comprehensive studies on China's energy issues, including energy economics, energy security, energy technology policy, energy and the environment (such as emissions from coal-fired power plants and climate change), and renewable energy. The institute also facilitates international cooperation, for example, in the fields of emission inventories, modelling tools and Joint Implementation mechanisms.

Thermal Power Research Institute (TPRI)

TPRI (*see* www.tpri.com.cn) is a research organisation, based in Xi'an, that is involved mainly with engineering technologies and equipment for thermal power plants. It is controlled by its five shareholders, namely China Huaneng Group, China Datong Corp, China Huadian Corp, China Guodian Corp and China Power Investment Corp R&D activities cover the fields of thermal power plant operation, power plant automation and information management, clean coal power generation, gas turbine technology and power generation by renewable energy resources. TPRI has been actively involved in key R&D projects funded by government authorities, such as NDRC and MOST, and has been active in many international cooperation projects. The key coal programmes include RD&D of key equipment for 700°C USC power generation units (funded by NDRC), and research on key technologies for the economic and safe operation of power plants, on mechanisms and behaviour of key materials for advanced power generation systems, and materials selection for advanced 700°C USC power generation units, all funded by MOST.

Other important research institutions carrying out research into CCTs and CCS include the ***Huaneng Clean Energy Research Institute (CERI)***, ***Tsinghua-BP Clean Energy Research & Education Centre*** (financially supported by BP Company), ***National Institute of Clean- and Low-Carbon Energy*** (NICE, *see* www.nicenergy.com) which is funded by the Shenhua Group, and ***Shenhua Guohua Electric Power Research Institute***.

4 European Union

The European Union (EU) is an economic and political partnership between 28 European countries (Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, UK). Croatia was the last country to join in July 2013. In this chapter, EU28 denotes all 28 EU member states, whereas EU27 excludes Croatia.

The EU27 produced some 582.4 Mt coal in 2012, a slight increase of 4.6 Mt over 2011. This makes the EU27 the fourth largest global coal producer (after China, USA, and India). Within the EU, Germany is the biggest coal miner (~197 Mt in 2012 and 188.6 Mt in 2011), although Poland is the largest steam coal producer. Germany is one of the main producers and users of lignite. Overall, the EU27 consumed some 781.4 Mt of coal in 2012, an increase of 11.6 Mt over 2011. Including Croatia, the EU consumed some 782.7 Mt in 2012 and 771 Mt in 2011 (IEA, 2013c). Some 199.6 Mt of hard coal was imported by the EU27 in 2011, with about 68% coming from just three countries, namely Russia (52 Mt), Colombia (47.6 Mt) and the USA (36 Mt) (EC, 2013a). The falling price and increased availability of coal, as a result of shale gas fracking in the USA, has led to a sharp increase in exports from the USA to the EU, particularly into the Netherlands and UK. In 2012, the EU was the world's largest importer of hard coal (Froggatt, 2013).

The EU boasts a varied mix of power generation technologies with nearly half of the generation fleet being low carbon. In 2011, gross electricity generation in the EU27 was 3279.6 TWh, with nuclear forming 27.6%, solid fuels (coal and its products, and peat) 25.9%, gases (such as natural gas, coke oven gas and blast furnace gas) 22.2%, renewables 21.3%, petroleum and its products 2.2%, and others 0.7% (EC, 2013a). The reliance on coal for power generation varies within the member states, with Poland generating over 86% of its electricity from coal in 2011 (IEA, 2013c). The EU27 emitted 3542.7 $MtCO_2$ from fuel combustion in 2011, with 1320 $MtCO_2$ originating from electricity and heat production. Some 1107.9 $MtCO_2$ came from coal and peat, compared to 1087.5 Mt in 2010. Overall, the EU27 emitted 352 gCO_2/kWh from electricity production in 2011, an increase over 2010 when 347 gCO_2/kWh was emitted (IEA, 2013b). The IEA quotes electricity output as 3250.7 TWh in 2011 and 3314.7 TWh in 2010.

The use of hard coal has risen since 2009 and lignite since 2010 in the EU. With the continuing cost advantage of coal over gas, this increase is expected to continue in the short term (Froggatt, 2013). However, coal use is expected to decline in the mid-term due to the closure of coal-fired power plants as a result of emission pollution regulations, in particular, the Large Combustion Plant Directive and Industrial Emission Directive.

4.1 Energy and climate policy

The European Commission's Directorate-General for Energy is responsible for developing and implementing European energy policy. Climate policy now comes under the Directorate-General for Climate Action, which was established in February 2010, climate change being previously included in the remit of the Directorate-General for Environment. The EU energy and climate policy aims to establish a sustainable, secure and competitive energy system. A comprehensive package of measures has been published by the European Commission (EC) to advance the aims.

The EU's energy policy is outlined in EC (2007a) and the Energy 2020 strategy for competitive, sustainable and secure energy in EC (2010). Three specific targets have been set to be met by 2020, known as the '20-20-20' targets:

- 20% cut in emissions in GHG, compared with 1990 levels;
- 20% increase in share of renewable sources in the energy mix; and
- 20% cut in energy consumption through increased energy efficiency.

These targets commit Europe to become a highly energy-efficient, low carbon economy, and were enacted through the climate and energy package in 2009 (*see* http://ec.europa.eu/clima/policies/package/). The targets have been implemented into national laws by the Member States, resulting in different policies within each country.

RD&D is seen as an integral part of achieving the 20-20-20 targets and the energy policy aims outlined in EC (2007a). The importance of the development of CCT and CCS for a low CO_2 fossil fuel future is also recognised, for example, in the EC's communication on sustainable power generation from fossil fuels (EC, 2007b). Both the EC (EC, 2008) and the European Parliament (Official Journal of the European Union, 2010) support the early demonstration of CCS technologies in power plants. CCS is perceived as a promising technology that will not only enable the EU to meet its climate objectives, but will also be a major contributor towards the EU's innovation, jobs and growth agenda. Europe cannot be decarbonised cost-effectively, and maintain security of energy supply, without CCS. A Consultative Communication on the future of CCS in Europe (COM(2013) 180) was launched by the EC, with the aim of initiating a debate on the options available to ensure its timely development. The Communication and the response received can be found at http://ec.europa.eu/energy/coal/ccs_en.htm, along with a list of Directives on CCS. A recent review of EU energy security strategy also recognised the need to support CCS demonstration projects to enable a long-term future for coal-fired power generation – one way of ensuring energy security in the EU (EC, 2014a).

The EU has set a long-term target of reducing GHG emissions by 80–95% to 2050 compared to 1990 levels. This goal also defines European energy technology policy towards 2050. The EC analysed the implications of the target in its ***Roadmap for moving to a competitive low-carbon economy in 2050*** (EC, 2011a) that covers all sectors of the economy, including power generation. The Roadmap outlines the milestones which would show whether the EU is on course for reaching its target, the policy challenges, and investment needs. The power sector is seen as having the biggest potential for cutting emissions, almost totally eliminating CO_2 emissions by 2050. The ***Energy Roadmap 2050*** (EC, 2011b) provides a similar analysis for the energy sector. It states that coal could continue to play an important role in a sustainable and secure supply in the future with the development of CCS and other emerging CCTs. Higher public and private investments in RD&D and technological innovation are seen as crucial in speeding-up the commercialisation of all the low carbon solutions in the energy sector.

A new policy framework for energy and climate covering the period 2020 to 2030 was proposed in January 2014 by the EC to continue the drive towards a low carbon economy that will ensure secure energy supplies and a competitive energy system (EC, 2014b). It will also assure that the EU will meet its 2050 GHG emissions goal. This ***2030 Framework for Climate and Energy*** abandons the binding individual country targets for renewables (as stipulated in the 20-20-20 targets set of policies). Instead, the EC is proposing legally binding targets for the EU as a whole:

- a 40% reduction in GHG emissions from 1990 levels by 2030; and
- for renewables to account for at least 27% of total EU energy consumption by 2030. This will increase the share of renewables in the electricity sector from the current 21% to about 45%.

The renewables target would not be translated into national targets via EU legislation, thus leaving greater flexibility for Member States to meet their GHG reduction targets in the most cost-effective manner in accordance with their specific circumstances, energy mixes and capacities to produce renewable energy. Energy efficiency still plays a vital role but no specific target is set. Increased RD&D efforts and commercial demonstration of CCS are still seen as being essential over the next decade so that it can be deployed by 2030. CCS will be a key technology for fossil fuel-based generation that can provide both base-load and balancing capacity in an electricity system with increasing shares of variable renewable energy. However, the EC stops short of explicitly proposing EU-level support mechanisms for CCS for the time being, calling on member states to take the lead.

The ***Emissions Trading System*** is expected to help drive the deployment of new technology. It puts a price on carbon emissions and so stimulates the development of technologies that will avoid them. In 2008, the European Parliament Environmental Committee voted in favour of an Emissions Performance Standard that would limit emissions for all new coal-fired power plants built in the EU after 2015. This would require the installation of CCS to meet the limit. But the standard was rejected by the Council of Ministers, and has not yet been implemented. Nonetheless, the European Investment Bank announced in July 2013 that it will introduce a new Emissions Performance Standard to be applied to new fossil fuel-fired power plants for which it provides investment (a limit of 550 gCO_2/kWh has been proposed).

4.2 CCT and CCS initiatives and programmes

Energy technology and innovation is an integral part of EU energy policy. Technology coordination at the EU level can avoid unnecessary duplication of national or regional initiatives. This is especially the case where substantial investment is required for commercial-scale demonstration and early deployment, and where projects (such as CCS) are not yet viable in the short-term. The prospects for CCTs and CCS in the EU and its member states have been reviewed in an earlier IEA CCC report by Mills (2010). This section discusses the main CCT and CCS initiatives that will help the EU achieve its energy and climate policy goals. CCT and CCS initiatives that provide funding for RD&D are covered in Section 4.3.

The policy framework for energy research at EU level is spearheaded by the ***Strategic Energy Technology Plan (SET Plan)***, which was adopted by the EC in 2008 and covers the period to 2020. The

Plan (*see* http://ec.europa.eu/energy/technology/set_plan/set_plan_en.htm) acts as the technology pillar of the EU's energy and climate policy. It outlines what needs to be done in terms of technology development, demonstration and deployment to achieve the EU's 2020 and 2050 energy and emission targets. This includes ensuring security of energy supplies and boosting European competitiveness in world markets. There is a strong emphasis on the pooling of national innovation efforts into a wider European cooperation. The use of CCS in fossil fuel-based power generation was recognised as one area on which European technology development should focus. A positive financial return from RD&D investment is expected. Wiesenthal and others (2010) estimate an internal rate of return of 15% for RD&D investments in the SET Plan over the period 2010 to 2030.

The SET Plan is based on a three pillar implementation structure:

- a Steering Group, which defines the overall strategy and reinforces the coherence between national, European and international efforts. It is composed of representatives from Member State governments and chaired by the EC;
- European Industrial Initiatives (EIIs), which help define the research objectives for the SET Plan. Within these Initiatives, strategic objectives are formulated based on Technology Roadmaps that identify R&D priority actions for the period 2010 to 2020. More specific Implementation Plans are developed that cover the first three year periods, and are revised every year. There are seven EIIs covering CCS, bioenergy, electricity grids, sustainable nuclear energy, solar, wind and smart cities (*see* http://setis.ec.europa.eu/set-plan-implementation/european-industrial-initiatives-eiis). These EIIs supplement two earlier initiatives, which have already been implemented, the Fuel Cells and Hydrogen Joint Technology Initiative and the European Fusion research programme; and
- the European Energy Research Alliance (EERA), which was founded by the leading European research institutes. EERA identifies and implements joint research programmes in support of the SET Plan. Currently, these include smart grids, wind, photovoltaics, bioenergy, geothermal energy, sustainable nuclear energy, advanced materials and processes for energy application, and fuel cells and hydrogen.

The ***European Industrial Initiative on CCS (CCS EII***, *see* http://setis.ec.europa.eu/implementation/technology-roadmap/european-industrial-initiative-on-carbon-capture-and-storage) was launched in June 2010 with the strategic objective of demonstrating the commercial viability of CCS technologies in an economic environment driven by the emissions trading scheme – in particular, to enable the cost competitive deployment of CCS technologies in coal-fired power plants by 2020–25, and to further develop the technologies so that they can be widely used in all carbon-intensive industrial sectors. The technology roadmap (*see* Figure 2) is a 10-year programme of private/public actions that will lead to the construction of up to 12 large-scale power plants that capture, transport and store the majority of the generated CO_2. It calls for a R&D programme that will address fossil fuel conversion technologies aimed at improving power plant efficiency, and develop cost effective CO_2 capture technologies with improved efficiency and better integration in power generation. This includes research on oxyfuel, and pre- and post-combustion CO_2 capture technologies. The total public and private investment needed is estimated to be €10.5–16.5 billion, depending on the number of demonstration plants. The implementation plans for CCS, covering 2010–12 and 2013–15, can be downloaded from http://setis.ec.europa.eu/set-plan-implementation/european-industrial-initiatives-eiis/eii-implementation-plans. The 2013–15 implementation plan describes the key actions required to enable the cost-competitive deployment of CCS by 2020–25. It includes actions for supporting the EU CCS demonstration programme, reducing the costs of CCS through innovative R&D, establishing the commercial framework for CCS in Europe, and maximising the potential of CCS via European and international collaboration. It also lists the R&D priorities.

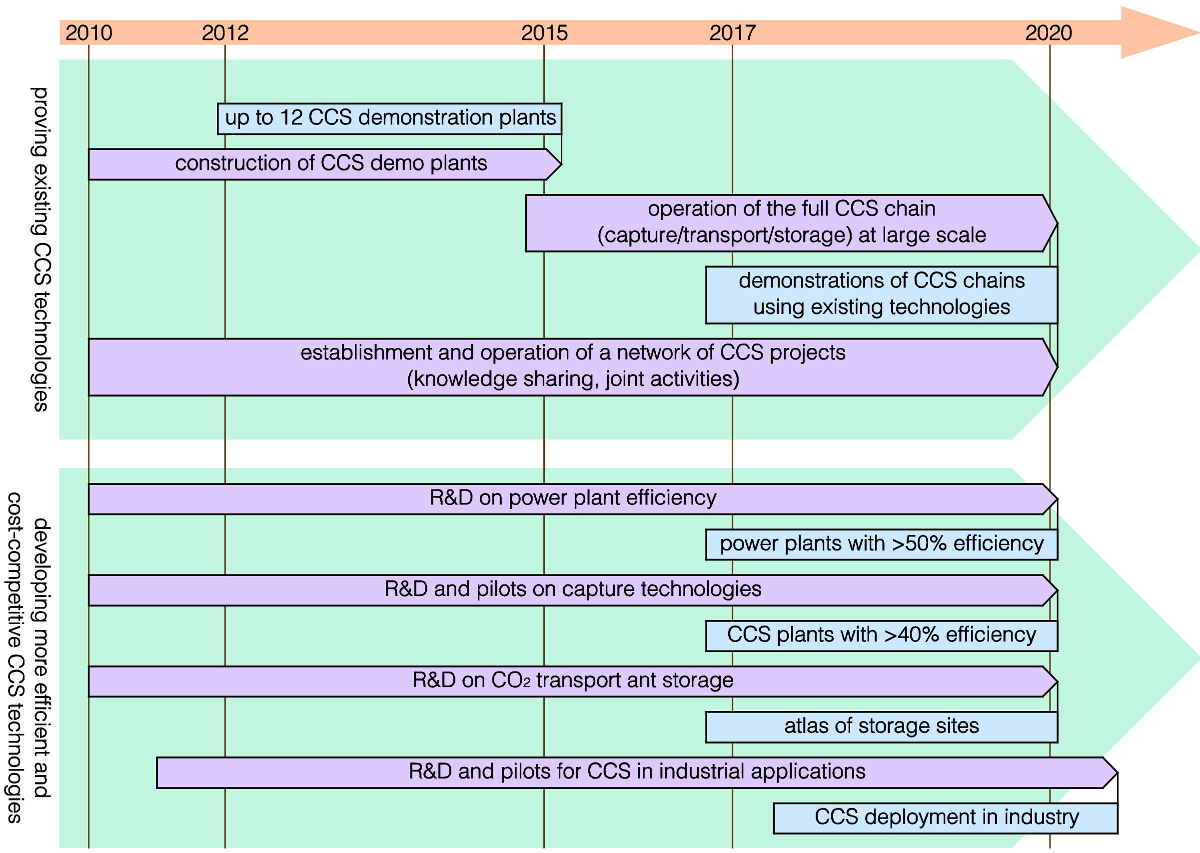

Figure 2 Technology roadmap for CCS (EC, 2009)

The ***Strategic Energy Technologies Information System (SETIS)*** plays a central role in the SET Plan by helping to identify energy technology and RD&D objectives, striving to build consensus around the SET Plan programme, identifying new opportunities, and assessing the effectiveness and efficiency of the SET Plan in delivering the EU energy and climate policy goals (*see* http://setis.ec.europa.eu). Technology maps, which provide up-to-date information on the status and prospects of low carbon technologies, and capacity maps, which provide assessments of current public and private R&D spending on CCS and other priority technologies, are produced. These include the 2011 technology map update that covers CCS in power generation, and advanced fossil fuel power generation (Tzimas and others, 2011). A materials research roadmap for fossil fuel energy technology encompasses materials for USC power plants, IGCC plants, as well as for CO_2 capture (Gomez-Briceño and others, 2011). It forms an integral part of a larger *Materials roadmap enabling low-carbon technologies* (EC, 2011c).

An integrated roadmap is being developed under the SET Plan Steering Group, as recommended in EC (2013b). This will consolidate the updated technology roadmaps of the SET Plan, whilst retaining the technology specificities. The entire research and innovation chain will be covered from basic research to demonstration and support for market roll-out. The roles and tasks for the various stakeholders, such as the EIIs, EERA, universities, investors and financiers will be identified. In particular, key research and innovation actions for the next six years will be proposed (*see* http://setis.ec.europa.eu/set-plan-implementation/integrated-roadmap).

The SET Plan is complemented by Energy Technology Platforms. These are led by industry and define RD&D priorities, timeframes and action plans. The ***European Technology Platform for Zero Emission Fossil Fuel Power Plants*** (the Zero Emissions Platform, ZEP) supports CCS as a key technology for achieving Europe's energy, climate and societal goals (*see* www.zeroemissionsplatform.eu). Its mission is to identify and remove the barriers to creating highly efficient power plants with near zero emissions, with a goal to make CCS commercially available by 2020. Founded in 2005, ZEP is a coalition of over 200 members from 19 countries and includes utilities, oil and gas companies, equipment suppliers, academic institutions and environmental non-governmental organisations. ZEP advises the EC on all aspects of CCS RD&D and defines research objectives with a medium- to long-term horizon. It provided input into the SET Plan. The latest update on R&D needs for CO_2 capture in the power industry was published in September 2013 (ZEP, 2013).

In 2010, the EC launched the ***European CCS Demonstration Project Network*** to accelerate the deployment of safe, large-scale and commercially viable CCS projects (*see* http://ccsnetwork.eu). Its main aim is to enhance coordination between the organisations involved with the development of the first demonstration projects. The network allows these early entrants in the field to exchange information and experience, and will help direct future R&D and policy-making requirements. It will also help to optimise costs through shared collective actions, and raise public understanding of the role of CCS in cutting CO_2 emissions.

The SET Plan expires in 2020. The EC has published a Communication (EC, 2013b) outlining an energy technology and innovation strategy that will continue to deliver EU policy goals, strengthen its competitiveness in the world energy market, and make better use of existing financial resources. The strategy tackles the challenges for 2020 and beyond, and includes actions for building on the SET Plan.

4.3 RD&D funding and projects

In 2010, two thirds of the public expenditure on energy research was funded directly by the Member States (EU27) through their own policies; the rest came from programmes under the EC. The combined EC and Member State public funding of energy research in 2010 was roughly twice that of the USA, both in absolute and GDP terms. Japan spent only half the European budget in absolute terms. However, in terms of GDP, Japan spent significantly larger amounts on energy research than the EC and its Member States combined. Historically, Finland has been the Member State with the largest spending on energy research compared to its GDP. It has recently increased its energy research budget significantly more than the other countries, although most of the increase was spent on energy efficiency RD&D (Energy Research Knowledge Centre, 2013).

An analysis of European investment, including EU public sector, Member States' national public sector, and corporate RD&D investments for the six technology areas of the SET Plan can be found in EC (2013c). Only some of the EU member states were included in the analysis. Total R&D investment in CCS technology in 2010 was some €400.39 million, or €593.39 million if the European Energy Programme for Recovery (EEPR) contribution (discussed below) is included. Overall, the EEPR provided €193 million (32%), the Framework Programme for Research and Technological Development FP7 (discussed below) €16.90 million (3%), public sources (national governments) €194.62 (33%), and private sources (corporate) €188.87 million (32%). The principal companies interested in CCS R&D are the large utilities and oil companies. A breakdown on government spending on coal and CCS RD&D for 19 Member States can be found in the IEA database on RD&D budgets (IEA, 2013d).

CCT and CCS RD&D in the EU is funded by a range of programmes. This section describes the main European funding sources. Funding of energy research within the member states is covered in Energy Research Knowledge Centre (2013).

Since 1984, RD&D activities within the EU have been implemented and funded predominantly through the ***Framework Programme for Research and Technological Development***. RD&D support for CCTs and CCS started in the Third Framework Programme (1990–94), and has continued through the following Framework programmes. The ***Seventh Framework Programme (FP7)***, which runs from 2007 to 2013, has a budget allocation of €50.5 billion, making it one of the largest research programmes in the world (*see* http://ec.europa.eu/research/energy/eu/index_en.cfm?pg=funding-fp7 and http://cordis.europa.eu/fp7/home_en.html). It is funded through contributions from the EU Member States and 13 associated countries. FP7 is made up of four specific programmes, namely Cooperation, Ideas, People and Capacities. Most activities relating to energy research are funded through the Cooperation Programme.

Energy research within the FP7 Cooperation Programme has a budget of €2.35 billion over the duration of the programme (2007–13), and is jointly managed by the Directorate-General for Research and Innovation and the Directorate-General for Energy. It is implemented through annual work programmes that outline the 'call for proposals'. The collaborative research programmes must include participants from different European countries. The main areas of research (which are aligned with the SET Plan) are:

- hydrogen and fuel cells;
- renewable energies for electricity, fuel production, and heat and cooling;
- CO_2 capture and storage technologies for zero emission power generation;
- clean coal technologies, with the aim of reducing CO_2 emissions;
- smart energy networks;
- energy efficiencies and savings;

- knowledge for policy making; and
- horizontal programme activities (future emerging technologies, materials for energy applications).

The CCT area covers RD&D of technologies to substantially improve plant efficiency and reliability, and to lower costs through the development and demonstration of clean coal and other solid fuel conversion technologies. The production of secondary energy carriers (including hydrogen) and liquid and gaseous fuels are also included. The activities are linked, when appropriate, to the CO_2 capture and storage technologies or co-utilisation of biomass areas. A list of CCT projects relevant to power generation that are still running in 2014 is given in Table 2. It was compiled from the http://cordis.europa.eu/projects website under FP7 – Energy programme. About €200 million has been spent on CCT and CCS under FP7 (Schuppers, 2013).

Table 2 Current FP7 research projects on power generation and CCS

Project title	Acronym	Coordinator	Comments
Design technologies for multi-scale innovation and integration in post-combustion CO_2 capture: from molecules to unit operations and integrated plants	CAPSOL	Centre for Research and Technology Hellas (Greece)	Runs 1 Nov 2011 to 31 Oct 2014. Total cost is €3,255,110, of which EU share is €2,337,282. www.capsol-project.eu
Support to the European CCS Demonstration Project Network	CCP-PNS	Global Carbon Capture and Storage Institute (Australia)	Runs 21 Mar 2012 to 20 Mar 2016. Total cost €3,670,745, EU share €2,994,389.
Demonstration of a cost effective medium size chemical looping combustion through packed beds using solid hydrocarbons as fuel for power production with CO_2 capture	DemoCLOCK	Stiftelsen Sintef (Norway)	Runs 1 Jun 2011 to 31 May 2015. Total cost €8,193,558, EU share €5,304,510. www.sintef.no/Projectweb/DemoClock/
Dense membranes for efficient oxygen and hydrogen separation	DEMOYS	Ricerca sul Sistema Energetico - RSE SpA (Italy)	Runs 1 May 2010 to 31 Jul 2014. Total cost €5,164,084, EU share €3,442,696. http://demoys.rse-web.it
Graded membranes for energy efficient new generation carbon capture process	GREEN-CC	Forschungszentrum Jülich GmbH (Germany)	Runs 1 Sep 2013 to 31 Aug 2017. Total cost €8,194,173, EU share €5,462,714. www.green-cc.eu
Highly efficient tubular membranes for oxy-combustion	HETMOC	Danmarks Tekniske Universitet (Denmark)	Runs 1 Sep 2011 to 31 Aug 2015. Total cost €7,812,392, EU share €5,534,142. www.hetmoc.eu
High performance capture (of CO_2)	HiPerCap	Stiftelsen Sintef (Norway)	Runs 1 Jan 2014 to 31 Dec 2017. Total cost €7,732,350, EU share €4,890,111. www.sintef.no/Projectweb/HiPerCap/
Innovative enzymes and polyionic-liquids based membranes as CO_2 capture technology	INTERACT	Technische Universität Dortmund (Germany)	Runs 1 Sep 2013 to 28 Feb 2017, Total cost €6,170,384, EU share €4,775,552. www.fvt.bci.tu-dortmund.de
Novel ionic liquid and supported ionic liquid solvents for reversible capture of CO_2	IOLICAP	Demokritos, National Center for Scientific Research (Greece)	Runs 1 Dec 2011 to 30 Nov 2014. Total cost €5,770,719, EU share €3,978,128. www.iolicap.eu
Energy efficient MOF-based mixed matrix membranes for CO_2 capture	M4CO2	Technische Universiteit Delft (Netherlands)	Runs 1 Jan 2014 to 31 Dec 2017. Total cost is €10,497,585, EU share €7,932,375. www.tnw.tudelft.nl
Component performance-driven solutions for long-term efficiency increases in ultra-supercritical power plants	MACPLUS	Centro Sviluppo Materiali SpA (Italy)	Runs 1 Jan 2011 to 30 Jun 2015. Total cost €18,204,522, EU share €10,704,674. http://macplusproject.eu

Table 2 continued			
Advanced materials and electric swing adsorption process for CO_2 capture	MATESA	Stiftelsen Sintef (Norway)	Runs 1 Sep 2013 to 31 Aug 2016. Total cost €5,709,173, EU share €2,965,707. www.sintef.no/Projectweb/MATESA/
Meeting the materials and manufacturing challenge for ultra high efficiency power plants with CCS	NextGenPower	KEMA Nederland BV (Netherlands) (now part of DNV GL Group)	Runs 1 May 2010 to 30 Apr 2014. Total cost €10,262,366, EU share €5,996,880. www.nextgenpower.eu
Optimisation of oxygen-based CFBC technology with CO_2 capture	O2GEN	Fundacion CIRCE - Centro de Investigación de Recursos y Consumos Energéticos (Spain)	Runs 18 Oct 2012 to 17 Oct 2015. Total cost €11,856,914, EU share €6,604,702. www.o2genproject.eu
Optimisation of CO_2 capture technology allowing verification and implementation at utility scale	OCTAVIUS	IFP Energies Nouvelles (France)	Runs 1 Mar 2012 to 28 Feb 2017. Total cost €13,492,943, EU share €7,928,238. www.octavius-co2.eu
Optimising gasification of high ash content coals for electricity generation	OPTIMASH	Centre National de la Recherche Scientifique (France)	Runs 1 Nov 2011 to 31 Oct 2015. Total cost €5,303,906, EU share €3,430,036. http://optimash.eu
Reliable and efficient combustion of oxygen/coal/recycled flue gas mixtures	RELCOM	University of Glamorgan (UK)	Runs 1 Dec 2011 to 30 Nov 2015. Total cost €9,736,057, EU share €6,349,100. www.relcomeu.com
Technology options for coupled underground coal gasification and CO_2 capture and storage	TOPS	Imperial College of Science, Technology and Medicine (UK)	Runs 1 Nov 2013 to 31 Oct 2016. Total cost €4,096,731, EU share €2,996,239. www.imperial.ac.uk
Zero emissions platform support secretariat	ZEPPORT	Triarii BV (Netherlands)	Runs 1 Aug 2012 to 31 Jan 2015. Total cost €1,143,828, EU share €500,000. www.triarii.nl

The successor Framework Programme to FP7 is ***Horizon 2020***, which runs from 2014 to 2020 and has a budget of nearly €80 billion for the programme's duration (*see* http://ec.europa.eu/programmes/horizon2020/). This is in addition to the private and national public investment that the programme will attract. For the first time, a single EU programme integrates the full innovation cycle (from R&D to commercialisation) with coherent funding provided throughout the cycle. Innovation is seen as a means to drive economic growth and create jobs. There are considerable changes between FP7 and Horizon 2020. First of all, the work programmes are biannual under Horizon 2020. Secondly, Horizon 2020 takes a challenge-based approach where the problem is defined, giving researchers more freedom to come up with innovative technology solutions. Thirdly cross-cutting actions have been introduced to ensure a more integrated approach. International cooperation is an important element of Horizon 2020, and the work programmes are open to participants outside the EU.

Horizon 2020 is split into three major priorities:

- excellent science, which aims to raise the level of excellence in Europe's science base;
- industrial leadership to turn Europe into a more attractive place for business and investment into R&D; and
- societal challenges which are of major concern to Europeans, such as climate change, clean and efficient energy, green transport, and food security.

Secure, clean and efficient energy (Energy Challenge) was identified as one of the seven priority societal challenges (*see* http://ec.europa.eu/programmes/horizon2020/en/h2020-section/secure-clean-and-efficient-energy). The Challenge covers non-nuclear energy research and is designed to support the transition to a reliable, sustainable and competitive energy system. It has a budget of €5.931 billion for the period 2014–20 and is structured around seven specific objectives and research areas:

- reducing energy consumption and carbon footprint;
- low cost, low carbon electricity supply;
- alternative fuels and mobile energy sources;
- a single, smart European electricity grid;
- new knowledge and technologies;
- robust decision making and public engagement; and
- market uptake of energy, and information and communication technology innovation.

One of the focus areas of the first work programme under the secure, clean and efficient energy heading is competitive low carbon energy. This carries on and extends the themes from FP7 and will help the EU achieve its energy and climate objectives, while ensuring growth and creating jobs in Europe. Actions within this area will be in line with the SET Plan, Energy Roadmap 2050 and Low Carbon Economy Roadmap. Two topics under this focus area relevant to coal-fired power generation are: enabling decarbonisation of the fossil fuel-based power sector and energy intensive industry through CCS, and highly flexible and efficient fossil fuel power plants. A call for proposals (H2020-LCE-2015-1), which include these two topics and two others, was published on 11 December 2013, with a budget of €94 million.

Alongside FP7 and Horizon 2020 runs a complementary research programme, the ***Research Fund for Coal and Steel (RFCS)***. This provides funding for research, pilot and demonstration projects in coal and steel, such as coal utilisation and conversion, and CCS (*see* http://cordis.europa.eu/coal-steel-rtd/home_en.html). The RFCS was set up in February 2003 when assets from the European Coal and Steel Community (ECSC) were transferred to the EU on expiry of the ECSC Treaty in 2002. Its budget is not financed by the EU but arises from the interest on the assets which were built up by levies on the European coal and steel industries. The programme distributes about €55 million each year, of which 27.2% and 72.8% go to coal and steel projects, respectively. A cost benefit analysis of 23 projects completed between 2003 and 2010 assessed the annual financial return at the level of beneficiaries at ~€103 million per year. The total budget for the 23 projects was €53 million, of which RFCS funding was €31 million. This gives an annual return of 2 or 3 times (EC, 2013d). The EC, with assistance from the Coal and Steel Committee, and the Coal and Steel Advisory Groups, manages the programme.

The RFCS Programme is coordinated with other funding activities carried out in the Member States, such as national or regional programmes, and with the Framework Programmes, complementing aspects not covered by these schemes. Summaries of past and on-going projects are given in EC (2013e). Current projects of interest to the power generation sector are listed in Table 3.

Table 3 Current RFCS funded CCT research projects			
Project title	Acronym	Coordinator	Comments
Advanced coal chemical-looping combustion, aiming at highest performance	ACCLAIM	Chalmers Tekniska Högskola AB (Sweden)	Runs 1 Jul 2012 to 31 Dec 2014. Total cost is €3,200,765, of which EU share is €1,591,434. www.sintef.no/acclaim
Amine-impregnated alumina solid sorbent for CO_2 capture	ASC2	Fundacion CIRCE - Centro de Investigación de Recursos y Consumos Energéticos (Spain)	Runs 1 Jul 2013 to 30 Jun 2016. Total cost €3,093,285, EU share €1,546,642.
Economic low carbon power production and emissions control for future and flexible biomass cofired power stations	BiOxySorb	Universität Stuttgart (Germany)	Runs 1 Jul 2013 to 30 Jun 2016. Total cost €2,105,362, EU share €1,263,217. http://bioxysorb.eu-projects.de
Carbon capture by means of indirectly heated carbonate looping process	CARINA	Technische Universität Darmstadt (Germany)	Runs 1 Jul 2010 to 30 Sep 2014. Total cost €2,458,416, EU share €1,475,050. www.est.tu-darmstadt.de/rfcs-carina/
Advanced substitute natural gas from coal with internal sequestration of CO_2	CO2freeSNG2.0	Friedrich-Alexander Universität Erlangen-Nürnberg (Germany)	Runs 1 Jul 2013 to 30 Jun 2016. Total cost €1,834,169, EU share €1,100,502. www.co2freesng20.eu
Crack mechanism understanding and failure avoiding treatment of T24 tube material in advanced super critical coal fired steam generators	CRAMUFAT24	Universität Stuttgart (Germany)	Runs 1 Jul 2013 to 30 Jun 2015. Total cost €2,138,151, EU share €1,282,891.
Efficient conversion of coal to electricity - direct coal fuel cells	DCFC	University Court of the University of St Andrews (UK)	Runs 1 Jul 2011 to 30 Jun 2014. Total cost €2,030,301, EU share €1,218,181. http://dcfc.wp.st-andrews.ac.uk
European network for component integration and optimisation	ENCIO	VGB PowerTech eV (Germany)	Runs 1 Jul 2011 to 30 Jun 2017. Total cost €23,886,488, EU share €9,554,596. www.encio.eu
Development of scale-up methodology and simulation tools for the demonstration of PC-FLOX burner technology in full-scale utility boilers	FLOX-COAL-II	Universität Stuttgart (Germany)	Runs 1 Jul 2011 to 30 Jun 2014. Total cost €2,690,872, EU share €1,614,524. http://floxcoal2.eu-projects.de
Novel calcium looping CO_2 capture process incorporating sorbent reactivation by recarbonation	RECaL	Endesa Generacion SA (Spain)	Runs 1 Jul 2012 to 30 Jun 2015. Total cost €2,697,943, EU share €1,618,765. www.recal-project.eu

In the revised Emission Trading Systems Directive, adopted in 2008, 300 million emission trading allowances were set aside from the so-called 'New Entrants Reserve' for the support of large-scale demonstrations of CCS and innovative renewable energy projects, the ***NER300 Programme*** (*see* http://ec.europa.eu/clima/policies/lowcarbon/index_en.htm). Over €2 billion has been raised from the sale of the emission allowances. The programme is managed jointly by the EC, the European Investment Bank and Member States. The money is being distributed to projects selected through two rounds of calls for proposals, covering 200 and 100 million allowances respectively. Unspent funds from the first round were carried over to the second round. In December 2012, €1.1 billion was awarded to 20 renewable energy projects under the first call for proposals; but no CCS project was selected. The plan in 2008 was to fund up to 12 CCS demonstration projects over the two calls for proposals of the NER300 programme. The EC expressed its regrets that no CCS projects received funding. It commented that member states had not confirmed their projects due to reported funding gaps or lack of CCS project maturity (Global CCS Institute, 2013). Only one CCS project has applied for funding under the second call for proposals. This is the White Rose project (*see* www.whiteroseccs.co.uk), which plans to build a new 426 MW oxyfuel power plant at Drax in North Yorkshire, UK. If the project is implemented, some 90% of CO_2 (~1.8 Mt/y) will be captured from the coal- and biomass-fired unit, and transported by pipeline for undersea storage in the North Sea. The second award decision (of up to €300 million) was confirmed in July 2014.

The ***European Energy Programme for Recovery (EEPR)*** was set up in 2009 to speed up investment in energy technology and infrastructure and to boost economic recovery (*see* http://ec.europa.eu/energy/eepr/index_en.htm). It is managed by the Directorate-General for Energy, and co-finances projects designed to make energy supplies more reliable and to help reduce GHG emissions. In 2009, €1 billion (with a maximum of €180 million per project and one project per Member State) was allocated to fund six CCS projects in the power generation sector, namely Bełchatów (Poland), OXY300 Compostilla (Spain), Don Valley (UK), Jänschwalde (Germany), Porto Tolle (Italy), and Rotterdam Opslag en Afvang Demonstratie Project (ROAD) in The Netherlands. The Jänschwalde oxyfuel project was withdrawn in 2012 due to the lack of a national regulatory framework for CO_2 storage and public acceptance issues (EC, 2013f). The low carbon price under the Emissions Trading System has eroded the economics of the remaining demonstration projects. Moreover, the current economic situation has made it more difficult for projects to access the additional financing needed. The Bełchatów project was terminated in May 2013, partly because it was unable to secure the necessary financing. In August 2013, the Porto Tolle project, which aimed to capture 1 $MtCO_2$/y from an existing coal-fired power plant, was cancelled due to delays in project delivery after the decision of the Italian State Council to annul the environmental permit for the Porto Tolle power plant, and difficulties in achieving financial support. Phase 1 of the OXYCFB 300 Compostilla Project (pilot plant technology demonstration and front end engineering design) was completed as planned in October 2013. It was decided not to proceed to full-scale demonstration, which had intended to capture ~1 $MtCO_2$/y from a new build coal-fired 300 MW unit (Global CCS Institute, 2014).

The ongoing *Don Valley project* (formerly known as Hatfield) plans to capture at least 90% of CO_2 (up to 5 Mt/y) from a 920 MW gross (650 MW net) coal-fired IGCC plant sited in the UK. The CO_2 will be transported by pipeline for storage in offshore formations under the North Sea. The project currently expects to be operational in 2018/19 and will cost up to £5 billion (*see* www.2coenergy.com/don_valley_power_project.html). It was awarded €180 million in 2010 from the EEPR. Front end engineering and design studies have been completed.

The second active project is *Rotterdam Opslag en Afvang Demonstratieproject (ROAD)* which will capture 1.1 $MtCO_2$/y from a 250 MW capture unit being installed as a component of the new 1.1 GW power plant (Maasvlakte Power Plant 3) in Rotterdam, Netherlands (*see* http://road2020.nl/en/). The power plant can burn coal and biomass. The CO_2 will be transported by pipeline for storage in depleted gas reservoirs under the North Sea. The project was awarded €180 million from the EEPR and up to €150 million from the Dutch government, and is expected to cost some €1.2 billion. The capture unit plans to be operational in 2017.

Another European level research programme is the ***Fossil Energy Coalition Network (FENCO-NET)***, which was launched in 2010 as the successor of FENCO-ERA, the Fossil Energy Coalition European

Research Area. It is a grouping of European organisations having responsibilities relating to the funding of national R&D programmes in the field of fossil energy (*see* www.fenco-era.net/home-fenco-net). The objective is to step up co-operation and co-ordination of research activities on the development of near zero emission power plants. FENCO-NET complements and supports the SET Plan and is linked to FP7 as an implementation tool. The UK, Greece, Poland and Norway committed national funding for a joint call on CCS projects, with about €300–600 thousand available for each project (overall budget is about €2 million). Three CO_2 capture projects (FENCO-NET, 2013) were selected in September 2013:

- metal organic framework (MOF) materials for post-combustion CO_2 capture, a collaboration between the UK, Norway and Greece (€670,000);
- amine impregnated synthetic zeolites for post-combustion CO_2 capture (Poland and UK); and
- minerals for chemical looping combustion (Norway, UK, Greece and Poland).

4.4 International collaboration

The EU collaborates with several countries on CCT and CCS RD&D through membership of international organisations (such as the Global CCS Institute and Carbon Sequestration Leadership Forum), and bilateral and multilateral agreements. Countries include South Africa (working group on coal, CCT and CCS – *see* http://ec.europa.eu/energy/international/bilateral_cooperation/south_africa_en.htm), the USA (EU-US Energy Council – *see* http://ec.europa.eu/energy/international/bilateral_cooperation/usa_en.htm), China (EU-China Energy Dialogue, including a Working Group on Near Zero Emissions Coal – *see* http://ec.europa.eu/clima/dossiers/nzec/index_en.htm), and India (EU-India Energy Panel, including working groups on coal and clean coal technologies – *see* http://ec.europa.eu/energy/international/bilateral_cooperation/india_en.htm). Researchers in countries outside the EU can collaborate with EU member states in research projects funded under FP7 and Horizon 2020. India, for example, is participating in the OPTIMASH project, listed in Table 2 on page 45.

4.5 Research organisations

The ***Joint Research Centre*** (*see* http://ec.europa.eu/dgs/jrc) is the EC's in-house service providing scientific and technical support for EU policies. Its activities are funded through Horizon 2020 and many of its actions address the seven societal challenges. The *Institute of Energy and Technology* (*see* http://iet.jrc.ec.europa.eu) is one of seven scientific institutes of the Joint Research Centre. Its mission is to provide support to EU policies and technology innovation to ensure sustainable, safe, secure and efficient energy production, distribution and use, and to foster sustainable and efficient transport in Europe. As part of this mission, it carries out research on clean fossil fuels, hydrogen and fuel cells, renewable energies, and energy techno/economic assessment, among other topics.

5 India

India has the ninth largest economy in the world, with a real GDP growth rate of 8.7% in the last 5 years and 7.5% over the last 10 years (Central Statistics Office, 2013). It is the fourth biggest energy consumer after the USA, China and Russia. Coal plays a crucial role in meeting its energy needs – it is the primary source of energy, followed by petroleum and biomass. India is the world's third largest coal consumer and producer. In 2012, coal consumption was estimated by the IEA to be 753.2 Mt, an increase of 43.1 Mt over 2011 (710.1 Mt). Some 595 Mt of coal was produced in 2012 (7.6% of world total), 12.7 Mt more than in 2011 (IEA, 2013c).

In 2012, coal resources were estimated to be 293.5 Gt, of which 118.1 Gt were proven reserves. There are also lignite reserves of 42 Gt, of which 6.18 Gt were proven (Central Statistics Office, 2013). Unfortunately, the majority of the hard coals (bituminous and anthracite) have a high ash content, low calorific value, variable properties, and are difficult to clean. However, they generally have a low sulphur content (Mills, 2007). Despite its large coal reserves, India imported 159.6 Mt in 2012, up from 132.1 Mt in 2011, becoming the third biggest coal importing country, after China and Japan. In 2012, 118.8 Mt of steam coal (92.2 Mt in 2011) came from just two countries, Indonesia (~78%) and South Africa (~19%) (IEA, 2013c). The amount of coal imported reflects the growing gap between coal production and consumption. Reliance on coal imports is expected to grow in the future due to coal supply issues, such as railway logistics. The IEA predicts that India will become the largest coal importer by the early 2020s (IEA, 2013a). India is also heavily dependent on imported oil. Consequently, energy security forms a major component of India's energy policy.

The power sector consumes the majority of the coal, about two-thirds of the demand in 2011, with almost all of the balance dominated by the iron and steel, and cement sectors (IEA, 2013a). As of 30 September 2013, total installed electricity capacity (power utilities) was 228.7 GW (*see* www.powermin.nic.in), an 18 GW increase over September 2012, ranking India fifth in terms of global generating capacity (after the USA, China, Japan and Russia). Fossil fuels accounted for about 68% of the installed capacity, renewables (including hydro power) ~20% and nuclear ~2%. Of the fossil fuels, coal made up ~59% (at 134.4 GW), natural gas ~9% (20.4 GW) and oil ~0.5% (1.2 GW) of total installed capacity. The US Energy Information Administration, in its International Energy Outlook 2013 Reference case scenario, predicts that coal-fired generation will grow by 3.1% per year over the period 2010–40 as the country strives to provide enough electricity to meet growing demand; generation from both nuclear and renewable energy (including hydropower) will grow more rapidly than other sources. Over this period, India's net coal-fired electricity generation will increase by 910 TWh (to 1524 TWh in 2040), more than double the 2010 total. Consequently, its coal consumption for electricity generation nearly doubles (EIA, 2013b). There is therefore a need for R&D to improve the efficiency and performance of coal-fired power plants.

India's rising energy demand, underpinned by fossil fuels, has resulted in the country emitting over 5% of global CO_2 emissions from fuel combustion in 2011. Some 1745.1 Mt of CO_2 from fuel combustion were emitted, of which 1205.2 $MtCO_2$ came from coal combustion. The electricity and heat production sector generated 900.6 $MtCO_2$, or 52% of CO_2 emissions. Electricity generation produced 856 gCO_2/kWh; 1052.3 TWh of electricity was generated (IEA, 2013b). However, CO_2 emissions per capita (1.4 tCO_2/person in 2011) is about one-third of the world's average. CO_2 emissions trebled in India between 1990 and 2011, and will continue to grow with the rising energy demand. The IEA's World Energy Outlook New Policies Scenario projects that CO_2 emissions in India will increase by 3.4% per year from 2011 to 2035, at which time India would account for 10% of global emissions.

5.1 Energy and climate policy

The ***Integrated Energy Policy*** (IEP), approved by the Cabinet in 2008, is India's first comprehensive energy policy. It was prepared by an Expert Committee of the Planning Commission with the brief 'to prepare an integrated energy policy linked with sustainable development that covers all sources of energy and addresses all aspects of energy use and supply including energy security, access and availability, affordability and pricing, as well as efficiency and environmental concerns' (Planning Commission, 2006). The amount of energy India needs to sustain a high economic growth rate of 8–9% per year to 2031–32 was addressed by looking beyond the traditional five year cycle to determine how India could best meet its large energy demand. The IEP recognises that coal will remain India's most important energy source in the long-term. Thus there is a need for India to develop CCTs and also pursue new coal extraction technologies, such as in-situ gasification to tap its vast coal reserves that are difficult to extract economically using conventional technologies. Issues of climate change were discussed, and a number of initiatives were proposed that would reduce the GHG intensity of the economy by as much as one third. These included energy efficiency measures, technology missions on CCTs, and focusing R&D on climate friendly technologies.

R&D was recognised as crucial to augment India's energy resources, meet long-term energy needs, promote energy efficiency, attain energy independence and enhance energy security. The IEP acknowledges that energy-related R&D has not been allotted the resources that it needs, and therefore proposed setting up a National Energy Fund to finance energy R&D. A levy of 0.2% of turnover on all energy firms whose turnover exceeds Rs100 crore (Rs1000 million) could produce a fund of Rs1000–1500 crore, which would increase each year. There was a strong case for funding by the government, either directly or through fiscal incentives, since much of the R&D is for the public good. The IEP therefore suggests that the government could make a Rs1000 crore contribution to the fund in the first year (excluding atomic energy). Energy companies should be mandated to spend at least 0.4% of turnover on R&D, and tax incentives could encourage companies to invest more.

Three approaches to energy R&D are used in India:

- technology development missions that require coordinated R&D of all stages of the innovation chain to reach a targeted goal;
- technology roll out missions to develop and roll out commercial or near commercial technology; and
- broad-based R&D support to research institutions, universities and other organisations through project funding.

The setting up of technology missions on underground coal gasification, IGCC, CCS, and advanced materials, amongst others, is recommended in the IEP. The IEP also recognises that cooperation with other countries and international initiatives would allow India to obtain relevant technologies earlier and at a lower cost. Discussions are currently underway for replacing the IEP with a new long-term energy security policy.

The Indian government implements economic policy, like China, through five-year plans. The plans are formulated, executed and monitored by the Planning Commission and are traditionally focused on reducing poverty. Instead of adopting a set of notional targets, and outlining what is necessary to achieve them, the latest ***12th Five-Year Plan*** (2012–17), which has the aspiration of 'faster, sustainable and more inclusive growth', outlines three scenarios. The first scenario of 'strong inclusive growth' would yield an average GDP growth rate of around 8% over the Plan period, the preferred outcome. The second and third scenarios result in a 6% and 5% growth rate, respectively (Planning Commission, 2013a). One of the most important goals is to achieve universal access to electricity.

The demand for energy during the Plan will increase as the economy grows and as access to electricity in rural areas expands. Coal will remain the dominant fuel source for power generation, accounting for ~69% of total generation in 2017, and 58% in 2030. A target of 88.537 GW new capacity (excluding renewables) has been set, with coal accounting for 69.8 GW (79%). Renewables would add an extra 30 GW of new capacity. The majority of India's fleet of coal-fired power plant is based on subcritical technology. The 12th FYP expects that ~50% of new coal-fired power plants will use supercritical technology and, in the next 13th FYP (2017–22), all new coal-fired plant would be at least supercritical. This could help drive R&D of USC power generation, including research into advanced materials. The 12th FYP recognises that R&D plays a major role in its development plans for the power sector, and the need for R&D into underground coal gasification and other advanced coal technologies. It also suggests experimenting with new ways of funding scientific research. Instead of all government research funds being allocated to the budget of different scientific departments, a new National Research Fund could be created. The Fund would select research projects from those submitted by research institutions, or combinations of institutions. Research funding for particular projects would be continued only on the basis of periodic peer reviews (Planning Commission, 2013a,b).

India ratified the Kyoto Protocol in 2002 but, as a Non-Annex I Party, it has no obligations to reduce its CO_2 emissions. In 2008, the Indian Government published its National Action Plan for Climate Change where it states that 'India is determined that its per-capita GHG emissions will at no point exceed that of developed countries even as we pursue our development goals'. In the following year the Government announced that it would aim to reduce emissions intensity by between 20 and 25% of 2005 levels by 2020. A number of green goals, such as increasing the role of renewables within the energy production sector to 20% by 2020 were also declared. However, there is no specific CCS policy and there is little government support for the application of CCS technologies, although the IEP notes that CCS will become crucial in the future.

The 2008 ***National Action Plan for Climate Change*** (NAPCC) outlines existing and future policies and programmes for mitigating and adapting to climate change. The Plan's aim is to 'achieve a sustainable development path that simultaneously advances economic and environmental objectives' (Prime Minister's Council on Climate Change, 2008). Eight core national missions that would run through 2017 were identified, with each mission given the task of developing strategies, plans of action, timelines, and monitoring and evaluation criteria. These plans were to be submitted to the Prime Minister's Council on Climate Change by December 2008. Among the eight missions are:

- National Solar Mission to increase the share of solar energy in the energy mix;
- National Mission for Enhanced Energy Efficiency, including a new market-based mechanism (implemented in the Perform, Achieve and Trade Scheme) to improve energy efficiency in energy intensive large industries and facilities. It requires power generation plants to reduce their specific energy consumption by improving overall plant efficiency; and
- National Mission on Strategic Knowledge of Climate Change to gain a better understanding of climate science, impacts and challenges. A Climate Change Research fund would be set up to support research.

Existing initiatives addressed in the NAPCC include GHG mitigation in power generation, where R&D of IGCC and supercritical technologies are recommended. The Government is in the process of formulating a new ***Mission on Clean Coal (Carbon) Technologies*** to reduce CO_2 emissions from power plants. The mission would foster work on IGCC, advanced USC technology, and CCS, amongst other areas.

An ***Expert Group on Low Carbon Strategy for Inclusive Growth*** was set up to develop a roadmap for low carbon development within the power generation, transport, industrial and other sectors. An interim report published in 2011 said that while research into USC and IGCC technologies should be pursued, commercial deployment of these technologies is unlikely before 2020. No demonstration of coal-fired plants with CCS was recommended. Instead, it was proposed to watch the development of the technology in the USA and EU where commercial plants are being built or are under consideration, and to undertake a few technical and economic studies to examine the potential and feasibility of CCS in India (Expert Group on Low Carbon Strategies for Inclusive Growth, 2011). The final report reiterates the need for advanced coal technologies R&D (such as underground coal gasification), but gives no further details (Expert Group on Low Carbon Strategies for Inclusive Growth, 2014).

5.2 R&D initiatives

The main bodies controlling R&D policy and priorities for CCTs are the Planning Commission (*see* http://planningcommission.nic.in) and Ministry of Power (*see* http://powermin.nic.in). The Ministry of Coal (*see* http://coal.nic.in) is responsible for policies governing the exploration and development of coal and lignite reserves, and includes research on coal beneficiation and utilisation. However, the research topics are generally outside the scope of this report.

The R&D policy of the Government is to promote R&D projects that help the nation to become self-reliant in technology. R&D projects relevant to the power sector are executed through the National Perspective

Plan and the Research Scheme on Power, both of which were initiated by the Ministry of Power. The ***National Perspective Plan (NPP) for R&D in Power Sector***, published in June 2002, identified and prioritised the crucial R&D needs in the power generation, transmission and distribution subsectors, and drew up a 15 y roadmap. For thermal power generation, the NPP recommended measures to improve plant availability, reliability, efficiency and safety, coal blending, green technology approaches, coal gasification, and supercritical technologies (*see* www.cpri.in/index.php/r-a-d-schemes/research-scheme/national-perspective-plans-npp.html). NOx and SO_2 control technologies were also listed under the environmental section. The NPP scheme provides funding for R&D projects.

The ***Research Scheme on Power*** (RSoP) was initiated by the Ministry of Power in 1961, and is administered by the Central Power Research Institute. It funds R&D relevant to the power sector, including the solving of operational problems encountered in the power system (*see* www.cpri.in/index.php/r-a-d-schemes/research-scheme/research-scheme-on-power-rsop.html). Ongoing projects include the design of a 25 kWe pressurised circulating fluidised bed unit.

The Department of Science and Technology (DST) commissioned an in-depth study into CCT in 2006 in order to identify the areas for R&D. A CCT roadmap was produced that was discussed at a joint DST-BHEL workshop held in October 2006 (Goel, 2010). The proposed roadmap (*see* Figure 3) provides a direction for R&D efforts on CCTs. A finalised CCT roadmap does not appear to have been published.

Ongoing and near-term (up to 2012):

- Improved coal recovery, coal beneficiation, reduction in cost
- More emphasis on fluidised bed combustion, supercritical power plant boilers, IGCC demonstration
- Enhanced energy recovery from coal, such as coalbed methane, coal mine methane
- Pilot-scale studies on coal liquefaction

Medium-term (2012–17):

- IGCC, pressurised fluidised bed combustion, ultra-supercritical power plants
- Enhanced energy recovery from coal: coalbed methane, underground coal gasification
- Commercial-scale coal liquefaction
- Pilot-scale zero emission technologies
- Pilot-scale carbon storage

Long-term (2017 and beyond)

- Commercialisation of zero emission technologies
- Carbon sequestration demonstration plant
- Integrated gasification fuel cell and production of hydrogen fuels from coal

Figure 3 Proposed CCT roadmap (Goel, 2010)

It has also been proposed to set up a ***National Clean Coal Technology Centre*** which would identify and pursue coal related R&D programmes, and major development and demonstration projects. The entire coal chain would be covered including coal beneficiation, conversion, and emissions monitoring and control (Sachdev, 2007). It is not clear whether this Centre has, in fact, been established.

A ***Working Group on Power*** was set up by the Planning Commission to formulate a programme for the development of the power sector under the 12th FYP. The importance of R&D in the development plans is acknowledged in the chapter on R&D in its published report (Ministry of Power, 2012). The report identifies the major areas of concern for R&D, and emphasized the need for proactive and collaborative R&D involving utilities, industry (such as manufacturers), academia, research institutes (both in India and abroad) and other organisations. Proposed projects for R&D include USC and advanced USC, IGCC, waste heat recovery and integration, development of artificial neural networks, development of pressure swing adsorption process for CO_2 capture, microalgae process for CO_2 fixation, improvement of electrostatic precipitators, coal combustion, and emission control technologies for NOx, SOx and mercury. It is suggested that the Government should fund the proposed projects through various schemes such as the NPP and RSoP.

In addition, the report proposes that the Standing Committee on Research and Development, which currently manages NPP R&D, should be strengthened and empowered to make policy on R&D for the power sector and prioritise problems of national importance that have short-, medium- and long-term impacts. It also recommends setting up a Power Academy that would coordinate research with the Standing Committee on Research and Development. All manufacturing firms, utilities and other power sector organisations would report their problems, and R&D requirements, to the Academy. Currently, there is little R&D coordination between the government, academia and industry.

The budget for the proposed projects for the power sector (power generation, transmission, distribution, energy and environment), and the proposed Centre of Excellence and Power Academy came to Rs1500 crore, of which the direct government grant needs to be Rs750 crore. The balance would come from central public sector organisations, utilities and industry. A R&D Conclave was held in 19-20 October 2012 at New Delhi to discuss further R&D in the Indian power sector during the 12th Plan and beyond.

5.3 RD&D funding

India spent Rs72,620.44 crore or 0.88% of its GDP on RD&D in the financial year 2011–12. The majority of RD&D funding comes from the government. Gross expenditure on RD&D was Rs53,041.3 crore in FY2009–10, of which the central government provided 54.4%, state governments 7.3%, higher education 4.1%, and public sector industries 5.3%. The private sector industry contributed just 28.9% (Department of Science and Technology, 2013a). This compares with industry accounting for more than two-thirds of all RD&D spending in China and the USA. The low contribution by private companies is recognised by the Indian government, and ways to enhance their R&D expenditure are discussed in the 12th FYP (Planning Commission, 2013b).

The allocation of energy RD&D funds is complicated in India because of the different layers within the government. The Ministry of Finance sets the budget for the five-year plans, which in turn determine the directions of energy policy. It also provides funding and financial incentives for various energy technologies. The Planning Commission proposes RD&D initiatives, and their expenditure, but the ministries and departments have to execute the allocation. Moreover, the ministries and departments include organisations responsible for allocating energy RD&D funds, as well as those that receive the funds (Kempener and others, 2010). This makes it difficult to obtain figures on the amount the Indian government is spending on CCT and CCS R&D. The projected costs of the proposed RD&D initiatives in the 11th FYP relating to coal are given in Table 4.

Table 4 Projected cost for proposed RD&D initiatives in the 11th FYP (Planning Commission, 2008)

Initiative	Projected cost, Rs crore
Combustion research	200
Advanced coal technologies	
Setting up of first 100 MWe IGCC demonstration plant	350
In situ gasification of coal and lignite	30
Coal-to-oil conversion	200
Coalbed methane	35
Carbon capture and storage (including climate change issues)	125
Ultra-supercritical technologies	30

RD&D funding within the Ministry of Power is directed to the Central Power Research Institute, which as well as carrying out in-house R&D on power generation, transmission and distribution, also manages and allocates funds from the RSoP and NPP programmes. The Institute's budget for FY2013–14 is Rs298.73 crore, of which Rs22 crore is directed to Plan R&D, the RSoP and NPP for new approved projects (Ministry of Power, 2013). In FY2009–10, the state-owned NTPC (National Thermal Power Corporation, which comes under the Ministry of Power) spent Rs22 crore on R&D (Department of Science and Technology, 2013b).

The Department of Heavy Industry also funds R&D projects. BHEL (*see* www.bhel.com), a public sector undertaking that comes under the Department, invested about Rs1250 crore on R&D during FY2012–13. This was nearly 2.5% of the company's turnover. The company's investment in R&D is amongst the largest in the Indian corporate sector (*see* Section 5.6).

The Ministry of Coal is concerned with the exploration, mining and development of coal deposits, and is therefore outside the scope of this report, although it is interested in underground coal gasification and exploitation of coalbed methane. The Ministry of Science and Technology also runs R&D programmes through the Department of Science and Technology (such as the National Programme on Carbon Sequestration Research, which includes CO_2 capture) and Department of Scientific and Industrial Research.

A ***National Clean Energy Fund (NCEF)*** has been created for funding research and innovative projects in clean energy technology. It is financed by a levy on Rs50 per tonne of coal produced or imported (Prasad, 2014). The Government expects to collect Rs10,000 crore by 2015 (Planning Commission, 2013a). The guidelines on projects eligible for funding, outlined in an office memorandum published by the Ministry of Finance in 2011, included CCT and CCS (Ministry of Finance, 2011). The performance of the fund is reviewed by Panda and Jena (2012). Most of the fund remains unspent.

The RSoP and NPP funding schemes were described in the previous section. The Ministry of Power also provides a ***Research Contingency Fund*** (*see* www.cpri.in/index.php/r-a-d-schemes/research-scheme/research-contingency-rc.html). Ongoing projects under this scheme include the impact of blended coal on power plant performance, and assessment and erosion resistance of coal burner tip materials.

A ***Research Funding Organisation*** is being set up to fund research projects selected through a competitive process. Contributions to the organisation would be eligible for tax benefits. It was proposed by the Finance Minister, while presenting the Interim Budget 2014/15 in Parliament on 17 February 2014 (*see* http://indiabudget.nic.in/ub2014-15/bs/bs.pdf). No further details were given, so it is not clear what types of projects are included.

5.4 International collaboration

India collaborates with several countries on CCT and CCS RD&D and information exchange through membership of international organisations (such as the Global CCS Institute, represented by NTPC, and the Clean Energy Ministerial), bilateral (for example, the India-Japan Energy Dialogue (Prasad, 2014)) and multilateral agreements, academic co-operation and industrial collaboration. Of particular interest is technology transfer through joint ventures, which have a potential to maximise technology access by domestic companies, as opposed to foreign direct investment. For example, joint ventures between Japanese and Indian companies have enabled the introduction, and production, of high-efficiency, low-emission coal technologies for power generation.

Two examples of CCT collaboration are between the EU and USA. The ***EU-India Energy Panel*** was created in June 2005 as the formal instrument for EU-India cooperation in the energy sector (*see* http://ec.europa.eu/energy/international/bilateral_cooperation/india_en.htm). It includes a working group on clean coal technologies (with the Ministry of Power) for the development and deployment of clean energy production. BHEL is collaborating with the TREC-STEP on an EU funded project on developing a cluster for CCTs and CCS technologies for the Indian power sector (*see* www.carboncap-cleantech.com). Indian companies are also participating in R&D projects in the FP7 programme.

The ***US-India Energy Dialogue***, established in 2005, is a mechanism for policy dialogue and technical cooperation, such as facilitating the deployment of clean energy technologies (*see* www.energy.gov/ia/initiatives/us-india-energy-cooperation). Two of the Working Groups cover power and energy efficiency, and coal (Mills, 2007; Smouse and others, 2010). A Partnership to Advance Clean Energy (PACE), which contains both research and deployment components, was launched under the Dialogue. The US-India Joint Clean Energy Research Centre has been set up under the research component. The initial priority research areas are solar energy, biofuels and building energy efficiency, although clean coal, CCS and IGCC are amongst the research topics in the agreement, signed in 2011. The deployment component includes accelerating the deployment of cleaner fossil fuel technologies. The USAID programme is additionally funding various projects and programmes in India, as well as PACE (Smouse and others, 2010).

5.5 Demonstration projects

RD&D activities are predominantly government-led, with Indian research directed towards goals set by the government. Large public sector enterprises, such as BHEL and NTPC Ltd, have their own R&D facilities, but also collaborate on national projects. This section will describe two collaborative projects, both of which are national mission technologies.

Advanced ultra-supercritical project

The project is a joint venture of BHEL, NTPC and the Indira Gandhi Centre for Atomic Research (IGCAR) to design, develop and build an 800 MW advanced USC power plant. The project is expected to cost over Rs6000 crore. IGCAR is developing the materials for the boiler capable of operating at 710°C (superheater)/720°C (reheater) and 30 MPa steam parameters. BHEL is designing and manufacturing the boiler and associated equipment, whilst NTPC will operate the plant. It is planned to test the new alloys in one of NTPC's power plants in 2014. Funds for the R&D phase, which will require ~Rs1200 crore, are expected to be released by the end of 2013. The project is partly being funded by the Department of Heavy Industry. The 'project design memorandum', which includes the technical and economic details of the 800 MW plant, was submitted by BHEL to the office of the Principal Scientific Adviser to the government in 2013 (IANS, 2013; Nicol, 2013).

IGCC demonstration plants

In May 2008, an agreement was signed between BHEL and Andhra Pradesh Power Generation Corporation Ltd (APGENCO, a state-owned company) to build a 125 MW IGCC plant at the Vijayawada Thermal Power Station, in Andhra Pradesh. Later on it was scaled up to 182 MW. It would be an air-blown pressurised fluidised bed gasification system, but the plant has not yet been built. A lack of funding appears to be the main reason behind the delay. The Indian government agreed to contribute Rs300 crore, but the money has not yet been received (Ramesh, 2013a,b), and both BHEL and APGENCO are reluctant to invest more of their own capital. BHEL and NTPC are now in talks to form a joint venture to build a 100 MW IGCC plant using BHEL's technology. The talks were initiated by the Indian government. The project will cost some Rs700 crore, to be equally shared between the two companies (Ramesh, 2013b). NTPC had already planned to build a 100 MW IGCC demonstration plant, based on fluidised bed technology, at Dadri (Dubey, 2013).

5.6 Research organisations

Various public and private sector organisations are engaged in CCT related R&D. This section will examine the principal national research institutes and two large public sector enterprises (BHEL and NTPC) pursuing clean coal R&D of interest to the power industry.

Bharat Heavy Electricals Ltd (BHEL)

BHEL (*see* www.bhel.com) is India's largest manufacturer of power plant equipment, and one of the largest corporate investors in R&D (about Rs1250 crore in FY2012–13). It operates a number of R&D facilities, including the Clean Coal Research Centre at Tiruchirappalli, and a Pollution Control Research

Institute at Haridwar. Key research areas include Indian coal characteristics, advanced USC boilers, fluidised bed combustion, IGCC, oxyfuel combustion, biomass cofiring, CO_2 capture, and reduction of SO_2 and NOx emissions.

Central Institute of Mining and Fuel Research (CIMFR)

The newly formed national laboratory CIMFR, Dhanbad (*see* www.cmriindia.nic.in), which operates under the auspices of the Council of Scientific and Industrial Research, was formed by merging the Central Fuel Research Institute and Central Mining Research Institute. Its mission is to provide R&D input over the entire coal-energy chain from mining to consumption. Under the clean coal initiative, the institute carries out basic research on topics such as coal beneficiation, power generation efficiency improvement, near-zero emission technologies, coal gasification, co-combustion and co-gasification of coal and biomass, oxyfuel combustion and post-combustion CO_2 capture.

Central Power Research Institute (CPRI)

CPRI (*see* www.cpri.in), which operates under the aegis of the Ministry of Power, serves as a national laboratory for applied research in electrical power engineering. It also serves as an independent authority for testing and certification of power equipment. Research areas include power system planning and improvement, and reliability enhancement, diagnostics and condition monitoring of power system equipment. One current project in the power generation area is the performance improvement of electrostatic precipitators. CPRI also manages the NPP and RSoP programmes.

National Centre for Combustion Research and Development

The Centre (*see* www.nccrd.in) was established to develop state-of-the-art capabilities in combustion research and will involve all the known experts in the area in India. It is funded by the Department of Science and Technology.

NTPC

NTPC (*see* www.ntpc.co.in) is the largest power generating company in India. The Centre for Power Efficiency and Environmental Protection (CenPEEP) was set up in collaboration with the US Agency for International Development, with a mandate to reduce GHG emissions per unit of electricity generated by improving the overall performance of coal-fired power plants. The Centre functions as a resource centre for acquisition, demonstration and dissemination of state-of-the-art technologies and practices for performance improvement of coal-fired power plants for the entire power sector of India. In 2009, NTPC established the *NTPC Energy Technology Research Alliance* (NETRA) to conduct research technology development and scientific services related to electric power generation. NETRA's focus areas are climate change, CO_2 mitigation/fixation (such as pressure swing adsorption process for CO_2 separation), new and renewable energy, efficiency improvement and reliability enhancement of thermal power generation, and waste management. It is involved in collaborative research projects into clean and economic power generation with key national institutes and universities. NTPC has committed 0.5% of its profit after tax towards R&D and another 0.5% of its profit after tax towards climate change research (Smouse and others, 2010).

6 Japan

Japan has the third largest economy in the world, after the USA and China, and is also one of the largest energy consumers and energy importers due to scarce indigenous reserves. It was the world's second largest importer of coal in 2012, importing around 99% of its requirements. About 183.8 Mt were imported, an increase of 9.7 Mt over 2011. Some 82% of the coal came from just two countries, Australia (62.8%) and Indonesia (19.2%). With global demand for coal expected to grow in the emerging economies, in particular China and India, competition for coal will increase. In fact, China overtook Japan in 2011 to become the world's largest coal importer (IEA, 2013c). Hence a stable energy supply (that is, energy security) is of utmost importance for Japan and forms a major component of its energy policy.

In 2012, Japan consumed 183.8 Mt of coal, of which 131.6 Mt was steam (thermal) coal, making it the world's fifth biggest coal consumer. This was increase over 2011, when total coal and steam coal consumption were 174.1 Mt and 120.3 Mt, respectively. About 27% of electricity is generated from coal, 281.14 TWh in 2011 (IEA, 2013c). The country was also the fifth largest global emitter of CO_2 from fuel combustion in 2011, releasing 1186 $MtCO_2$, of which 400 $MtCO_2$ (33.7%) came from coal. Some 519.5 $MtCO_2$ was emitted from electricity generation, or 497 gCO_2/kWh; electricity output was 1042.7 TWh (IEA, 2013b). In 2010, coal-fired power generation produced 902 gCO_2/kWh (IEA, 2012c).

6.1 Energy and climate policy

The ***Basic Act on Energy Policy***, enacted in 2002, upholds the three fundamental aspects of Japan's energy policy. These can be summed up as the three Es:

- energy security;
- economic growth; and
- environmental sustainability.

Environmental sustainability is principally concerned with global warming mitigation. Under the Kyoto Protocol, Japan is legally committed to reducing its GHG emissions by 6% from the base year of 1990 within the first 5 y commitment term, 2008–12 (a target that was achieved). The ***Kyoto Protocol Target Achievement Plan*** (drawn up in April 2005, and comprehensively revised in March 2008) aimed to keep the amount of CO_2 associated with energy consumption, which accounts for about 90% of Japan's GHG emissions, to 1076–1089 Mt in FY2010. The bulk of these emissions is from the combustion of fossil fuels. Unfortunately, 1138 $MtCO_2$ was emitted from fuel combustion in 2010, a 7.2% increase over 1990 (1061.6 $MtCO_2$) (IEA, 2013b).

The 15th Conference of the Parties (COP) of the UNFCCC held in Copenhagen, Denmark in December 2009 (the 'Copenhagen Accord'), discussed a new international framework to cover emissions after 2013. Under this Accord, Japan increased its target to a 25% reduction compared to 1990 (Hatoyama Initiative), provided a fair and effective international framework was established in which all the major economies participate, and on the agreement by those economies on ambitious reduction targets (Agency for Natural

Resources and Energy, 2010). However, at COP19, held in Warsaw, Poland in November 2013, Japan announced that it was revising its target as a shutdown of its nuclear power plants in the wake of the incident at the Fukushima Daiichi nuclear power plant (caused by the East Japan earthquake and tsunami on 11 March 2011) had made the previous target unattainable. The less ambitious new target is a 3.8% reduction from 2005 level by 2020 (Ishihara, 2013). This, in effect, would release 3% more GHGs in 2020 than in 1990. The new goal is based on Japan never turning on its idled nuclear power plants, and will be revised in the future when the new energy policy and energy mix is agreed. The new 3.8% target would be met by improving energy efficiency by 20%, and other mitigation measures.

Japan also reaffirmed at COP19 the goal to reduce GHG emissions by 50% at the global level and by 80% in the developed world by 2050 (Ishihara, 2013). The promotion of further technology innovation and the transfer of advanced low carbon technologies to emerging economies would help meet this goal, as outlined in the diplomatic strategy for countering global warming, ACE: Actions for Cool Earth. Measures and policies for achieving the GHG emission targets are set out in the ***Global Warming Measures Plan*** (which replaces the Kyoto Protocol Target Achievement Plan); the Plan is currently being revised (Ministry of the Environment, 2014). A new ***Low Carbon Technology Plan*** to help meet the emission targets (and achieve economic development) listed high efficiency coal-fired power generation as one of the technologies for development in the short- to medium-term (around 2030), and CCS in the longer term (Council for Science and Technology Policy, 2013b).

The ***Strategic (or Basic) Energy Plan*** was devised to help implement Japan's energy policy. It was established in 2003, and revised in 2007, 2010 and 2014 to meet the changing economic and energy situation. The 2010 version planned to increase power dependence from nuclear energy to 53% in 2030. Power generation from fossil fuels would decrease to 26%, of which coal would contribute 11%. In comparison, fossil fuels were responsible for 66% of power generation in 2007, with coal contributing 25%, and nuclear energy production was 26% (Ando, 2012). New coal-fired power plants would need to be equipped with CCS by 2030.

The latest Strategic Energy Plan (approved by the Cabinet on 11 April 2014) was formulated in the aftermath of the Fukushima Daiichi nuclear power plant incident to show the direction of Japan's energy policies in the medium- to long-term, about the next 20 years (Energy Supply and Demand Policy Office, 2014). It is based on the 3E's but includes a safety element (3Es + S). The energy mix is still to be determined but will include a higher level of renewable energy and a lower dependence on nuclear power than the previous plan. Only nuclear power plants whose safety has been confirmed by the new Nuclear Regulation Authority will be reopened. Coal is being re-evaluated as an important base load power supply as it has the lowest geopolitical risk and lowest price per unit of heat energy among the fossil fuels. Consequently, the government is promoting the construction of high efficiency state-of-the-art coal power plants and the replacement of aging thermal power plants. The development and introduction of next-generation high efficiency coal generation technology, such as IGCC, will be promoted, as well as CCS technology. The export of these technologies will also be encouraged. Thus energy RD&D will play a significant role in achieving Japan's energy policy objectives, as well as meeting its GHG emissions reduction commitments. Hence the importance of CCTs and CCS research programmes.

6.2 Coal policy

Coal plays an important part in Japan's energy policy. A separate policy for coal was published in 2004, the ***Clean Coal Cycle (3C) Initiative***, which was aimed at collating the strategies and developing plans for the effective utilisation of coal over a period to 2030. It was produced by a study group drawn from the major energy organisations, industry and academia in Japan. Its targets, along the aims of the overall energy policy, are to:

- reduce the environmental impact of coal utilisation (in particular CO_2);
- diversify energy sources; and
- secure stable supplies of coal.

These aims were to be realised (Harada, 2005) through the following five basic directions:

- promotion of high efficiency to reduce emissions and cost in the power generation industry (that is, clean coal technologies);
- development and deployment of technologies for the reduction of emissions, including CO_2, and the utilisation of by-products, such as coal ash;
- seeking new coal uses;
- expansion of coal supply and removal of supply bottlenecks; and
- improvement of procurement to preserve the cost advantage of coal as its demand in Asia increases.

The Initiative has driven a substantial body of RD&D in Japan, mainly centred on coal gasification (IGCC and integrated gasification fuel cell (IGFC)) for higher efficiency power generation and hence lower CO_2 emissions, and CCS. The ultimate goal is to achieve near zero-emission power generation. Another driver for CCT RD&D is the need to meet national emission regulations for coal-fired power plants established by the Ministry of the Environment (www.env.go.jp).

An important aspect of the coal policy is to disseminate CCT overseas, particularly to Asian countries to help mitigate their CO_2 emissions, a policy reiterated in the new Strategic Energy Plan. Technology transfer would also create business opportunities for Japanese companies. The new Strategic Energy Plan has additionally strengthened coal RD&D, at least in the short- to medium-term.

6.3 Science and Technology Basic Plan

Japan places a high priority on energy R&D. Its Science and Technology Basic Plan provides the framework for science and technology policy, identifying the priority areas for R&D over a 5 y period. It is drawn up by the Council for Science and Technology Policy, which is the top decision making body for R&D in Japan (*see* www8.cao.go.jp/cstp/english/). The Council includes the prime minister, other ministers and knowledgeable stakeholders. Earlier plans placed a strong emphasis on upgrading the basic capabilities of the Japanese research systems and the prioritisation of four research fields. One of the fields was environmental sciences, in which energy R&D is included.

The ***4th Science and Technology Basic Plan***, adopted in 2011 and covering FY2011–15, differs slightly from previous plans as the emphasis is on integrating science with innovation ('research and innovation'), and there is a slight shift away from the previously prioritised fields (Council for Science and Technology Policy, 2010). The need to link the scientific system more closely with innovation and industry had been recognised for some time, since science, technology and innovation are seen as the driving forces for economic growth. There is also a need to strengthen the industrial competitiveness of Japan. The 4th Basic Plan is closely aligned with the economic growth initiative ('New Growth Strategy') published by the Government in 2010. Green Innovation is one of the two major innovations seen as a pillar of growth. It includes R&D investment in power generation technology and CCS to help achieve a low carbon society. These particular R&D programmes are managed by the Ministry of Economy, Trade and Industry (METI) and the Ministry of the Environment.

In August 2011, the Cabinet accepted the 4th Basic Plan. In addition, a longer term strategy on science, technology and innovation, the ***Comprehensive strategy on science, technology and innovation*** has been formulated (Japanese Cabinet, 2013). Five challenges to be addressed are given, one of which is realising a clean and economic energy system. This challenge maintains consistency with the medium-term 4th Basic Plan. For example, R&D on highly efficient and clean innovative technologies for power generation and combustion is still included. The strategy additionally includes measures for the revitalisation and regeneration of Japan after the March 2011 earthquake, tsunami and nuclear crisis.

6.4 R&D roadmaps

The Japanese government places a high priority on roadmaps for energy R&D. These lay out a general path for R&D projects, setting out the key objectives and milestones, and clarifying the technological challenges that need to be overcome. Roadmaps are created for individual projects, as well as general programme areas. The roadmap covering CCTs and CCS, produced as result of the 4th Science and Technology Basic Plan, is given in Figure 4. It is centred on high efficiency coal-fired power generation (advanced USC, IGCC, IGFC) and CCS. The goal is for the implementation of advanced USC and 1700°C-class gas turbine technologies by around 2020, and the development of IGCC by 2020 and IGFC by 2030. The improvement of the efficiency and durability of fuel cells, and the development of solid oxide fuels is planned by 2020. A large-scale demonstration of underground CO_2 storage will have been carried out by 2020, enabling the implementation of CCS by 2030. High performance coal-fired power generation combined with CCS could reduce emissions to near zero. The national CCT demonstration projects are described in Section 6.7. Separate roadmaps for high efficiency coal-fired power generation, CCS and fuel cells are given in the new low carbon technology plan (Council for Science and Technology Policy, 2013c).

The roadmap is a continuation of earlier roadmaps for CCTs and CCS, such as those produced in the C3 Initiative, the Energy Technology Strategy Map, published by the Agency for Natural Resources Energy in 2007, and the Cool Earth – Innovative Energy Technology Program Technology Development Roadmap, produced by METI in 2008. These roadmaps are described in the IEA CCC report by Henderson and Mills (2009). The Cool Earth roadmap was a result of the 'Cool Earth 50' initiative, announced in May 2007, in which it was proposed to halve global GHG emissions from the current level by 2050. Innovative technologies, such as IGCC, IGFC and CCS were seen as essential to help meet this target (METI, 2008). The Japan Coal Energy Center (JCOAL) has recently updated its CCT R&D roadmap (Yoshimura and Matsuda, 2014).

vision
society that achieves both economic growth and environmental burden reduction through advanced power generation technologies

target
implementation of innovative highly efficient power generation/combustion systems and application of CO_2 collection/storage technologies
- improvements in efficiency and durability of stationary fuel cells
- implementation of CO_2 separation/collection/storage technologies

measures toward social implementation
- establishment of legal (for example promoting, licensing) for practical application
- promotion of international standardisation of technical standards, authentication systems and so on pertaining to international competitiveness

Interim goals to be achieved at the intermediary stage (around 2020)
- thermal power generation
  - a practical application of 1700°C-class gas turbine and advanced ultra-supercritical power generation
- fuel cells
  - functional improvements
- CO_2 collection/storage technologies
  - practical application of integrated systems

main measures

present	2015	2020 – 2030
development of highly-efficient thermal generation		
• elemental technology development - develop temperature-increasing technologies for thermal generation (for example high temperature gas turbines, high heat-resistant materials) - develop coal gasification technologies - conduct elemental technology development for fuel cell combined cycle generation • development of operation methods	• practical technology development - develop 1700°C-class gas turbine technologies - develop integrated coal gasification combined cycle technologies - implement advanced ultra-supercritical thermal generation • development of operation methods	• practical technology development - develop hybrid fuel cell/gas turbine combined cycle generation technologies for natural gas - develop integrated coal gasification fuel cell combined cycle generation
development of fuel cells		
• elemental technology development - develop solid polymer fuel cell component and manufacturing technologies (for example cost reduction, durability improvement) - develop solid oxide fuel cell component and manufacturing technologies (for example cost reduction, durability improvement) • practical technology development - develop solid polymer fuel cell vehicles - develop solid oxide fuel cell industrial technologies (for example combination with gas turbine generation)	• elemental technology development - develop solid polymer fuel cell component and manufacturing technologies (for example cost reduction, durability improvement) - develop solid oxide fuel cell component and manufacturing technologies (for example cost reduction, durability improvement) • practical technology development - develop solid oxide fuel cell industrial technologies (for example combination with gas turbine generation)	• elemental technology development - develop solid polymer fuel cell component and manufacturing technologies (for example cost reduction, durability improvement) - develop solid oxide fuel cell component and manufacturing technologies (for example cost reduction, durability improvement)
development of CO_2 separation, collection and storage technologies		
• elemental technology development - develop existing and new CO_2 separation and collection technologies - develop construction technologies • practical technology development - commence demonstration fields for integrated systems • technology development of operation methods - consider environmental impact assessment, for example techniques - develop monitoring/maintenance technologies	• elemental technology development - conduct technology development for cost reduction • practical technology development - conduct large-scale demonstration (underground storage) • technology development of operation methods - establish environmental impact assessment, etc methods - develop monitoring/maintenance technologies	• elemental technology development - conduct technology development for cost reduction • practical technology development - implement CO_2 separation, collection and storage technologies

related indicators
- implementation of 1700°C-class gas turbine and advanced ultra-supercritical thermal generation (by around 2020)
- improvement of efficiency and durability of fuel cells
- implementation of CO_2 separation, collection and storage technologies (by around 2020)

Figure 4 Roadmap for highly efficient and clean innovative technologies for power generation and combustion (Council for Science and Technology Policy, 2013a)

6.5 RD&D funding

Japan has long been a world leader in energy RD&D, with government spending on RD&D as a percentage of GDP being one of the largest in the IEA member countries (IEA, 2008a). The 4th Science and Technology Basic Plan set the target for all R&D investment in the public and private sectors at more than 4% of GDP, and at 1% in the public sector alone (Council for Science and Technology Policy, 2010). Some 0.0715% of GDP was invested in energy-related RD&D in 2011 by the Japanese government. The government spent 13,909 million yen (US$174.3 million, both in 2012 prices) on coal and CCS RD&D in 2011, an increase over 2010 (*see* Table 5). This was around 0.00299% of its GDP, or around 0.00037% of GDP on coal RD&D alone (IEA, 2013d). It is amongst the largest expenditure, as a proportion of GDP, of IEA member countries on CCT and CCS, showing the importance attached by Japan to research in these technology areas.

Table 5 Japanese RD&D budgets for coal and CCS (IEA, 2013d)

		2008	2009	2010	2011
Total RD&D in million yen (million US$, in 2012 prices and exchange rates, where US$1 = 79.81 yen in 2012)	Coal production, preparation and transport	805.625 (10.094)	911.827 (11.425)	252.965 (3.17)	125.973 (1.578)
	Coal combustion (including IGCC)	6200.996 (77.697)	706.566 (8.853)	1309.182 (16.404)	1571.417 (19.689)
	Coal conversion (excluding IGCC)	734.973 (9.209)	0	0	0
	Other coal	0	0	0	0
	Total coal	7741.594 (97)	1618.392 (20.278)	1562.147 (19.573)	1697.39 (21.268)
	CO_2 capture/separation	1326.28 (16.618)	1269.476 (15.906)	3909.429 (48.984)	5212.671 (65.314)
	CO_2 transport	0	0	175.13 (2.194)	998.061 12.505)
	CO_2 storage	2280.866 (28.579)	10778.533 (135.052)	6791.139 (85.091)	6001.276 (75.195)
	Total CCS	3607.147 (45.197)	12048.009 (150.959)	10875.697 (136.270)	12212.008 (153.014)

In the FY2013 budget, METI has requested R&D subsidies of 7 billion yen for demonstration tests of oxygen-blown IGCC (the fundamental technology for IGFC), 1.52 billion yen for advanced USC power generation commercialisation, 2.25 billion yen for the development and demonstration of high efficiency gas turbines, and 12.59 billion yen for large-scale CCS demonstration, among its other R&D budget requests (METI, 2013a). An increase of 1.63 billion yen to 14.67 billion yen for technology development for high efficiency coal-fired power generation, and a slightly lower amount (12.36 billion yen) for CCS has been requested by METI in its FY2014 budget (METI, 2013b).

Funding is generally directed to CCTs and CCS R&D projects by the New Energy and Industrial Technology Development Organisation (NEDO, *see* www.nedo.go.jp/english/). NEDO was established in 1980 as an independent administrative agency under METI and is Japan's largest public R&D management organisation. Its activities include development and promotion of new energy and energy conservation technologies, management of industrial technology R&D projects, coordination of international cooperation involving joint R&D, and information dissemination and exchange. NEDO's budget was ~121.1 billion yen in FY2013. R&D is carried out in line with the government's energy and policy goals.

Basic research on energy carried out at universities and institutes is funded through the Ministry of Education, Culture, Sports, Science and Technology (MEXT). The Japanese government provides tax incentives to stimulate R&D in the private sector and actively supports R&D cooperation between universities and industry.

6.6 International collaboration

Japan collaborates with several countries on CCT and CCS RD&D and information exchange through membership of international organisations (such as the Global CCS Institute, represented by METI, International Energy Agency and the Clean Energy Ministerial), and bilateral (for example, with China, EU, India, Indonesia and the USA, typically through Energy Dialogues) and multilateral agreements. Of particular interest to Japan is technology transfer of its high efficiency power generation and CCS technologies. The 4th Science and Technology Basic Plan specifically calls for an expansion of Japan's international activities. RD&D collaboration is seen as an opportunity to advance the science needed at a lower cost and at a more rapid pace than either organisation could achieve by working separately. Japanese researchers, for example, participate in projects under the EU's FP7 programme. One demonstration project in which Japan is involved is the Callide oxyfuel project in Australia, discussed in Section 2.5.

6.7 RD&D projects

This section outlines the current CCT and CO_2 capture projects funded by the Japanese government. It excludes research being carried out at universities and private companies. Other CCTs projects, current in 2007, are described in the report compiled by NEDO and the Japan Coal Energy Center (JCOAL) (Japan Coal Energy Center, 2007).

Advanced ultra-supercritical power generation

The advanced USC project began in 2008 with the aim of developing materials and components that can operate at steam temperatures of 700°C and withstand a pressure of 35 MPa. Thermal efficiencies of 46–48% (net, HHV) are expected in a coal-fired advanced USC power plant. Advanced USC technology could be retrofitted to older power plants to improve their thermal efficiencies and mitigate CO_2 emissions. Twelve companies and institutions are working together on the project, under the auspices of METI. Materials for the boiler, turbine and valve components are being developed and tested in the first half of the project. In the second half, boiler components and small turbine tests will be carried out to verify the reliability of each component. Throughout the project, long term creep rupture tests will be performed on each candidate material and welded joint. The target is to have an operational large-scale demonstration plant by 2021 (Fukuda, 2012a,b; Nicol, 2013).

EAGLE project

The EAGLE (Coal Energy Application for Gas, Liquid and Electricity) project is developing oxygen-blown, two-stage entrained flow gasification for power generation, and CO_2 capture technologies under NEDO and J-POWER (Electric Power Development Co Ltd, *see* www.jpower.co.jp/english). The project:

- carried out work on the design and construction of a 150 t/d coal gasifier at J-POWER's Wakamatsu Research Institute (FY1995–2001);
- further developed and tested the oxygen-blown entrained flow gasifier for IGFC, and established the gas cleanup technology (FY2002–06);
- investigated CO_2 capture by chemical absorption, the gasification of different coal types and trace element behaviour (FY2007–09); and
- is testing CO_2 capture by physical absorption, and evaluating innovative CO_2 capture technologies during FY2010–13 (Sagara, 2013).

Nakoso IGCC demonstration plant

The aim is to demonstrate IGCC for power generation using a MHI air-blown, two-stage entrained flow gasifier (Japan Coal Energy Center, 2007; Sagara, 2013) by:

- constructing and operating a 200 t/d (equivalent to 2.5 MWe) IGCC pilot plant, under the management of NEDO, to acquire data to design a demonstration plant (FY1986–96); and
- building a 250 MW demonstration plant in Nakoso, Iwaki City, Fukushima, that began operating in 2007. The demonstration was conducted by the Clean Coal Power R&D Co. Ltd. (set up by ten power companies in 2001, *see* www.ccpower.co.jp/en/). 30% of the project costs were subsidised by METI, with the rest coming from the ten power companies and the Central Research Institute of Electric Power Industry (CRIEPI).

After all the test objectives were achieved, the demonstration plant became the first commercial IGCC plant in Japan (Nakoso Unit 10) on 1st April 2013. There is now a NEDO funded project at the IGCC plant to capture, transport and store CO_2 in the depleted parts of the Iwaki-oki gas field. Feasibility studies started in FY2008 (Abe, 2011).

Osaki CoolGen project

The Osaki CoolGen Corp (established by the Chugoku Electric Power Co and J-POWER in 2009) will conduct large-scale demonstration tests on oxygen-blown entrained flow IGCC with CO_2 capture, for eventual inclusion in IGFC power generation (*see* www.osaki-coolgen.jp). The project enables large-scale testing of the technologies developed in the EAGLE project. Construction of the 170 MW demonstration plant started in March 2013 at Chugoku Electric Power Co's Osaki power plant site, Hiroshima. After verification of the coal gasification system, the next step will be the retrofitting and testing of CO_2 separation and capture equipment. Finally, fuel cells will be added to further increase thermal efficiency, with testing scheduled for 2021 (Nagasaki and others, 2013). The project will cost ~90 billion yen.

6.8 Research organisations

This section describes the principal research organisations that carry out research related to the national CCT RD&D programmes.

Japan Clean Energy Center (JCOAL)

JCOAL, established in 1990 and supervised by METI, supports the development, commercialisation, transfer and dissemination of coal technologies. It is the only non-profit organisation in Japan which covers all fields from coal mining, coal preparation through to coal utilisation and CCS (*see* www.jcoal.or.jp). Its main activities are subsidised by METI and NEDO, and supported financially by its 105 member companies and associations. JCOAL is supporting the Callide A oxyfuel combustion demonstration in Australia (*see* Section 2.5), the development of IGCC and IGFC, and the efficient utilisation of low rank coals (in cooperation with Australia), along with other coal and CO_2 storage projects. The thermal efficiency of pulverised coal-fired power plants can be improved by removing water from low rank coals. Moreover, the efficient conversion of low rank coals into clean fuels (via gasification and liquefaction) that can replace oil and natural gas, will improve Japan's energy security.

Research Institute for Innovative Technologies for the Earth (RITE)

Much of the public R&D on global warming countermeasures is conducted through RITE (*see* www.rite.or.jp/en), which was established in 1990 by the Japanese government (METI). The Chemical Research section is conducting R&D on chemical absorption, solid sorbents and membranes for CO_2 capture. This is in preparation for the CCS roadmap target of CCS application by 2020 (RITE, 2013).

Central Research Institute of Electric Power Industry (CRIEPI)

CRIEPI, established in 1951, is a non-profit organisation which conducts R&D on energy and the environment. It is mainly funded through Japan's electric utilities from a tax on electricity sales. CRIEPI's mission is to ensure energy security and address global environmental issues (such as global warming), which are among the objectives of Japan's energy policy. It is contributing to some of the government's national R&D projects. It includes funding (through NEDO) for research on IGCC power generation, coal gasification, the development of IGCC with CO_2 capture, and oxyfuel IGCC. The design and operation of the Nakoso IGCC demonstration plant was supported by CRIEPI. Furthermore, research on pulverised coal combustion, utilisation of low grade coal, cofiring of coal and biomass, and the development of high temperature fuel cells, such as solid oxide fuel cells is additionally being performed at the Energy Engineering Research Laboratory (CRIEPI, 2011). CRIEPI is also conducting research on the policies and strategies for promoting research, development and deployment of energy technologies. CRIEPI has a number of research agreements with organisations in other countries and with various international organisations (*see* www.denken.or.jp/en/).

7 Republic of Korea

The Republic of Korea (or South Korea) is the world's thirteenth largest economy and the eleventh highest in terms of energy consumption (IEA, 2012b). It relies on imports to meet over 96% of its energy needs due to a lack of domestic fossil fuel reserves. Some 125.5 Mt of coal were imported in 2012, a decline of 3.7 Mt from 2011, making South Korea the fourth largest coal importer (after China, Japan and India). The majority of the coal was imported from Indonesia (41%), Australia (29%) and Russia (11%). The country was the tenth largest coal consumer in 2012 (127.3 Mt), but the seventh in terms of steam coal consumption (95.7 Mt) (IEA, 2013c). Over 50% of the coal is utilised in the power sector, and most of the rest by industry.

In 2010, South Korea overtook Canada to become the world's seventh biggest CO_2 emitter from fuel combustion. In 2011, 587.7 MtCO_2 was emitted, of which 296 Mt (~50%) came from coal combustion. CO_2 emissions have been climbing due South Korea's rising energy consumption. Some 299.7 MtCO_2 was emitted from electricity and heat production in 2011 or 545 gCO_2/kW; electricity output was 520.1 TWh (IEA, 2013b). About 42% (224.5 TWh) of the electricity in this year was generated from coal (IEA, 2013c). In 2010, coal-fired power generation produced 960 gCO_2/kWh (IEA, 2012c).

7.1 Energy policy

South Korea's energy policy aims to strike a balance between economic growth and environmental sustainability. The three main policy drivers can be summarised as:

- energy security;
- energy efficiency and conservation; and
- environmental protection.

The National Basic Energy Plan, which is reviewed every 5 years, sets out the mid- to long-term targets for meeting the energy policy goals. The first plan, the ***2008 National Basic Energy Plan***, covering the period 2008–30 (*see* www.keei.re.kr), was released by the then Ministry of Knowledge Economy in September 2008. The Plan serves as a cornerstone for the 'Low Carbon, Green Growth' strategy announced by the President in August 2008 (*see* Section 7.2). One of its aims is to reduce the dependency on fossil fuels by increasing the share of nuclear and renewable energy in the energy mix. This is also seen as a way of meeting CO_2 emission targets. The power sector is currently dominated by coal, nuclear and natural gas, with coal accounting for 40.2%, nuclear for 31.1% and natural gas for 20.8% of the 497 TWh generated in 2011 (Korea Energy Economics Institute, 2012). The plan also includes the development of CCTs as a measure to help lower CO_2 emissions.

Power demand has increased every year since the 1980s, and is expected to continue to do so over the coming years. However, the plan to meet the rising demand by building more nuclear power plants appears to be on hold due to concerns by the government about their reliability, and public concerns about safety. Instead, the construction of 6 new gas-fired power plants, with a total capacity of 5.06 GW, and 6 new coal-fired power plants, with a combined capacity of 10.74 GW, are being considered under the new power supply plan (Williams, 2013). This would be an increase of about 43% over 2011 coal-fired capacity. But there is then the question of whether South Korea could meet its CO_2 emissions target of a 30% reduction compared to its business-as-usual case by 2020, a commitment announced by the government in July 2009. Consequently, the funding of research on CCT and CCS could possibly increase.

The change in government at the beginning of 2013 has led to changes in South Korea's energy policy. According to President Park, the most significant challenge for energy today is the trade-offs between energy security, social equity and environmental sustainability. She is promoting the idea of a 'creative economy', which means energy conservation and environmental protection by the use of information and communication technology, and new technologies. On 14 January 2014, the Cabinet adopted the ***second National Basic Energy Plan***, which covers the period 2013–35. The plan has shifted the focus to energy demand instead of supply, and is more concerned with energy security than green growth. However, it does include environmental protection. One of its goals for improving sustainability is to reduce GHGs from the power generation sector by over 20% from business-as-usual levels by 2035 by the use of USC power generation, CCS and other advanced technologies. CCS technologies are expected to be incorporated in new coal-fired power plants, although this will increase electricity prices. The proportion of nuclear power in the energy mix in 2035 has decreased to 22–29% (from the first plan), whilst the renewable energy target remains at 11% (Swedish Agency for Growth Policy Analysis, 2013). Thus could result in more coal and natural gas power plants being built to meet the increase in energy demand.

7.2 National Strategy for Green Growth

In August 2008, 'Low Carbon, Green Growth' was announced by President Lee Myung-bak as the new vision to guide South Korea's long-term development, and to drive its economic growth in an environmentally sustainable manner. The Presidential Commission on Green Growth was established in February 2009 to realise this vision (*see* www.greengrowth.go.kr/english). The National Strategy for Green Growth was adopted in July 2009 to implement the policy, along with a Five-Year Plan, which sets out the mid-term policy goals. To provide the legal and institutional basis for the country's green growth strategy and the legal basis for financing green technology R&D, the Framework Act on Low Carbon, Green Growth was enacted in January 2010. The commitment to reduce GHG emissions by 30% from the predicted level by 2020 has been integrated into the Strategy.

The ***National Strategy for Green Growth*** (2009–50) consists of three objectives and ten policy directions. The three objectives are:

- mitigate climate change (greenhouse gases) and promote energy independence. One of the policies to achieve this is to reduce the use of fossil fuels;
- create new engines for economic growth, such as the development of green technologies; and
- improve the quality of life and the country's international standing. South Korea is planning to become a global leader among low carbon societies through its Green Growth policy.

The implementation of the strategy over 2009 to 2013 is detailed in the ***Five-Year Plan for Green Growth*** (2009–13). R&D is focused on 27 core technologies (which includes IGCC and CCS). The decision on whether to include a technology in the list was based on its potential contribution to economic growth and environmental sustainability, and its strategic importance. The Plan has a budget of 107.4 trillion Korean won (KRW), which is equivalent to 2% of annual GDP. The high level of spending is due in part to the inclusion of large construction projects, such as the one for railway construction. R&D programmes will consume 12% of the budget. The R&D investment in the 27 core technologies will expand gradually from KRW1.9 trillion in 2009 to KRW3.5 trillion by 2013. This equates to KRW13 trillion in total. It will boost green R&D from 16% of the government's total R&D spending in 2009 to 20% by 2012. The plan includes investment in public R&D, as well as fiscal support for green R&D by small and medium sized enterprises (Jones and Yoo, 2011).

In order to co-ordinate R&D policy, the Green Growth Committee is closely linked to the National Science and Technology Council (NSTC). The NSTC sets the ***Science and Technology Basic Plan***, which lays out the government's support for scientific research and technology development. The stated objectives of the Third Basic Plan is for R&D to contribute to 40% of economic growth by 2017. The strategic development of 30 priority and 120 technologies (including energy, environment and CCS) are given (British Embassy Seoul, 2013).

7.3 National Energy R&D plan and roadmaps

A number of plans have been drawn up to implement the National Strategy for Green Growth. One of these is the second ***National Energy Technology R&D Plan (2011)***, which covers the period 2011–20 (Choi, 2011). Its objective is energy technology innovation for low carbon and green growth, and also the acceleration of economic growth. Three strategic roadmaps form part of the ***Energy Technology RD&D Strategy Roadmap***. These give the mid- to long-term R&D milestones for the core technologies (Chung, 2012):

- Green Energy Strategy Roadmap, which has the goal of enhancing South Korea's competitiveness in global green energy through technology innovation;
- GHG Reduction Technology Strategy Roadmap to help achieve the national GHG reduction target through industry orientated energy technology R&D; and
- Resources Development Technology Strategy Roadmap to assist South Korea enhance its energy security. Unconventional gas is one of the 84 core technologies.

The ***Green Energy Strategy Roadmap*** covers technologies relevant to the power generation industry. The 2011 version was established by the Korea Institute of Energy Technology Evaluation and Planning (KETEP). It includes 88 strategic items and 288 key technologies which South Korea will focus on within 15 green energy fields. The strategic directions, R&D schedule by year, commercialisation strategy and capital requirements are given. Among the key technologies (DI Energy, 2011) are:

- clean fuels, for example, low rank coal gasification, coal-to-synthetic natural gas, and coal-to-liquids;
- fuel cells, which includes IGFC;
- IGCC, where a 300 MW IGCC demonstration plant, a 500 MW plant, and a hybrid IGCC + fuel cell are among the strategic items;
- CCS, which includes pre- and post-combustion CO_2 capture, and oxyfuel combustion; and
- clean thermal power generation, which was not listed in the 2009 roadmap. It covers gas turbines, replacement of old thermal power plants with high efficiency ultraclean facilities, and high efficiency 700°C generation technology development.

Roadmaps have also been produced for the core technologies, such as CCS. A ***CCS master plan***, for example, was planned and announced in July 2010 by the Presidential Committee on Green Growth and five ministries. It covers innovative CO_2 capture technology development and demonstrations, as well as CO_2 transport, storage and utilisation. Two large-scale integrated CCS demonstration plants are planned, one online by 2017 and the other by 2019. A total of US$1.9 billion will be invested in these two demonstration projects over 2010-19, with the government contributing 52%, and the private sector 48%. The Korean Electric Power Corp (KEPCO), a state run utility, and its five subsidiaries have additionally committed KRW1.3 trillion (US$1.1 billion) in funding for CCS over the next 10 years (to 2020) (Carbon Sequestration Leadership Forum, 2013).

A new CCS programme, the ***Korea CCS Project***, was launched in November 2011 as part of the government's overall plan for CCS commercialisation. It is run by the Korea Carbon Capture and Sequestration R&D Center (KCRC). The project (*see* www.kcrc.re.kr) is 100% funded by the Ministry of Science, ICT and Future Planning, and has a KRW172.7 billion (US$144 million) budget for its 9 y lifetime (Nov 2011–May 2020). A roadmap has been produced to achieve the objectives of developing third generation CO_2 capture technology, CO_2 capture-storage integrated technology, and CO_2 conversion utilisation technology. About 50 projects from industry, universities and institutes are being funded, and each of the selected technologies has its own roadmap, as detailed in KCRC (2012). The technologies include CO_2 capture using solvents, dry solvents and membranes. One of the objectives is to develop over four types of new technologies to capture and store CO_2 at an additional cost of 30% below the operating costs of the power plant or large-scale emitting plant. KCRC also supports international cooperation, including international joint research.

A ***National Greenhouse Gas Emissions Reduction Roadmap 2020*** was announced by the Ministry of Environment in January 2014 (Ministry of Environment, 2014). It maintains the target of a 30% reduction in CO_2 emissions from the business-as-usual level by 2020 that was set by the previous government. National emission reduction targets and action plans for various sectors are given. Power generation must cut emissions by 26.7%, transportation by 34.3%, building by 26.9%, public sector by 25.0%, industry by 18.5%, waste by 12.3%, and agriculture and fishery by 5.2%. This will reduce GHG emissions by 233 Mt, equivalent to a 30% cut on the 776 $MtCO_2$-e predicted in the 2020 business-as usual scenario. Technology development will help meet the targets.

7.4 RD&D funding

Korea has a large R&D budget. Total R&D investment by the Korean Government in 2014 will be KRW11.6750 trillion, an increase of 2.2% over 2013 (InvestKorea, 2013). The money will be invested in 414 national R&D projects. Government expenditure on just energy-related RD&D has increased significantly over the last 10 years and is now among the highest in the OECD. The largest increase has been in funding for new and renewable energy technologies. Investment in energy-related RD&D was over KRW602 billion in 2011, about 0.0486% of GDP (IEA, 2013d).

About 0.0032% of GDP was spent by the Korean government on coal and CCS RD&D projects in 2011. Some KRW6635.488 million (US$5.893 million, 2012 prices and exchange rate) was invested in coal RD&D (about 0.00052% of GDP), of which KRW1105.829 million (US$0.982 million) was on coal combustion (where IGCC is included). The total budget for CCS RD&D was KRW34101.951 million (US$30.288 million), of which KRW31848.293 million (US$28.286 million) was for CO_2 capture and separation (*see* Table 6). As can be seen in the table, the RD&D budget for coal decreased from 2009 to 2011, although the budget for IGCC increased in 2010. The importance that the Korean government attaches to the abatement of CO_2 emissions is seen in the increased expenditure on CCS where it nearly doubled between 2009 and 2011.

Table 6 Korean RD&D budget for coal and CCS (IEA, 2013d)

		2008	2009	2010	2011
Total RD&D in million KRW (million US$, in 2012 prices and exchange rates, where US$1 = 1,125.93 KRW in 2012)	Coal production, preparation and transport	15062.665 (13.378)	8471.535 (7.524)	6766.443 (6.01)	3209.415 (2.85)
	Coal combustion (including IGCC)	0	541.935 (0.481)	1118.507 (0.993)	1105.829 (0.982)
	Coal conversion (excluding IGCC)	0	26825.806 (23.825)	0	0
	Other coal	4619.92 (4.103)	4223.845 (3.751)	6449.707 (5.728)	2320.244 (2.061)
	Total coal	19682.585 (17.481)	40063.123 (35.582)	14334.656 (12.731)	6635.488 (5.893)
	CO_2 capture/separation	17429.239 (15.48)	17983.587 (15.972)	28762.347 (25.545)	31848.293 (28.286)
	CO_2 transport	0	0	0	0
	CO_2 storage	0	0	2299.733 (2.043)	2253.659 (2.002)
	Total CCS	17429.239 (15.48)	17983.587 (15.972)	31062.08 (27.588)	34101.951 (30.288)

One source of government funding is the Korea Institute of Energy Technology Evaluation and Planning (KETEP, *see* http://ketep.re.kr/english), which comes under the Ministry of Trade, Industry and Energy (MOTIE). KETEP, founded in 2009, plans, evaluates and manages the national energy technology R&D programmes (Choi, 2011). This includes the CCTs programmes, and pre- and post-combustion CO_2 capture, oxyfuel combustion and chemical looping. In 2013, its budget was US$707 million. KETEP has taken over the funding activities of the New & Renewable Center, KEPCO and Korea Energy Management

Corp. KETEP also manages the international collaboration R&D activities and helps promote the developed advanced energy technologies on the global market.

The Korean government provides tax benefits to encourage energy R&D investment in the private sector. MOTIE is facilitating research centres as a means for companies, universities and institutes to pool information on R&D. The government is also fostering exports its CCT to the emerging economies.

7.5 International collaboration

South Korea cooperates with various countries on CCT and CCS RD&D and technology exchange through membership of international organisations (such as the International Energy Agency and Global CCS Institute), and bilateral (with China, EU, Japan, UK and the USA, among others) and multilateral agreements. The government recognises the importance of international collaboration for successful innovative energy technology development. Both KETEP and the Korea Carbon Capture and Sequestration R&D Center, for example, support international joint research projects.

7.6 Demonstration projects

Most of the research carried out at universities are on subjects within the national R&D programme, but are not covered in this report. This section will just describe the current principal national IGCC and CO_2 research and demonstration projects.

IGCC project

A task force on IGCC was launched in December 2006 in order to facilitate the research, development, demonstration and deployment of IGCC in South Korea. The IGCC R&D Organisation (*see* www.igcc.or.kr) was setup under MOTIE to oversee the project to construct a 300 MW demonstration plant at Taean. IGCC is one of the strategic technologies listed in the Green Energy Strategy Roadmap. The Taean IGCC project is the first commercial IGCC plant to be developed under South Korea's Renewable Energy Portfolio Standard.

The first phase of the project, which included the design of the demonstration plant, was completed in 2010. The Shell gasification process was selected as the preferred technology. In the second phase (2011–16), a 300 MW demonstration plant will be constructed at Taean. The budget is US$1.4 billion, with the government contributing US$0.1 billion and the rest by the participants (Korea Western Power, Doosan Heavy Industries and other consortium partners). The demonstration plant will then be operated from December 2015 to July 2016 and its performance enhanced (Kim, 2011). The long-term plan is to build two more 300 MW IGCC plants, one at Youngnam by December 2017, and one at Gunjang by December 2019. CCS will be incorporated in the plants, using a CO_2 capture process developed under the CCS programme. One of the planned large-scale CCS demonstrations will be either the Taean 300 MW IGCC plant or a 500 MW oxyfuel combustion power plant. There are plans for a 600 MW IGCC plant and to export the design abroad.

Various research projects are also being carried out in support of coal gasification. For example, the development of regenerable solid sorbents for desulphurisation of coal gas (hot gas desulphurisation) for IGCC (Park and others, 2013), low rank coal gasification for generating coal liquids or power (via IGCC), and coal-to-liquids and coal-to-gas via coal gasification (Choi and Yoo, 2012).

KPCC project (post-combustion CO_2 capture)

The KPCC project (KoSol Process for CO_2 Capture), under the leadership of the KEPCO Research Institute (KEPRI), is developing advanced amine solvents for capturing CO_2 from flue gas in pulverised coal-fired power plants. It has a budget of US$41 million, and is funded by nine organisations and companies, and the Korean government (Jegarl, 2013). The first stage of the project (2008–10) used a 0.1 MW (2 tCO_2/d) test bed sited at the Boryeong power plant to develop alkanolamine solvents with a regeneration energy of at least 30% below that of monoethanolamine (MEA). Under stage 2 (2011–14), a 10 MW pilot plant that captures 200 tCO_2/d from a slipstream at the Boryeong power plant was constructed between March 2012 and May 2013. The plant utilises the proprietary solvent KoSol-4, which aims to capture over 90% of the CO_2 from the slipstream at a purity in excess of 99%. The target is a regeneration energy of between 2.5 and 3 GJ/tCO_2 compared to a regeneration energy of 3.6 to 3.9 GJ/tCO_2 for MEA (Van Puyvelde, 2013). The last stage (2015–18) is a commercial-scale demonstration (Jegarl, 2013), where the process could be part of one of the two planned CCS demonstration plants.

Solid sorbent post-combustion CO_2 capture

This project, under the leadership of KEPRI, is developing dry, regenerable solid sorbents for capturing CO_2. It is funded by the Korean government and 10 participating companies and organisations, and has a budget of US$39 million. A 0.5 MW facility, capable of capturing 10 tCO_2/d using KIER's fluidised bed CO_2 capture process, was built at the Hadong power plant. It was commissioned in March 2010, testing regenerable sorbents (KEP-CO2P) developed by KEPCO. A 10 MW pilot plant (200 tCO_2/d) has now been built (construction finished in Aug 2013) at the Hadong power plant (Jegarl, 2013). The last stage (2014–18) is a 300 MW demonstration at the Samcheock power plant (Ryu, 2011).

Solid sorbent pre-combustion CO_2 capture

The aim is to minimise the energy penalty and cost for pre-combustion CO_2 capture in IGCC plants by using KIER's one-loop fluidised bed system with solid sorbents developed by KEPRI (warm gas cleanup and sorption enhanced water gas shift). A 0.1 MW facility treating gas from a 3 t/d coal gasifier was built in 2011. Scale-up to a 1–10 MW plant by 2018, and a 300 MW demonstration from 2018 are planned (Jegarl, 2013).

Oxyfuel combustion

After the conceptual design of oxyfuel combustion (2007–10), a FEED study was undertaken over 2010–12. Over the period 2012–15, it is planned to design and retrofit a 100 MWe oxyfuel unit at the Youngdong coal-fired power plant. This will be demonstrated over 2015–17, with a 500 MWe commercialisation plant planned for 2017–20. Advanced coal-fired oxyfuel combustion will then be developed after 2020 (Jegarl, 2013; Kim and others, 2011). However, plans for the 100 MW demonstration plant have been put on hold because of funding constraints and uncertainties over CO_2 storage.

7.7 Research organisations

This section covers the principal organisations carrying out research on CCTs and CCS relevant to the power generation industry.

Korea Institute of Energy Research (KIER)

KIER (*see* www.kier.re.kr/eng/), affiliated to the Ministry of Science, ICT and Future Planning, is Korea's major energy technology research institution. It carries out R&D on clean and new energy technologies and their efficient use, with a long term view on future energy security and to contribute to the low carbon, green growth vision. The budget in March 2013 was KRW159,963 million, with the government contributing 51%, and revenue from R&D contracts making up some 47%. R&D programmes cover CCT and CCS for both the power and industrial sectors. CCT programmes include coal gasification (partitioned fluidised bed coal gasifier), coal-to-liquids, upgrading low rank coal (fluidised bed dryer), ash-free coal (by solvent extraction) and processing of coalbed methane. Fuel cells R&D includes those suitable for IGFC. R&D on the processes and materials for the capture, storage and treatment of CO_2 from large emitters is also carried out. This includes CO_2 capture by absorption in aqueous ammonia, advanced amines, reaction promoted K_2CO_3 solution and membranes, and by fluidised bed adsorption using a dry sorbent. Pre-combustion CO_2 capture, oxyfuel combustion and chemical looping combustion are also being investigated (Kim, 2009). KIER additionally collaborates with overseas energy-related research institutions.

KEPCO Research Institute (KEPRI)

The KEPCO Research Institute (KEPRI or Korea Electric Power Research Institute, *see* www.kepri.re.kr/english) is contributing to KEPCO's goal of becoming one of the world's top five electric utilities for green energy by 2020. Eight green technologies have been selected in step with the Government's stress on low carbon, green growth. Current research programmes within the Future Technology Development Laboratory include CO_2 capture using dry regenerable sorbents and chemical solvents (as described in Section 7.6), CO_2 utilisation, CO_2 storage, and renewable energy. Research within the Power Generation Laboratory includes both oxyfuel and circulating fluidised bed combustion.

8 South Africa

South Africa's economy is heavily dependent on coal. Coal is the top revenue earner, ahead of platinum and gold (Fisher, 2013), contributing R50.5 billion or 57.5% of foreign revenue value in 2011 (Hall, 2013). Currently, South Africa is the world's seventh largest coal producer and the sixth largest exporter. It is also one of the cheapest producers. In 2012, it produced some 259.3 Mt of coal, of which about 29% (74.3 Mt) was exported (IEA, 2013c). The coal is mostly sent to India, China and Europe. According to BP, proven coal reserves (bituminous coal and anthracite) were 30.156 Gt in 2012, the ninth largest in the world (BP, 2013). However, a new report by the Council for Geoscience more than doubles this figure, with an estimate of 66.7 Gt of run-of-mine coal reserves (Ryan, 2014). Therefore, South Africa has the potential to substantially expand its exports (and consumption).

There are only limited proved reserves of natural gas and oil, and consequently, South Africa is heavily reliant on its coal to meet its energy needs. In 2012, ~72% of South Africa's total primary energy consumption came from coal, followed by oil (~22%), natural gas (~3%), nuclear (~2%), and renewables (<1%) (BP, 2013). Some 187.2 Mt of coal was consumed in 2012, an increase of 0.9 Mt over 2011 (186.3 Mt), making South Africa the sixth largest global coal consumer. About 93% of electricity and 30% of liquid fuels are produced from coal. Coal is additionally used in the steel and other industries, and for domestic heating and cooking. The state-owned utility, Eskom, dominates the electricity sector, providing 95% of the country's electricity (Fisher, 2013). Electricity supply has been struggling to meet increasing demand. During 2013, Eskom was operating with a reserve margin as low as 1%, against an international benchmark of 15%. This has not been helped by delays in the construction of two new 4800 MW coal fired power plants (Medupi and Kusile).

South Africa's dependence on coal has helped place the country as the twelfth largest CO_2 global emitter (Fisher, 2013). Looking at CO_2 emissions from just fossil fuel combustion, South Africa was the world's 17th biggest emitter in 2011 (but with only 1% of the global total), releasing 367.6 $MtCO_2$, of which 290.2 $MtCO_2$ came from coal. The electricity and heat sector accounted for 61% of the country's emissions in 2011, generating 203.1 $MtCO_2$, or 869 gCO_2/kWh. Electricity production was 259.6 TWh, of which 94% was generated from coal (IEA, 2013b). CO_2 emissions from the electricity sector are likely to increase in the short-term when the new Kusile and Medupi coal-fired power plants are built.

8.1 Energy policy and initiatives

An ***Integrated Energy Plan*** (IEP), as envisaged in the 1998 White Paper on Energy Policy, was published in 2003. The Plan was intended to provide a roadmap of the future energy landscape for South Africa that would guide future energy infrastructure investments and policy development. It is currently being updated. The 2013 draft update (Department of Energy, 2013a) identifies eight key objectives, namely to:

- ensure security of supply;
- minimise the cost of energy;
- increase access to energy;

- diversify supply sources and primary sources of energy;
- minimise emissions, particularly CO_2, from the energy sector;
- advance energy efficiency in the economy;
- promote localisation and technology transfer and the creation of jobs; and
- promote the conservation of water.

The draft IEP does not provide recommendations but instead presents modelling outcomes from a 'base case' and various test cases, which are premised on a set of core assumptions relating to factors such as demand growth and energy prices. The cases take into account national government policies that influence the energy sector, such as the National Development Plan, Integrated Resource Plan and climate change policies (discussed below). The possible implications of pursuing alternative energy policy options can therefore be seen. Recommendations will be included in the final report.

In the base case, new coal technologies will continue to contribute to the electricity supply (an additional ~50 GW by 2050). Although coal-fired power plants with CCS were considered as an option, the model did not select any CCS technologies in the test cases with CO_2 emission limits due to their relatively high cost, and the availability of cheaper alternatives (namely, wind and solar technologies).

In 2011, the South African government published the ***Integrated Resource Plan (IRP) for Electricity 2010–30*** and a comprehensive update in 2013. The 2011 IRP identified the preferred generation technologies required to meet expected demand growth up to 2030 under a policy-adjusted scenario that is a compromise between low carbon and low cost strategies (Department of Energy, 2011). The electricity generation scenario is based on an electricity growth projection of 2.9% per year on average. By 2030, it is projected that coal will supply 65% (compared to the current ~93%), nuclear 20%, hydro 5%, gas 1% and renewable energy 9% of the electricity demand. This calls for the addition of 6.3 GW of coal, 9.6 GW of nuclear power, 17.8 GW of renewable energy, and 8.9 GW of other generation sources between 2010 and 2030, in addition to all existing and committed power plants (including 10 GW pre-IRP committed coal). Research priorities identified for the next IRP were underground coal gasification (as the coal gas could potentially be used in place of natural gas) and CCS (since this would allow coal generation to continue to have a large presence, even in a carbon-constrained world). Implementation of the plan would see a 34% decline in emissions intensity from the sector by 2030.

There have been a number of developments in the energy sector since the promulgation of the 2011 IRP. In addition, the electricity demand outlook has changed markedly from that expected in 2010. The demand in 2030 is now projected to be in the range 345–416 TWh in the IRP Update instead of 454 TWh in the policy-adjusted scenario in the 2011 IRP (Department of Energy, 2013b). The Update reflects the country's ambitious economic growth aspirations set out in the National Development Plan to reduce unemployment and alleviate poverty in South Africa. This growth rate (an average of 5.4% per year until 2030) is also aligned with a shift in economic development away from energy intensive industries. The Update IRP base case projects that life extension will have increased the existing coal fleet to 36.23 GW by the end of 2030, and puts new coal at 2.45 GW, substantially less than the 2011 IRP. In the short term it is recommended that a new set of fluidised bed combustion coal generation should be launched for a total capacity of 1000–1500 MW (as a preferable implementation of the 'Coal 3' power plant programme). These should be based on discard coal.

A number of other government policies refer to the importance of CCT R&D. The ***National Development Plan*** aims to eliminate poverty and reduce inequality in South Africa by 2030. It outlines the 2030 vision for the energy sector, which reaffirms that coal will continue to be the dominant fuel for the next 20 years. Consequently, a national coal policy is urgently needed to ensure a sustainable supply of domestic coal for power, synthetic fuels and industrial chemicals, while expanding the growing coal export market. However, coal will contribute proportionately less to primary energy needs, while gas and renewable energy resources will play a larger role by the end of the period. In addition, CCTs (which includes USC power plants, fluidised bed combustion, underground coal gasification, IGCC plants, and CCS) will be supported through R&D and technology transfer agreements (National Planning Commission, 2012).

The ***Beneficiation strategy*** provides a policy framework that will enable the orderly development of South Africa's mineral resources, through beneficiation, to enhance their export value, increase sources for domestic consumption, and create job opportunities (Department of Mineral Resources, 2011). Interventions identified for optimal value creation (beneficiation) of coal include investment in:

- CCT RD&D and CCS (as these could provide a significant opportunity for major reductions in emissions);
- R&D to find innovative means for the beneficiation (recycling) of gases emitted in the generation of electricity; and
- technology to optimise the use of coalbed methane.

Despite the dependence of South Africa's economy on coal, especially for power production, the country has no explicit coal policy. A coal policy roadmap has now been published. The ***South African Coal Roadmap*** was developed to explore the short-, medium- and long-term activities and interventions needed to support the coal industry in South Africa to maximise its contribution to the economy (The Green House, 2013). It takes a scenario-based approach, where two drivers, the global climate change response and South Africa's mitigation response, were used to define a set of four distinct future worlds with very different implications for the coal value chain. The four future worlds are:

- more of the same, where limited action is taken on climate change globally and in South Africa;
- lags behind, where the world moves ahead with GHG emissions mitigation, but South Africa continues to pursue coal as its primary energy source;
- at the forefront, where South Africa joins the global leaders in emissions mitigation, while much of the remainder of the world takes limited action; and
- low carbon world, where strong action is taken globally and locally on GHG emissions mitigation.

It is recognised that the results of the analysis will need to be updated with the release of the updated IEP and IRP. Coal-fired power generation is expected to continue to play a core role in the medium term. In the longer term, the role of coal in a low carbon future is likely to be largely dependent on the successful implementation of GHG mitigation measures, particularly increased combustion efficiency and the implementation of CCS, as well as measures to mitigate other environmental impacts associated with coal-fired power plants. A number of actions and key policy requirements are given. These include focusing R&D in the medium-term on determining the applicability of USC combustion, IGCC, oxyfuel combustion and fluidised bed combustion (such as advanced supercritical fluidised bed combustion) to South African coals. Additional research in the medium-term on flue gas desulphurisation, underground coal gasification and CCS is also recommended. This includes continued engagement with international R&D progress in the capture and transport components of CCS. Other research opportunities include cofiring coal with biomass.

8.2 Climate policy and initiatives

Since South Africa is a Non-Annex I party to the Kyoto Protocol, it has no obligations to reduce its CO_2 emissions. However, President Jacob Zuma, at the Copenhagen summit in 2009, committed South Africa to reducing GHG emissions by 34% by 2020 and 42% by 2025, on condition that it received the necessary financial and technological support from developed countries. The government's vision for an effective climate change response and long-term transition to a low-carbon economy is outlined in the ***National Climate Change Response White Paper***, adopted in October 2011 (Department of Environmental Affairs, 2011). The paper proposes using a National GHG emissions trajectory range, based on the Copenhagen commitment, against which mitigation efforts will be measured.

The White Paper recognises that the most substantial climate change mitigation contributions will have to come from reduced emissions from energy generation and use. The majority of South Africa's CO_2 emissions from energy result from electricity generation, which constituted around half of its energy emissions and just under 40% of total emissions in 2000. Eight near-term flagship programmes were identified to help address climate change issues; some of these were already underway when the White Paper was published. One programme relevant to the energy sector is the *Carbon Capture and Sequestration Flagship Programme*, led by the Department of Energy and the South African National Energy Development Institute (through the South African Centre for Carbon Capture and Storage). This will help drive CCS RD&D.

An earlier ***Vision, Strategic Direction and Framework for Climate Policy***, announced in July 2008, also highlighted the need for developing CCS for coal-fired power and coal-to-liquid plants, and that new power plants that are not CCS ready should not be approved (*see* www.environment.gov.za/mediastatement/strategicframework climatepolicy). In addition, a shift to cleaner coal by, for example, introducing more stringent thermal efficiency and emission standards for coal-fired power plants was recommended. Both CCS and CCTs are part of South Africa's energy policy and initiatives, as discussed in the previous section. These energy initiatives will also help South Africa meet the Copenhagen commitment.

The development of CCS is a national research priority. A South African Centre for Carbon Capture and Storage (SACCCS) was set up, commencing operations in March 2009 (*see* Section 8.7). The aim is to establish an operational CCS demonstration plant by 2020. A five stage CCS Roadmap (endorsed by the Cabinet in May 2012) has been developed to achieve this objective (*see* www.sacccs.org.za/roadmap), of which the first two stages have been completed (*see* Figure 5). The next phase is a pilot CO_2 storage project, where 10,000–50,000tCO_2 will be injected into an onshore saline aquifer site; injection is planned to commence in 2017. The project received R207 million from the Department of Energy in the 2012/13 financial year (SANEDI, 2013).

The five phases of the CCS Roadmap and their current status are:

- Preliminary Potential Investigation (completed). This was undertaken by the Council for Scientific and Industrial Research for the then Department of Minerals and Energy to ascertain whether South Africa had potential capturable CO_2 sources and storage sites. Results, released during 2004, showed that South Africa had capturable emissions and potential storage sites;
- Geological Storage Atlas (completed). The Carbon Dioxide Geological Storage Atlas (published in October 2010) has located and characterised potential storage sites at a theoretical level. The Atlas will be taken into SACCCS's programme of work and further developed to locate a storage site suitable for the pilot CO_2 storage project;
- Pilot CO_2 Storage Project Experiment, where 10,000–50,000 tCO_2 will be injected into an onshore saline aquifer site. Injection is planned to commence in 2017. The experiment will be informed by similar injection activities currently underway internationally. The ultimate purpose is to show to decision makers that CCS can be safely undertaken in South Africa;
- Demonstration Plant, which will test an integrated operating system under local conditions. This phase, planned to start in 2020, will demonstrate the capture, transport and safe injection of ~100,000 tCO_2/y into South African geological formations;
- Commercial Operation, planned for 2025. If positive outcomes of the demonstration plant ensue, a full scale commercial plant is envisaged, injecting over 1 MtCO_2/y. It is expected that this phase will not be a part of SACCS.

Figure 5 CCS roadmap (SACCCS, 2014)

8.3 R&D initiatives

A key policy document driving R&D in South Africa is the ***Ten-Year Innovation Plan***, covering 2008–18 (Department of Science and Technology, 2007). It seeks to transform the South African economy into a knowledge-based one, in which the production and dissemination of knowledge will lead to economic benefits and enrich all fields of human endeavour. Among the 'grand challenges' identified in the plan are energy security, with CCTs as a major R&D area, and climate change. One of the targets is to increase the energy supply with over 50% of new capacity coming from clean coal and nuclear technologies. The plan also envisages South Africa becoming a world leader in climate science and the response to climate change. This means expanding investment in R&D in these subjects.

8.4 RD&D funding

South Africa spent R22.209 billion on R&D in the financial year 2011/12 or 0.76% of GDP. This was an increase from the R20.254 billion recorded in 2010/11 (again 0.76% of GDP). R&D expenditure as a percentage of GDP has declined since its peak of 0.95% in 2006/07 to 0.76% (Centre for Science, Technology and Innovation Indicators, 2014). It is recognised that this is below the OECD average expenditure of 2.37% of GDP in 2011/12, and that the percentage should be increased. The 2002 National Research and Development Strategy (Department of Science and Technology, 2002) set an investment target of 1% of GDP for 2008, but this figure has still not been met today. The growth in R&D expenditure has been driven by public money, injected since 2002 as part of the National R&D Strategy. The government is the largest funder of R&D, contributing 43.1% in 2011/12, with the business sector providing 39% (Centre for Science, Technology and Innovation Indicators, 2014). The bulk of the R&D funded by government is undertaken by higher education institutions and science councils. Applied research accounted for the largest proportion of R&D expenditure in 2011/12, comprising 42.3%, followed by experimental development at 33.2% and basic research at 24.5%.

Coal and CCS RD&D is mainly funded via the Department of Science and Technology, Department of Energy, and Department of Mineral Resources. There does not appear to be any published information on the amount the South African government is spending on CCT and CCS RD&D. One government funded organisation that both finances and carries out CCT and CCS research, amongst other activities, is the South African National Energy Development Institute (SANEDI, *see* Section 8.7). It is principally funded by the Department of Energy, with smaller amounts coming from the Department of Science and Technology, and elsewhere. Its applied energy research budget for 2013/14 is R44.12 million, and will increase to an estimated R182.762 million in 2014/15 (National Treasury, 2014a). R111 million has been allocated in 2014/15 for RD&D related to the CCS demonstration project being undertaken by SACCCS (*see* Section 8.7) and the hydraulic fracturing for shale gas projects. SANEDI also funds some CCT research at universities. Internal budget requirements for fulfilling its mandate are estimated at R139.231 million for CCT research (4 projects) and R213.98 million for CCS (3 projects) over the 5 y period from 2012/13 (SANEDI, 2011).

The National Research Foundation, which receives ~55% of its income from the Department of Science and Technology, funds research at various national research institutes (none of which includes coal research) and universities. Its budget for 'research and innovation support and advancement' (excluding national research facilities) is R1.931 million for 2013/14, rising to R2.012 in 2014/15. The Council for Scientific and Industrial Research, CSIR (*see* Section 8.7) also receives funding from the Department of Science and Technology, as well as income from contract R&D and other non-government sources. Its Materials Science and Manufacturing unit (which includes CCT R&D) has a budget of R252.543 million and R263.624 million for 2013/14 and 2014/15, respectively (National Treasury, 2014b).

The Technology Innovation Agency supports the development and commercialisation of technology innovation in various sectors, which include mining and energy. CCTs, including advanced coal power and GHG emission control technologies are covered in the energy sector (*see* www.tia.org.za/industrial-sectors/energy). The Agency's income is derived mainly from the government via the Department of Science and Technology, royalty payments, interest from loans, and dividends received on investments.

8.5 International collaboration

South Africa collaborates with several countries on CCT and CCS RD&D through membership of international organisations (such as the Global CCS Institute, Carbon Sequestration Leadership Forum and Clean Energy Ministerial), bilateral (with the EU, Norway and USA, amongst others) and multilateral agreements (such as the India-Brazil-South Africa Dialogue Forum (*see* www.ibsa-trilateral.org), and academic and industrial co-operation.

One example of international collaboration is with the European Union. A ***Working Group on Coal, CCT and CCS*** has been established between the EU and South Africa to facilitate information exchange and R&D on CCTs and CCS. It was established by the EU-South Africa Dialogue and Cooperation on Energy in March 2008 (*see* http://ec.europa.eu/energy/international/bilateral_cooperation/south_africa_en.htm). South Africa is one of the most successful third country participants in the EU's FP7. Projects include the OCTAVIUS CO_2 capture project (*see* Table 2 on page 45). Another partnership, born out of the FP6 programme is the European South African Science and Technology Advancement Programme (ESASTAP). This again promotes cooperation in CCTs and CCS (*see* http://ec.europa.eu/environment/ecoap/about-eco-innovation/policies-matters/eu/335_en.htm).

8.6 Demonstration projects

R&D activities are predominantly government-led, with South African research directed towards goals set by the government. Large state-owned companies can also have their own R&D facilities. This section describes the current state of underground coal gasification (UCG) projects. The national project to build a CCS demonstration plant was outlined earlier (*see* Figure 5).

UCG projects

A 5000 m^3/h pilot plant was commissioned by Eskom on the Majuba coalfield in January 2007. The UCG technology was licensed from Ergo Exergy Technologies in Canada. In October 2010, the plant commenced delivery of the gas (15,000 m^3/h) to one of the units at the Majuba power plant. The gas was cofired with coal, and contributed 3 MW to the unit's electricity production of ~650 MW (Department of Energy, 2013a). The UCG plant was shut down in September 2011. Eskom is planning to start work on a larger demonstration plant at its Majuba power plant, as soon as environmental approvals are received. The gas will still be cofired with coal, although the next phase plans to fire only gas in the gas turbines (Kolver, 2013). Eskom eventually wants to develop a 2100 MW combined cycle gas power plant utilising gas generated through UCG technology (Gross and Van der Riet, 2011). UCG is seen as a way to use the 'unmineable' coal in the Majuba coalfield. The cavities left by the process, along with the coal char and ash, could possibly be used for CO_2 storage.

In June 2013, Eskom and Sasol New Energy announced the formation of a R1 billion joint UCG development programme to commercialise UCG in South Africa (Green, 2014). Sasol New Energy had already been evaluating UCG as a cleaner coal mining and conversion technology. Like Eskom, it has a licensing agreement with Ergo Exergy Technologies. Sasol is interested in UCG as a method of producing syngas for its coal-to-liquids processes (Couch, 2009). Africary Holdings (Pty) Ltd has obtained rights to develop the Theunissen coal resource in the Free State province, and has agreed with an international power plant operator to construct a 60 MWe power plant on the coalfield. Exxaro Resources has licensed Linc Energy's UCG technology for sub-Saharan commercial UCG projects (Green, 2014). In October 2013, CDE Process announced that it is using its third generation UCG design for a power plant project in South Africa. The first phase will provide 50 MW to the national grid by 2016 (ESI Africa, 2013).

8.7 Research organisations

Research activities at universities generally follow government policy objectives. A South African Research Chairs Initiative, managed by the National Science Foundation, was set up in 2006, and is designed to significantly expand the scientific research base of South Africa in a way that supports implementation of national R&D strategies. The objective is to strengthen and improve research and innovation capacity of universities for producing high quality postgraduate students, research and innovation outputs. Professor Rosemary Falcon at the University of the Witwatersrand currently holds the research chair in CCT. Research activities at South African universities are summarised in The Green House (2011). This section describes the principal national research institutes and one state-owned company, Eskom, who are carrying out research on CCT and CCS.

Coaltech Research Association

The Coaltech Research Association (*see* www.coaltech.co.za) was established in 1999 as the Coaltech 2020 Research Programme. It is a collaborative initiative between industry, the state, universities and other research organisations to develop technology and apply research findings to the coal mining industry. Among its shareholders are Anglo Coal, Eskom, CSIR, the Department of Minerals and Energy and the National Research Foundation. R&D areas include coal preparation (such as dry beneficiation and treatment of coal fines) and spontaneous combustion.

Council for Scientific and Industrial Research (CSIR)

CSIR, established in 1945, has the mandate to foster, through directed and multi-disciplinary research and technological innovation, industrial and scientific developments that contribute to the improvement of the quality of life of the people of South Africa (*see* www.csir.co.za). Income is derived from an annual Parliament Grant through the Department of Science and Technology, contract R&D, intellectual property exploitation, and other sources. In 2012/13, the Parliament Grant was R594.5 million and income from other sources amounted to R1474.743 (CSIR Strategic Communication, 2013). The Materials Science and

Manufacturing unit includes a research group on CCTs, with a focus on coal gasification, fluidised bed technology, closed-loop combustion, cofiring and CCS.

Eskom

State-owned Eskom (*see* www.eskom.co.za) generates, transmits and distributes electricity, generating ~95% of the electricity used in South Africa. It invested R500 million in RD&D in the FY2011, and plans to increase this by an effective 18% year-on-year growth over the next 5 y (Eskom Holdings Ltd, 2011). The largest portion of funds is being invested in research on renewable energy, improving efficiency of production, and the reduction of Eskom's impact on the environment. A comprehensive CCT R&D programme has been running for several decades, with the focus primarily on fluidised bed combustion, fluidised bed gasification (IGCC), UCG combined with IGCC, primary emissions reduction (such as reburn technologies and cofiring), combustion optimisation, coal beneficiation, power plant efficiency improvement, and CCS (The Green House, 2011). Eskom is one of the major drivers of technological innovation in South Africa – research carried out at universities and elsewhere is often on topics of interest to Eskom.

South African National Energy Development Institute (SANEDI)

The two public research agencies South African National Energy Research Institute (SANERI) and National Energy Efficiency Agency (NEEA) were merged into the new South African National Energy Development Institute (SANEDI) in 2011. SANEDI (*see* www.sanedi.org.za) is an implementing agency of the South African government, reporting to the Department of Energy, whose main function is to direct, monitor and conduct applied energy RD&D, as well as to undertake specific measures to promote the uptake of green energy and energy efficiency throughout the country (SANEDI, 2013). These are undertaken in line with the government's policy objectives. CCTs and CCS (through SACCCS, discussed below) are covered in the Advanced Fossil Fuels Programme. SANEDI awards research projects to universities, public research organisations and other organisations to carry out research on CCTs, such as IGCC, cleaner liquid fuels from coal, and CO_2 adsorption onto coal.

South African Centre for Carbon Capture and Storage (SACCCS)

SACCCS, a division of SANEDI, was established in 2009 to undertake CCS RD&D (*see* www.sacccs.org.za). CCS is one of South Africa's Near-Term Priority Flagship Programmes. SACCCS's work involves the development of the Pilot CO_2 Storage Project (*see* Figure 5 on page 83), as well as other support activities for CCS in South Africa.

9 USA

The USA has the largest economy in the world. It is the second largest global coal producer and consumer (after China). Coal production, though, fell in 2012 to its lowest level in almost two decades. In 2012, some 922.2 Mt of coal was produced, a decline of 7.2% (or 71.8 Mt) from 2011; it fell further to 908.1 Mt in 2013 (EIA, 2014a). Coal consumption has also decreased to 806.7 Mt in 2012, a 11.3%, or 103.2 Mt, decline from 2011. This is the lowest level since 1988. The decline was mainly due to lower electric power sector demand (the largest coal consuming sector). Some 747.1 Mt of coal was consumed by the electric power sector in 2012, an 11.3% (or 98.8 Mt) decrease from 2011. However, consumption is forecast by the Energy Information Administration (EIA) to have risen to 838.2 Mt in 2013 (EIA, 2014b).

The USA is the world's fourth largest coal exporter, with exports rising to 114.1 Mt in 2012 from 74.1 Mt in 2010 (IEA, 2013c). This was partly a result of coal being displaced by natural gas in the domestic power sector. The main market is Europe. Revenue from coal exports was about US$15 billion in 2012. In the longer term, coal production is forecast to increase to some 1017 Mt in 2040, consumption to 888.1 Mt, and exports to 146.1 Mt in the Annual Energy Outlook 2014 reference case (EIA, 2013a).

In 2012, coal accounted for 18% of US primary energy consumption and natural gas for 27%. Petroleum and liquid fuels had the highest share at 37%. As noted above, the majority of US coal is used for power generation – 91% of total coal consumption (in energy terms) in 2012. Coal-fired electricity generation has traditionally been the largest component. In 2012, coal's share of total electricity generation was 37%, with natural gas at 30%, nuclear 19%, renewables 19%, and petroleum and liquid fuels 1%; some 3,826 billion kWh of electricity was generated. But coal's share of the electricity market has been decreasing – in 2011 it was 43%. The decrease is largely because of low natural gas prices (partly the result of the expansion of shale gas production), the retirement of aging coal-fired power plants due to new emission regulations, and uncertainty about future regulations. EIA predicts about 50 GW of coal-fired capacity will be retired by 2021. The Annual Energy Outlook 2014 reference case expects electricity generation to grow to some 4,954 billion kWh in 2040, an average annual rate increase of 0.9%. Natural gas and coal will each account for 34% of total electricity generation in 2035, but by 2040, coal's share drops to 32% and the natural gas share increases to 35%. Nuclear's share will decline to 16%, and renewables increase to 16% (EIA, 2013a).

The USA is the second largest global emitter of CO_2 (after China), although in cumulative and per-capita terms it is the largest emitter. In 2011, the USA released 5.29 $GtCO_2$ from fuel combustion or 16.9% of global emissions. The trend in CO_2 emissions over the years has generally been upwards, although CO_2 emissions decreased to 5.2 Gt in 2009 mainly due to the economic recession (IEA, 2013b). Emissions have since risen to 5.28 Gt in 2012, with coal responsible for 1.65 $GtCO_2$ (EIA, 2014a). Energy-related CO_2 emissions are expected to be some 2.1% higher in 2013, because of a small increase in coal consumption (EIA, 2014b). Electricity and heat production produced 2.21 $GtCO_2$ in 2011, with electricity generation accounting for 503 gCO_2/kWh; electricity output was 4326.6 TWh. Some 1.83 $GtCO_2$ was emitted from coal combustion or about 34.6% of total energy-related CO_2 emissions in 2011 (IEA, 2013b). CO_2

emissions from coal are projected to decline by 2.5% in 2015 as the power sector responds to the Mercury and Air Toxics Standards regulations by retiring more power plants (EIA, 2014b).

9.1 Energy policy

Energy policy in the USA is set by both the Federal and State governments. This chapter is only concerned with federal policy and federal-funded RD&D programmes on CCT and CCS relevant to power generation.

The ***Energy Policy Act of 2005*** (Public Law 109-58, *see* www1.eere.energy.gov/femp/pdfs/epact_2005.pdf) was the first comprehensive energy policy act since 1992, and was intended to help promote secure, affordable and reliable energy. The Act covers energy efficiency, renewable energy, oil and gas, coal, nuclear issues, vehicles and fuels, hydrogen, electricity, and R&D, among other issues. For coal, it includes measures for promoting CCTs and CCS. Authorisation of US$200 million for each of the fiscal years 2006 to 2014 for the Clean Coal Power Initiative (discussed later) is provided. The total US$1.8 billion covers loan guarantees, loans and direct grants to advanced coal use facilities with the specific provision that 70% of the amount has to be spent on gasification projects. US$1.3 billion is offered in tax credits to advanced coal projects, US$800 million of which is ring-fenced for gasification projects. Gasification projects can claim up to 20% of the investment for tax credit, while other advanced coal projects can claim up to 15% (IEA, 2008b).

In 2007 the ***Energy Independence and Security Act*** (Public Law 110-140, *see* www.gpo.gov/fdsys/pkg/PLAW-110publ140/html/PLAW-110publ140.htm) was passed with the intention to move the USA towards greater energy independence and security. Among its provisions are measures to increase the production of clean renewable fuels, and to promote research on, and the deployment of, GHG capture and storage options. It amends the Energy Policy Act of 2005 to include authorisation for seven large-scale CCS demonstration projects (in addition to FutureGen) that would integrate the carbon capture, transportation, and storage steps. Since the policy was enacted, funding within the DOE CCS RD&D programme has shifted towards large-scale capture technology development through CCS demonstration projects.

Presidential initiatives are also driving RD&D policy on CCT and CCS. The clean and efficient use of coal is a key part of President Obama's energy strategy since coal will continue to be an important source for electricity generation. A priority goal is to 'catalyse the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in clean energy technologies' (NETL, 2012). Related to this goal, the Administration established the following targets:

- to reduce energy-related GHG emissions by 17% by 2020 and 83% by 2050, from a 2005 baseline; and
- to generate 80% of America's electricity from clean energy sources by 2035.

The ***2009 American Recovery and Reinvestment Act*** was designed to stimulate the US economy after the global financial crisis. It provided US$3.4 billion to support CCS RD&D. This is in addition to the annual budget appropriations for CCT and CCS (*see* Section 9.4). The funding included US$1.52 billion to the Industrial CCS programme, US$800 million to the Clean Coal Power Initiative, and US$1 billion to FutureGen 2.0 (discussed later). Moreover, the funding was intended to stimulate private sector investment due to the significant amount of cost sharing involved in the projects within these programmes.

An ***Interagency Task Force on Carbon Capture and Storage***, co-chaired by the DOE and Environmental Pollution Agency (EPA), was established in February 2010 to develop a more coordinated Federal strategy to help the development and deployment of CCS technology. It was charged with delivering a plan to overcome the barriers to the widespread, cost-effective deployment of CCS within ten years, with a goal of bringing five to ten commercial demonstration projects online by 2016. The plan, published in August 2010, highlights the importance of RD&D in bringing CCS technologies closer to deployment by reducing uncertainty related to cost or performance, thereby enabling their commercial viability. The report also recommends that the Administration should continue to support international collaboration that complements domestic CCS efforts and facilitates the global deployment of CCS (Interagency Task Force on Carbon Capture and Storage, 2010).

In June 2013, President Obama set out a broad ***Climate Action Plan*** (Executive Office of the President, 2013) to:

- cut carbon pollution in the USA;
- prepare the country for the impacts of climate change; and
- lead international efforts to combat global climate change.

In the absence of congressional agreement on climate policy, the plan relies mainly on executive powers. The President reaffirmed his 2009 commitment to reduce GHG emissions by 17% below 2005 levels by 2020 (equivalent to 4% on 2005 levels) if all other major economies agreed to limit their emissions as well. A key mitigation element of the Plan to help meet this goal is to cut CO_2 emissions from power plants. To accomplish this, a Presidential Memorandum directs EPA to complete carbon pollution standards for new and existing power plants. Power plants are the largest concentrated source of emissions in the USA, accounting for about one-third of all domestic GHG emissions. Coal plants will be unable to meet the proposed CO_2 standard (500 kg (1100 lbs)/MWh) without installing a CCS system. This could help drive CCS RD&D as EPA is required by law to ensure that its regulations are technologically viable and commercially available. Other regulations that have previously served as a focus for CCT RD&D include the Mercury and Air Toxics Standards and the Cross-State Air Pollution Rules. These regulations are currently subject to a number of legal challenges. Regulations on water discharge effluent limits and coal ash storage are also being drawn up.

A key component of the Climate Action Plan to spur investment in advanced fossil energy projects is an US$8 billion loan guarantee solicitation, which was released in December 2013. The loan guarantee was authorised through the Energy Policy Act of 2005. The solicitation covers a broad range of advanced fossil energy projects, and is designed to support investments in innovative technologies that can cost-effectively meet financial and policy goals, including the avoidance, reduction, or storage of anthropogenic GHG emissions.

The international element of the Plan includes working with other countries heavily dependent on coal-fired power plants to speed up the development and deployment of CCT. This could help drive RD&D on CCT and CCS. The Plan also ends US government support for public financing of new coal-fired power plants overseas, except for those employing the most efficient coal technology available in the world's poorest countries, or facilities deploying CCS technologies.

9.2 Coal and CCS initiatives and programmes

The Federal Government primarily supports energy technology innovation by investing in basic science, applied research, development and demonstration via the national laboratory system. Innovation is also supported through partnerships with industry, small business grants, loan guarantees for clean energy, and tax and regulatory policies. The close integration of private partners into public research ensures that the output of RD&D programmes has practical applicability. The DOE is the key federal agency involved in energy technology innovation.

The ***Clean Coal Research Program*** is administered by the DOE's Office of Fossil Energy, and implemented by the DOE National Energy Technology Laboratory's (NETL) Strategic Center for Coal. The Program is designed to enhance America's energy security and reduce environmental concerns over the future use of coal by developing a portfolio of innovative, near-zero emission technologies. It focuses on maximising the efficiency and environmental performance of advanced coal technologies, while minimising development and deployment costs. In recent years, the Program has been restructured to focus on CCT with CCS. NETL devotes the majority of the funding to R&D partnerships with industry, university, and other government entities, and the rest on onsite basic research. The Program comprises two major areas: CCS and Power Systems, and CCS Demonstrations.

The *CCS and Power Systems* programme conducts coal-related research under four sub-programmes, which are further divided into major technology areas. Each technology area (which consists of multiple projects) is organised to pursue the development of key technologies. The four sub-programmes (*see* www.netl.doe.gov/research/coal/) are:

- Advanced Energy Systems programme, which focuses on the development of gasification systems, advanced combustion systems, coal and coal/biomass technologies for the production of liquid fuels and hydrogen, fuel cells, and improved turbines for coal-fired power plants that are cleaner, more efficient and can capture CO_2;
- CO_2 Capture programme to develop technologies for lowering the costs of pre- and post-combustion systems, and CO_2 compression;
- CO_2 Storage, which advances CO_2 storage technologies that can reduce GHG emissions and mitigate global climate change; and

- Crossing-cutting Research, which develops technologies for improving the efficiency and environmental performance of advanced coal power systems through the use of novel sensors, process control systems, modelling, advanced simulation techniques (includes the Carbon Capture Simulation Initiative partnership), and advanced materials. It also includes a university and training research element, and serves as a bridge between basic and applied research.

The *CCS Demonstrations* is where the Federal Government has been collaborating with the private sector to co-fund large-scale demonstrations of CCT to speed their adoption into the commercial marketplace. Federal Government financial support is needed to help reduce the risks inherent in these first-of-a-kind projects. The first programme was the *Clean Coal Technology Demonstration Program* (*see* www.netl.doe.gov/research/coal/major-demonstrations/clean-coal-technology-development-program), launched in 1986. It produced 33 completed projects in four focus areas: environmental control devices, advanced power generation, fuel processing, and industrial applications. *The Power Plant Improvement Initiative* (*see* www.netl.doe.gov/research/coal/major-demonstrations/power-plant-improvement-initiative) was established in October 2000 to address electric power reliability concerns for new and existing power plants. It led to 4 completed projects. The *Industrial Carbon Capture and Storage* initiative (*see* www.netl.doe.gov/research/coal/major-demonstrations/industrial-carbon-capture-and-storage) addresses CO_2 emissions from non-power plant industrial sources. The *FutureGen* initiative is described in Section 9.6.

The *Clean Coal Power Initiative* (CCPI, *see* www.netl.doe.gov/research/coal/major-demonstrations/clean-coal-power-initiative) was created in 2002 to develop and demonstrate advanced coal-based technologies. The one project selected under Round 2 of the solicitation process that is still active and the three active projects selected under Round 3 are described in Section 9.6. Funding is provided through the annual congressional appropriations process. An additional US$800 million of funding was added by the government to Round 3 of the CCPI programme under the 2009 American Recovery and Reinvestment Act. All the projects include CCS, which has now become the exclusive focus of CCPI.

The ***Innovative Materials and Processes for Advanced Carbon Capture Technologies (IMPACCT)*** programme (*see* http://arpa-e.energy.gov/?q=arpa-e-programs/impacct) is administrated by the DOE's Advanced Research Projects Agency-Energy (ARPA-E). The goal is to develop technologies for existing coal-fired power plants that will lower the cost of carbon capture by developing materials and processes that have not been previously considered for this application. Short-term grants (lasting 1 to 3 y) are provided for accelerating projects from the basic research stage that are at too early a stage to attract private sector finance. ARPA-E also arranges strategic partnerships for the projects it funds (Reitenbach, 2013). Fifteen projects have been awarded under IMPACCT at a total cost of US$10 million. Funding for most of the projects finished in 2013, with the rest ending in 2014.

9.3 RD&D roadmaps

Roadmaps are important for prioritising research efforts given the limited amount of research funds available. The ***CURC-EPRI Coal Technology Roadmap***, originally produced in 2000, was last updated in

2012 (CURC and EPRI, 2012). CURC (Coal Utilization Research Council) is an industry advocacy group that promotes the efficient and environmentally-sound use of coal, whilst EPRI (Electric Power Research Institute) carries out R&D on behalf of member utility companies. The Roadmap identifies coal technology advancements that are needed to achieve specific cost, performance and environmental goals to help ensure that coal continues to provide economic, environmental and energy security benefits to America. A central goal is to reduce the cost of installing a CO_2 capture system, as well as lowering its energy consumption. The key performance goals for power plants with CCS over three time frames are given in Table 7. The performance and costs of the technologies that will have been demonstrated for each of these time frames, if the Roadmap is implemented, is at a first-of-a-kind commercial scale. Five to seven years need to be added in order to compare with DOE projections, which are for when technologies will be ready for commercial demonstration. The Roadmap analysis was divided into three distinct technology areas: combustion, gasification and cross-cutting technologies (that is, technologies that support both combustion and gasification systems). More details on the technologies options for IGCC plants with CCS can be found in the EPRI Roadmap for IGCC (EPRI, 2012).

Table 7 Goals for performance improvements for units with CCS (CURC and EPRI, 2012)

	2010 (Base)	2018	2025	2035
Size, MW	540	570–600	580–630	650–750
Plant efficiency (no CCS), %	39	39	45	48
Plant efficiency (with CCS), %	28–31	32–33	37–38	43–44
Emissions				
CO_2, % capture	–	90	90	90
CO_2, kg/MWh	–	91	82	64–73
(lb/MWh)	–	(200)	(180)	(140–160)
SO_2, kg/MWh	0.02–0.18	0.02–0.18	0.0005–0.09	0.00005–0.05
(lb/MWh)	(0.05–0.4)	(0.05–0.4)	(0.001–0.2)	(0.0001–0.1)
NOx, kg/MWh	0.2–0.32	0.2–0.32	0.11–0.18	0.05–0.16
(lb/MWh)	(0.44–0.7)	(0.44–0.7)	(0.25–0.4)	(0.1–0.35)
Particulate matter, kg/MWh	0.06	0.04	0.009–0.023	0.009–0.023
(lb/MWh)	(0.14)	(0.09)	(0.02–0.05)	(0.02–0.05)
Mercury, kg/GWh	0.003	0.00009–0.001	0.00009–0.0009	0.00009–0.0005
(lb/GWh)	(0.006)	(0.0002–0.003)	(0.0002–0.002)	(0.0002–0.001)
Water				
consumption, L/MWh (gal/MWh)	2271 (600)	1893 (500)	1514 (400)	757 (200)
withdrawal, L/MWh (gal/MWh)	3028 (800)	2650 (700)	1893 (500)	1136 (300)
discharge	treatment	treatment	zero liquid discharge	zero liquid discharge

Note: The 90% CO_2 emissions target identified in 2018 is dependent on the success of the first generation CCS and CCUS demonstration projects currently in design and development

The cost of implementing the CURC-EPRI Roadmap is approximately US$465 million/y over 2013–18, US$363 million/y over 2019–25, and US$189 million/y for 2026–35 for R&D. The demonstration part would cost US$120 million, US$6100 million (2–4 demonstrations) and US$3500 million (2–3 demonstrations) over the same time frames. Using the traditional public and private sector cost-sharing ratio, industry would contribute 20% of the costs and the Federal Government 80% to the R&D part of the Roadmap, and each would contribute about 50% in the demonstration part.

The ***DOE/NETL CCS Roadmap***, published in 2007 and updated in 2010, provides a roadmap for NETL's CCS RD&D effort. The projected timeline is consistent with the President's plan to overcome the barriers to the widespread, cost-effective deployment of CCS within 10 y (NETL, 2010). The goal of the CO_2 capture technology RD&D effort is to develop fossil fuel conversion systems that can achieve 90% CO_2 capture at less than a 10% increase in the cost of electricity for pre-combustion capture at IGCC power plants, and at less than 35% increase in the cost of electricity for post- and oxyfuel combustion capture at new and existing conventional coal-fired power plants. A wide variety of advanced CO_2 capture technologies, including liquid solvents, solid sorbents, membranes, oxyfuel combustion, and chemical looping combustion are being pursued. Figure 6 shows the CO_2 capture technology development cost-reduction benefits versus time to full-scale demonstration. It is planned to have full-scale CCS systems commercially available by 2030.

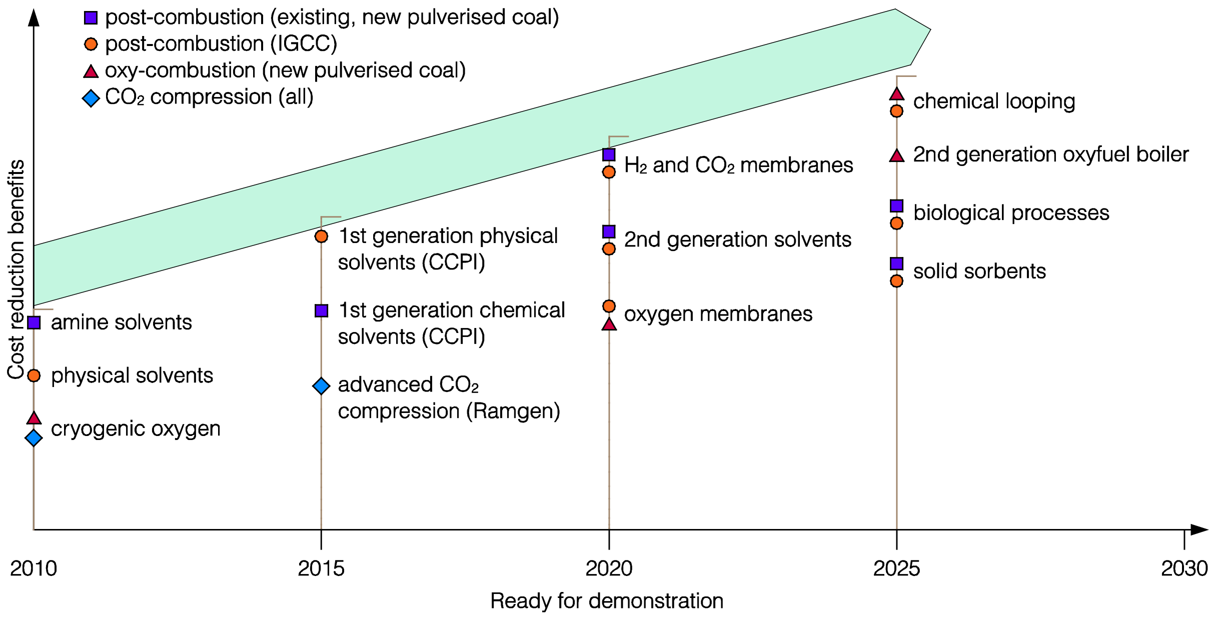

Figure 6 **CO_2 capture technology development** (NETL, 2010)

9.4 RD&D funding

The USA is the world's largest R&D investor, followed by China, although it is not the largest as a percentage of its GDP. In 2011, the Government invested 0.0422% of its GDP in energy RD&D (US$6.371 billion or US$6371 million), up from 0.032% in 2010 (IEA, 2013d). It spent nearly US$219 million ($2012) on coal RD&D in 2011 or about 0.0014% of its GDP. This was an increase over the budget in 2010, but less than that for 2009 (*see* Table 8). The large increase in 2009 was due to the one year appropriations contained in the 2009 American Recovery and Reinvestment Act. The importance the Government attaches to CCS RD&D (and the need to reduce GHG emissions) is seen in the increased expenditure on RD&D over the years.

Table 8 American RD&D budgets for coal and CCS (IEA, 2013d)

		2008	2009	2010	2011
Total RD&D in million US$ (2012 prices)	Coal production, preparation and transport	0	0	0	0
	Coal combustion (including IGCC)	364.415	2937.511	116.541	218.977
	Coal conversion (excluding IGCC)	0	5.264	7.284	0
	Other coal	0	44.221	30.176	0
	Total coal	364.415	2986.996	154	218.977
	CO_2 capture/separation	–	265.324	90.527	85.919
	CO_2 transport	–	–	0	0
	CO_2 storage	–	162.142	143.595	209.437
	Unallocated CO_2 capture and storage	204.774	45.273	0	0
	Total CCS	204.774	472.739	234.122	295.356

Note: The large increase in RD&D spending in 2009 was due to increased expenditures associated with the American Recovery and Reinvestment Act of 2009 (stimulus) spending. This is a one year appropriation (although actual expenditures may go into future years) and so 2010 saw a significant decrease.

Most of the Federal government's energy RD&D is funded through the DOE. DOE expenditure on fossil energy RD&D was US$498.75 million in FY2013, US$561.931 million in FY2014, and US$475.5 million in the FY2015 budget request (DOE, 2014). The bulk of the money goes to the Coal Program – about 69% in FY2013, 70% in FY2014, but only 58% in FY2015. The decrease in FY2015 is partly due to $25 million being assigned to a natural gas power system CCS demonstration. When this is included in the Coal Program (as the DOE includes CCS demonstrations in this program), then the figure is nearly 64%. Funding for the DOE Coal Program (CCS and Power Systems, as outlined in Section 9.3 but excluding the natural gas demonstration) for FY2012 to FY2015 is given in Table 9. This again reflects the focus on CCS RD&D.

Table 9 RD&D budget for CCS and power systems (DOE, 2013a, 2014)

	FY2012 current, US$ million	FY2013 current, US$ million	FY2014 current, US$ million	FY2015 budget request, US$ million
Advanced Energy Systems programme				
advanced combustion systems	15.499	14.79	18.5	15
gasification systems	37.918	36.051	36	22
hydrogen turbines	14.583	13.866	15	11
coal and coal-biomass to liquids	4.862	4.621	5	0
solid oxide fuel cells	24.307	23.110	25	3
total	97.169	92.438	99.5	51
Carbon Capture programme				
post-combustion	53.955	51.336	80	65
pre-combustion	13.031	12.389	12	12
total	66.986	63.725	92	77
Carbon Storage programme				
storage infrastructure (formerly Regional Carbon Sequestration Partnerships)	80.882	76.961	71.866	60.084
geological storage technologies	14.563	13.845	16.3	8.5
monitoring, verification, accounting and assessment	6.551	6.229	10	4.5
carbon use and reuse	0.756	0.719	0.8	0
focus area for carbon storage science	9.456	8.991	9.8	7
total	112.208	106.745	108.766	80.084
Cross-cutting Research programme				
plant optimisation technologies	13.284	12.69	17.025	7.042
coal utilisation science	24.472	23.293	19	23.55
energy analyses	4.95	4.711	0.95	0.85
university training and research	3.89	3.699	3.6	2.75
international activities	1.35	1.286	1.35	1.1
total	47.946	45.618	41.925	35.292
NETL coal R&D (funds in-house research relevant to CCS and power systems)	35.011	33.338	50.011	34.031
Total	359.32	341.864	392.202	277.406

The DOE funding in FY2011 for the Coal Program was US$389.6 million, made up of US$58.7 million for carbon capture, US$120.9 million for carbon storage, US$168.6 million for advanced energy systems, and US$41.4 million for cross-cutting research (DOE, 2012). The figures differ from those in Table 8 as the carbon capture and carbon storage figures only include those associated with coal-fired plants. The DOE figures also include some demonstrations and other funding, which are excluded by the IEA.

The benefits of a collaborative R&D programme can greatly exceed their costs. A study by Bezdek and Wendling (2013) estimated that the CCT R&D programme (current in 2008) would deliver total monetary benefits of US$111 billion between 2000–20 at a cost to the Federal budget of US$8.5 billion ($2008), that is, a 13-to-1 return for every taxpayer dollar invested. The benefits ranged from US$15 billion in fuel cost savings to $US39 billion for capital and technology cost savings in new and existing plants. However, the potential benefits of CO_2 reductions and indirect benefits were not taken into account, and so the monetary benefits could be higher.

9.5 International collaboration

The USA collaborates with several countries (such as Canada, China, India, Japan and the UK) to advance the development and deployment of clean coal and CCS technologies through membership of international organisations (such as the International Energy Agency), bilateral and multilateral agreements, academic co-operation and industrial collaboration. For example, a ***US-Japan Clean Energy Technologies Action Plan*** was developed between DOE and METI, which included an agreement to cooperate on a number of clean energy technologies, such as CCS.

The ***U.S.-China Fossil Energy Protocol*** (*see* http://energy.gov/fe/services/international-cooperation/bilateral-agreements-china) promotes scientific and technological cooperation between the USA and China in the field of fossil energy, particularly activities related to research, development, demonstration, and deployment. A new Annex was established for Advanced Coal-Based Energy Systems Research, Development and Simulation. Joint research projects on CCT are carried out through the ***US-China Clean Energy Research Institute*** (*see* Section 3.4). The ***US-India Energy Dialogue*** promotes increased trade and investment in the energy sector through co-operation and collaboration. Among the working groups are ones on coal and on power and energy efficiency. The ***US-India Partnership to Advance Clean Energy*** (PACE) consists of two components, namely research (PACE-R) and deployment (PACE-D). The current priority research projects do not include CCT, although the deployment component covers cleaner fossil technology (*see* www.pace-d.com).

9.6 RD&D programmes and demonstration projects

The following large-scale demonstrations are part of an integrated CCT RD&D programme that contributes to the DOE's strategic theme of 'Promoting America's energy security through reliable, clean and affordable energy' (DOE, 2013b).

Advanced Ultra-supercritical Power Plant Materials programme

The programme, which started in 2001, is financially supported by the DOE (US$50 million), the Ohio Office of Coal Development and industrial partners. The goal (*see* www.netl.doe.gov/research/coal/crosscutting/high-performance-materials/Ultrasupercritical) is to develop new materials that can be used in an advanced USC power plant capable of operating with steam temperatures of 760°C and pressures of 35 MPa, and with efficiencies of 45–47% (net, HHV) and a corresponding drop in CO_2 emissions of 15–22%. The programme is split into two consortia, one involving the major US boiler manufacturers, and the other the major steam manufacturers. Both consortia are supported by the Oak Ridge National Laboratory and NETL, with EPRI serving as the programme technical lead. The boiler part of the programme is assessing alloys for air- and oxygen (oxyfuel)-fired boilers, cyclic operation, material coatings, and the effects on fireside corrosion of firing domestic high sulphur coals. The steam turbine project is testing candidate materials that were identified in phase 1 of the project. A large-scale component test facility is planned to be operational from 2014 to 2017. More information can be found in the IEA CCC report by Nicol (2013). Plans are also under way for a 600 MWe design by 2015, with a full-scale demonstration plant operating by 2021 (IEA, 2012d).

FutureGen 2.0 project

The project, co-ordinated by the FutureGen Industrial Alliance, involves retrofitting the 200 MWe Unit 4 at the decommissioned Meredosia power plant in Illinois with advanced oxyfuel combustion technology (*see* www.futuregenalliance.org; http://sequestration.mit.edu/tools/projects/futuregen.html). The plant plans to burn a blend of high sulphur Illinois bituminous coal and low sulphur subbituminous Powder River Basin coal, and export 166 MW to the grid. About 90% of the CO_2 (~1.1 MtCO_2/y) will be captured and stored in a nearby deep saline aquifer. In January 2014, the DOE issued a Record of Decision to provide US$1 billion, which had been authorised under the 2009 American Recovery and Reinvestment Act. Total project cost is estimated to be US$1.75 billion (DOE, 2013b). The first phase of the project was completed in 2013, and Phase II started in February 2013. The front end engineering and design work has started. Construction is planned to begin in 2014, with the plant becoming operational in 2017.

Hydrogen Energy California (HECA) project

SCS Energy is planning to build a 400 MW (gross) IGCC plant near Bakersfield, CA, that coproduces up to 300 MWe (net) of electricity and ~1.02 Mt of fertilisers when using a 75% subbituminous coal and 25% petroleum coke blend (*see* http://hydrogenenergycalifornia.com). At least 90% of CO_2 will be captured and ~2.6 MtCO_2/y will be used for EOR in nearby oilfields. The plant will utilise the Mitsubishi Heavy Industries two-stage oxygen-blown gasification technology and the Rectisol® acid gas removal system for CO_2 capture, and also incorporate a zero liquid discharge system. Liquid sulphur will also be produced as a by-product. The project was awarded US$408 million in 2009 by the DOE under the CCPI Round 3 programme and through the 2009 American Recovery and Reinvestment Act. The total project cost will be ~US$4.028 billion (DOE, 2013b; NETL, 2013a). In January 2013, US$104 million was allocated to the project under Phase III of the US investment tax credits programme to support advanced coal projects with CCS. HECA received a final determination of Compliance from the San Joaquin Valley Air Pollution control districts for its required air permit in July 2013.

Kemper County Energy Facility project

This is a lignite-fuelled IGCC power plant, with CCS, that is being built in Kemper County, MS, that will be owned and operated by Mississippi Power, a subsidiary of Southern Co (*see* www.mississippipower.com/kemper). The plant incorporates two air-blown TRIG™ gasifiers. Peak capacity is 582 MW (net) when using syngas in the combustion turbine coupled with natural gas firing in the heat recovery steam generator duct burners. During syngas-only operations, the plant will achieve a net generating capacity of 524 MW. Over 65% of the CO_2 will be captured using the Selexol™ process (~3 MtCO_2/y) that will be sold for EOR. This gives a CO_2 emission rate of 363 kg (800 lb)/MWh. About 135,000 t/y of sulphuric acid and ~20,000 t/y of ammonia will also be produced and sold, helping to defray the plant's costs. The project has received US$270.2 million from the DOE under Round 2 of the CCPI programme and a US$133 million tax credit (which has been repaid since the project was not completed within five years). The estimated total plant cost has risen to ~US$5.55 billion. The combustion turbines were started in August 2013, and gasifier heat-up is planned for December 2013, with commercial operations beginning in early 2015 (NETL, 2013b; Pinkston, 2013).

Texas Clean Energy Project (TCEP)

Summit Power is developing a 400 MW IGCC plant at Penwell, TX, that coproduces electricity and chemicals, and incorporates CO_2 capture (*see* www.texascleanenergyproject.com; http://sequestration.mit.edu/tools/projects/tcep.html). The plant will use subbituminous coal that will be gasified in two Siemens entrained-flow, oxygen-blown gasifiers, and a Rectisol® acid gas removal system. About 90% of CO_2 (~2.6 MtCO_2/y) will be captured, 76% of which will be used for EOR and the rest for onsite production of urea (832,000 t/y). In addition, ~214 MW of electricity will be exported to the grid, and sulphuric acid will be produced and sold. Total project cost is estimated to be US$2.5 billion, of which the DOE is providing US$450 million through CCPI Round 3, which includes funding from the 2009 American Recovery and Reinvestment Act. TCEP is also receiving US$637 million in investment tax credits from the DOE and Treasury Department specially designed to stimulate clean coal power projects, on completion of the project. Front end engineering design was completed in June 2011, and the final environmental impact statement was released in July 2011 (DOE, 2013b; NETL, 2013c). However, CPS Energy has recently pulled out of the agreement to buy the generated electricity because of delays in the project and cheaper sources of generation elsewhere (Bastasch, 2014). This raises questions about the future of the project.

W A Parish CCS project

NRG Energy is retrofitting a 250 MW equivalent slipstream at its W A Parish coal-fired power plant at Thompsons, TX, with an advanced amine-based CO_2 capture system (*see* www.nrgenergy.com/petranova/waparish.html). The plant will capture 90% of the CO_2 (~1.4 MtCO_2/y), which will be used for EOR in the West Ranch oilfield. Total project cost is US$775 million, of which the DOE is providing US$167 million under Round 3 of the CCPI programme and the American Recovery and Reinvestment Act (DOE, 2013b; NETL, 2013d). The front end engineering design was started in 2010. The final environmental impact statement was issued by the DOE in February 2013 (NETL, 2013e). Construction of the demonstration facility started in 2014 and is expected to be operational by the end of 2016.

9.7 Research organisations

This section describes the principal research organisations that carry out research on CCT and CCS technologies. Academic institutions carrying out coal research over 1970–2010 are covered in Mathews and others (2013). A list of Federal funded R&D centres can be found at www.nsf.gov/statistics/ffrdclist/.

Electric Power Research Institute (EPRI)

EPRI conducts RD&D relating to the generation, delivery and use of electricity. It is an independent non-profit organisation, funded by its members, the majority of which are electric utilities. It also includes international participants from more than 30 countries. EPRI's RD&D portfolio addresses clean coal and CCS technologies at all stages of development and from economic and environmental perspectives, collaborating with universities, state and federal RD&D agencies, national laboratories, technology suppliers, other institutions, and power producers. Details can be found in the 2015 Research Portfolio (EPRI, 2015) and at www.epri.com.

EPRI's Technology Innovation (TI) programme supports exploratory research and early stage RD&D on advanced materials and generating cycles for higher efficiency coal plants, novel carbon capture and emission control systems, and environmental health and safety issues. The Fossil Fleet for Tomorrow and CO_2 Capture, Utilization and Storage programmes conduct independent technology assessments and monitor ongoing worldwide RD&D to provide data and information on the status, cost, performance, engineering, and environmental characteristics of emerging and near-commercial CCTs and CCS options. In addition, applied research is conducted to accelerate the development and demonstration of power generation and carbon capture technologies for pulverised coal, coal gasification and oxyfuel combustion applications. Technologies, environmental considerations, and regulatory issues relating to the utilisation and storage of captured CO_2 are also addressed.

National Energy Technology Laboratory (NETL)

NETL (*see* www.netl.doe.gov) is part of the DOE national laboratory system and is owned and operated by the DOE. As well as implementing and managing the Clean Coal Research Program, the research topics of which are discussed in the Coal and CCS initiatives and programmes section, NETL conducts onsite basic research and collaborative research with universities, industry and other organisations. The NETL Office of Research and Development carries out research on the minimisation and abatement of environmental problems associated with the development and use of fossil fuels, such as air pollution/particulate matter issues, and removal of toxins from coal utilisation system gases. Other research topics relate to computational and basic sciences, and materials science and engineering.

10 Discussion and conclusions

Coal will continue to be an important energy source in the coming decades for the power sector in many countries due to its low cost and abundance. Improving coal's environmental performance is key to its future role in the energy mix, especially as emissions regulations are becoming stricter and standards are now being introduced for previously unregulated pollutants, crucially for CO_2. There is therefore a need for technologies that can be retrofitted to existing power plants in developed countries and emerging economies in order to meet the national and international regulations. There is also an opportunity to employ CCTs in new build power plants, which are mainly being built in emerging economies. Developing these technologies will require significant investment in CCT and CCS RD&D.

An important driver of CCT RD&D is a country's energy policy. All countries face common challenges, including the need for energy security, environmental protection, economic growth and affordable energy. Preferably, energy policy needs to meet climate goals (CO_2 emission targets) without harming economic growth. Environmental issues are emphasised more in countries with a high income level and where environmental problems are perceived to be more urgent. Economic growth is a higher priority in emerging economies. Politics also play a significant role. Although, sustainable development ('green growth') had a key role in South Korea's energy policy, with a change of government it now has a lower, though still important, role in the country's second National Basic Energy Plan. As well as keeping environmental protection as an element in its new Strategic Energy Plan, Japan has introduced a safety element in the wake of the incident at the Fukushima Daiichi nuclear power plant (caused by the East Japan earthquake and tsunami on 11 March 2011). Energy security is of paramount importance for both of these countries due to their reliance on imports because of a lack of domestic fossil fuel reserves.

Coal imports are increasing in China and India, despite their large indigenous coal reserves, partly because of growing energy demand and their reliance on coal for power generation. Coal is expected to continue to play an important role in their power generation sector in the next decade or so. Environmental protection has been growing in importance in China due to environmental pollution from its power plants. Targets have been set for reducing SO_2, NOx and CO_2 levels in the 12th Five-Year Plan for National Economic and Social Development. India and South Africa are more concerned with alleviating poverty and bringing electricity to rural areas, and therefore invest less in CCT and CCS RD&D.

Australia and the USA are large coal exporters, as well as users, with revenue from exports contributing significantly to their economies. Thus clean coal and CCS technologies are important in the two countries, with clear policies in place for the development and deployment of these technologies. The policies could additionally enhance coal export growth by transferring CCTs abroad. However, with the election of a new government in Australia in September 2013, CCS policy may change and this could affect government-funded CCS RD&D. RD&D is seen as an integral part of achieving the EU's GHG emission targets and energy policy goals.

The importance a country attaches to CCT RD&D can be seen in the number of coal initiatives and programmes in place. Countries, such as China, Japan, South Korea, Australia and the USA, have coal R&D policies designed to help meet their energy policy goals. Clean coal power generation with CCS is beginning to get a higher profile in India where the government is in the process of formulating a new Mission on Clean Coal (Carbon) Technologies. Although South Africa's economy is heavily dependent on coal, it has no clear coal policy. Research into CCTs has been neglected as past efforts were dominated by research and investment into the production of synthetic fuels from coal. The recently published coal roadmap (The Green House, 2013) should help to change this. Most of the countries discussed in this report have developed coal and CCS roadmaps, which set out the key RD&D objectives and milestones, and clarify the technological challenges that need to be overcome.

In general, governments are fostering RD&D into advanced USC, IGCC, integrated gasification fuel cell (in particular, Japan), advanced fluidised bed combustion, oxyfuel combustion and pre- and post-combustion CO_2 control. This is reflected in the national RD&D demonstration projects. Substantial RD&D has been carried out on underground coal gasification in South Africa as it is seen as a way to use its 'unmineable' coal. India has no planned demonstrations of coal-fired power plants with CCS, as the technology is considered too expensive. Instead, the government will wait for other countries to develop and demonstrate the technology. The high cost of demonstrating CCTs, inadequate R&D infrastructure in academic institutions and national laboratories, and the lack of academic-industry interactions are all hindering the advancement of CCTs in India (Sahu, 2013). There is currently little formal R&D coordination between the government, academia and industry. This is in contrast to China, Japan and South Korea, amongst others, where there is good coordination between these sectors, and where research is aligned with the country's energy policy goals.

In the current economic climate and the squeeze on governments' budgets, there is a need for collaboration at both a national and international level, including public-private cooperation. International collaboration can enable governments to conduct more RD&D at a lower cost and with less duplication. As noted above, governments are investing in similar CCTs. But many collaborative activities with emerging economies focus on facilitating deployment of CCTs rather than RD&D. Collaborative RD&D can be difficult, because sharing knowledge is risky and national regulations and policies related to RD&D tend to differ. A clear policy, for example, on who owns the intellectual rights to the technology developed, is required. Australia, the EU, Japan, and the USA, amongst others, all regard international collaboration and knowledge transfer as important elements in developing and deploying CCTs and CCS. A number of demonstration projects, such as the Callide oxyfuel project in Australia and the GreenGen IGCC project in China, involve international participation. The EU has experience in funding collaborative research as its framework programmes for R&D must include participants from different European countries, and can include participants from non-member countries.

Government support for CCT and CCS RD&D is necessary to stimulate development of advanced clean coal power generation to meet the eventual goal of near-zero emission power generation. Innovation in the energy sector is challenging because of the long development times and, for CCS, the construction of the infrastructure for CO_2 transport and storage. This is costly and carbon storage still faces unresolved environmental, safety, legal and public acceptance issues. Furthermore, CCS is unlikely to be deployed until policies are in place to motivate the power industry to accelerate demonstration efforts. Several planned CCS demonstrations, such as the Porto Tolle project in Italy and the Bełchatów project in Poland, were cancelled in 2013, partly due to difficulties in obtaining the necessary finance. Nevertheless, the White Rose project in the UK was recently awarded funding through the European Commission's NER300 programme. China has the largest number of CCS demonstration projects in the world. It has focused on CO_2 utilisation, rather than only storage and transport, as a means of reducing CCS costs. Hence nearly all the Chinese coal-based CCS demonstration projects plan to use at least some of the captured CO_2 for enhanced oil recovery and/or in the food or chemical industries.

Detailed evaluations of the specific outcomes of RD&D are difficult to carry out, but positive financial returns are evident – that is, investing in RD&D pays off. A 13:1 return on the US government's investment in the CCT R&D programme over the period 2000–20 was calculated by Bezdek and Wendling (2013). Wiesenthal and others (2010) estimated an internal rate of return of 15% in the EU for RD&D investments in its Strategic Energy Technology Plan (which includes coal-fired power generation with CCS) over the period 2010 to 2030. Furthermore, investment in and commercialisation of clean coal and CCS technologies will contribute to innovation, create jobs and fuel economic growth.

The IEA, in its April 2013 update on progress in clean energy, has added its voice to a growing number highlighting how global funding for energy RD&D is failing to keep pace with the needs for a low carbon future (IEA, 2013e). Indeed, at a time when many people are calling for an increase in RD&D funding, the IEA estimates that the proportion of IEA governments' spending on energy RD&D has fallen from a peak of 11% of the total RD&D budgets in 1981 to 3–4% since 2000 (defence research receives the largest share). IEA member countries include Australia, Japan, South Korea and the USA, but not China, India or South Africa. Renewables, hydrogen and fuel cells have seen the biggest increases in funding since 2000, with renewables now accounting for over 24% of total public spending on clean energy RD&D. However, lowering CO_2 emissions from coal-fired power plants would make a larger contribution to global CO_2 reductions than renewable energy sources. Furthermore, energy RD&D expenditure by industry in OECD countries has been in decline since 1990 (CIAB, 2008). 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. Therefore governments will need to play a greater role in funding RD&D, and in promoting public-private joint RD&D efforts.

The IEA collects coal RD&D expenditure data from its member countries. Only limited data could be found for coal RD&D expenditure in the non-IEA countries China, India and South Africa. This is principally due to the way the money is allocated between and within the various government departments, and the lack of published information. In addition, state-owned enterprises carry out research which can be funded through their government and/or through generated profits. Moreover, few countries collect data on private RD&D expenditure. Collection of this data would help identify whether sufficient funds are being allocated to CCT and CCS RD&D and where the funding gaps are.

In 2011, IEA governments' spent US$398.221 million (in 2012 prices and exchange rates) on coal RD&D and $US1092.583 million on CCS (IEA, 2013d). The CCS data covers CO_2 capture and storage from large industrial sources, as well as fossil fuel power plants. The figures are probably on the low side as data from some member countries (such as Poland) were unavailable. Of the four countries discussed in this report covered in the IEA database, Australia spent the highest amount of its GDP on coal RD&D in 2011 (0.0033% or US$50.907 million), followed by the USA (0.0014% or US$218.977 million), South Korea (0.0005% or US$5.893 million) and Japan (0.0004% or US$21.268 million). The US dollars are given in 2012 prices and exchange rates. However, in terms of investment in CCS RD&D (where coal-fired power generation with CCS is included), Australia spent the largest amount as a percentage of GDP (0.1296% or US$200.05 million), followed by South Korea (0.0027% or US$30.288 million), Japan (0.0026% or US$ 153.014 million) and the USA (0.0019% or US$295.356 million). The rankings may not be the same for previous years. As might be expected, countries with large coal resources (Australia and the USA) have sizeable CCT RD&D portfolios. The share of CCS in fossil fuel RD&D expenditure has increased significantly since 2009, reflecting public concern over climate change.

The IEA estimated that RD&D investment in clean energy technologies needs to increase by 3 to 6 times to limit the average global temperature increase to 2°C by 2050, and probably even higher for CCS technologies (IEA, 2013e). Table 10 shows the estimated funding gap for higher efficiency coal-fired power generation and CCS. It amounts to an annual deficit of between US$700 and US$1800 million for higher efficiency coal. The IEA analysis indicated that public sources need to contribute at least half of overall low carbon RD&D needs (includes energy efficiency, advanced vehicles, renewables and nuclear fission, as well as CCT and CCS). However, since data on private RD&D investment are scarce, analysis to underpin any assumption is difficult. Experience with the development of advanced energy technologies, particularly where environmental and other public benefits are primary motivations for their development (as in the case of CCS), suggests that the required public share is typically greater than 80%.

Table 10 RD&D funding gaps for high efficiency coal generation and CCS (IEA, 2013e)

	Annual global total (private and public) RD&D needs to achieve 2°C scenario, US$ million		**Current global annual public RD&D spending,** US$ million	**Estimated annual RD&D spending gap**, US$ million	
	minimum	maximum		minimum	maximum
Higher efficiency coal (IGCC and USC steam cycle)	1,100	2,100	351	700	1,800
CCS (power generation, industry, fuel transformation)	12,500	25,000	902	11,600	24,100

Governments fund RD&D mainly through domestic research budgets, grants and loans. Revenue generated from carbon taxes, tax credits and incentives could be used to fund RD&D. The EU is already using funds raised from its emissions trading scheme to support large-scale CCS demonstrations. India is financing a National Clean Energy Fund by a levy on the amount of coal produced or imported, whilst

Australian bituminous coal producers are helping to fund low emission coal technology demonstrations by a voluntary levy. More schemes like these could accelerate the development of CCTs and CCS, especially as funding requirements tend to increase as a technology moves towards commercialisation. Project costs will come down as more CCT and CCS projects are deployed.

To conclude, the development of CCTs that improve the environmental performance of coal-fired power plants will enable coal to remain an attractive fuel option well into the future. Sustained RD&D effort is needed over the next decade or so to meet the eventual goal of near-zero emission power plants. This requires adequate resources and careful planning by governments, coupled with appropriate policies and mechanisms, to bring the technologies to the marketplace.

11 References

Abe M (2011) Large-scale demonstration project of CCS in Japan. Presentation at: *Indonesia-Japan CCS workshop*, Jakarta, Indonesia, 22 Feb 2011. Available from: www.rite.or.jp/Japanese/labo/choryu/workshop/indonesia-japanws2011/download.html Kyoto, Japan, Research Institute for Innovative Technologies for the Earth, 38 pp (2011)

Agency for Natural Resources and Energy (2010) *Energy in Japan 2010.* Available from: www.enecho.meti.go.jp/english/toprunnner/ Tokyo, Japan, Agency for Natural Resources and Energy, 51 pp (2010)

Ando H (2012) Review of Japan's energy policy and direction of the coal policy. Presentation at: *Clean coal day in Japan 2012 international symposium*, Tokyo, Japan, 4-5 Sep 2012. Available at: http://brain-c-jcoal.info/ccd2012/day1_keynote_1.pdf 29 pp (2012)

Australian Government (2011) *Securing a clean energy future. The Australian Government's climate change plan*. Canberra, ACT, Australia, Department of Climate Change and Energy Efficiency, 158 pp (2011)

Australian Government (2014a) *Portfolio budget statements 2014–15. Budget related paper no. 1.7. Environment portfolio*. Available from: www.budget.gov.au/2014-15/index.htm Canberra, ACT, Australia, Department of Environment, 302 pp (2014)

Australian Government (2014b) *Portfolio budget statements 2014–15. Budget related paper no. 1.12. Industry portfolio*. Available from: www.budget.gov.au/2014-15/index.htm Canberra, ACT, Australia, Department of Environment, 313 pp (2014)

Bastasch M (2014) *EPA agenda suffers setback as clean coal plant project is derailed*. Available at: http://dailycaller.com/2014/01/13/epa-agenda-suffers-setback-as-clean-coal-plant-project-is-derailed/ vp (13 Jan 2014)

BCIA (2011) *Research to slash costs from brown coal emissions capture*. Available at: www.bcinnovation.com.au/Assets/128/1/BCIA2011RDFundingRound-LoyYangProcessprojects21Dec2011.pdf Melbourne, Vic, Australia, Brown Coal Innovation Australia, 5 pp (21 Dec 2011)

BCIA (2014) *BCIA funds Victoria's first 24/7 capable CO_2 capture facility for brown coal power generation.* Available at: www.bcinnovation.com.au/Assets/726/1/14084_BCIAfundsVictoriasfirst247CO2capturefacilityforbrowncoalpowerMR.pdf Melbourne, Vic, Australia, Brown Coal Innovation Australia, 2 pp (4 Aug 2014)

Best D, Levina E (2012) *Facing China's coal future. Prospects and challenges for carbon capture and storage*. Working paper 2012, Paris, France, IEA, 65 pp (2012)

Bezdek R H, Wendling R M (2013) The return on investment of the clean coal technology program in the USA. *Energy Policy*; **54**; 104-112 (2013)

BP (2013) *BP statistical review of world energy June 2013*. Available at: www.bp.com/content/dam/bp/pdf/statistical-review/statistical_review_of_world_energy_2013.pdf London, UK, BP plc, 47 pp (2013)

British Embassy Seoul (2013) *South Korea: New Basic Plan for Science and Technology – July 2013*. Available at: http://opentoexport.com/article/south-korea-new-basic-plan-for-science-and-technology-july-2013/ London, UK, UK Trade & Investment, 2 pp (22 Jul 2013)

Bureau of Resources and Energy Economics (2013) *Energy in Australia May 2013*. Available at: www.bree.gov.au/publications/energy-australia Canberra, ACT, Australia, Bureau of Resources and Energy Economics, 140 pp (May 2013)

Carbon Sequestration Leadership Forum (2013) *Korea*. Available at: www.cslforum.org/technologyroadmap/korea.html Washington, DC, USA, U.S. Department of Energy, CSLF Secretariat, 1 pp (accessed 8 Oct 2013)

CAS (2012) *Strategic planning*. Available at: http://english.cas.cn/ST/sp2012/201208/P020120813577020730712.pdf Beijing, China, Chinese Academy of Sciences, 4 pp (2012)

Central Statistics Office (2013) *Energy statistics 2013*. Available at: http://mospi.nic.in/mospi_new/upload/Energy_Statistics_2013.pdf?status=1&menu_id=216 New Delhi, India, Central Statistics Office, 102 pp (2013)

Centre for Science, Technology and Innovation Indicators (2014) *South African national survey of research and experimental development. Main analysis report: 2011/12*. Available from: www.dst.gov.za/index.php/resource-center/rad-reports/889-2011-12-rad-survey-main-analysis-report Pretoria, South Africa, Department of Science and Technology, 74 pp (Mar 2014)

Choi G (2011) Energy technology R&D and international collaboration program of KETEP. Presentation at: *Korridor information day*, Barcelona, Spain, 6 Oct 2011. Available at: www.access4.eu/_media/KETEP_Gyun_Choi.pdf 48 pp (2011)

Choi G, Yoo J (2012) Coal policy in Korea. Presentation at: *APEC clean fossil energy technical and policy seminar*, Gold Coast, Qld, Australia, 21-24 Feb 2012. Available at: www.egcfe.ewg.apec.org/publications/proceedings/CFE/Austrailia_2012/index.html Asia Pacific Economic Cooperation (APEC), Expert Group on Clean Fossil Energy (EGCFE), 22 pp (2012)

Chung S-Y (2012) Korea, a bridge between emerging economies and OECD. Presentation at: *Experts' Group on R&D Priority Setting and Evaluation*, Beijing, China, 28-29 Nov 2012. Available at: www.iea.org/media/workshops/2012/egrdbeijing/WEBEGRDChung.pdf Paris, France, IEA, 22 pp (2012)

CIAB (2008) *Clean coal technologies. Accelerating commercial and policy drivers for deployment*. Paris, France, OECD/IEA, 54 pp (2008)

CO2CRC (2013a) *Researching and demonstrating carbon capture and storage*. Available at: www.co2crc.com.au/dls/brochures/CO2CRC_brochure_2013_A4.pdf Canberra, ACT, Australia, Cooperative Research Centre for Greenhouse Gas Technologies, 6 pp (2013)

CO2CRC (2013b) *Australian Government confirms support for CCS research*. Available at: www.co2crc.com.au/dls/media/13/SupportforCCS.pdf Canberra, ACT, Australia, Cooperative Research Centre for Greenhouse Gas Technologies, 1 pp (2 Aug 2013)

Couch G R (2009) *Underground coal gasification*. CCC/151, London, UK, IEA Clean Coal Centre, 129 pp (Jul 2009)

Council for Science and Technology Policy (2010) *Japan's science and technology basic policy report*. Available at: www8.cao.go.jp/cstp/english/basic/4th-BasicPolicy.pdf Tokyo, Japan, Cabinet Office, Council for Science and Technology Policy, 45 pp (24 Dec 2010)

Council for Science and Technology Policy (2013a) *Comprehensive strategy on science, technology and innovation. Chapter 2. Issues to be addressed by science, technology and innovation. Roadmap*. Available at: www8.cao.go.jp/cstp/english/doc/chapter2_roadmap_provisional.pdf Tokyo, Japan, Cabinet Office, Council for Science and Technology Policy, 40 pp (7 Jun 2013)

Council for Science and Technology Policy (2013b) *New Low Carbon Technology Plan*. Available at: www8.cao.go.jp/cstp/english/doc/new_low_carbon_tec_plan/nlctp_text.pdf Tokyo, Japan, Cabinet Office, Council for Science and Technology Policy, 18 pp (13 Sep 2013)

Council for Science and Technology Policy (2013c) *Attachment 3. Roadmap and other items pertaining to each item of technology*. Available at: www8.cao.go.jp/cstp/english/doc/new_low_carbon_tec_plan/attach3-1.pdf Tokyo, Japan, Cabinet Office, Council for Science and Technology Policy, 20 pp (13 Sep 2013)

CRIEPI (2011) *Energy Engineering Research Laboratory*. Available at: http://criepi.denken.or.jp/en/energy/about/img/energy-e-low_201103.pdf Kanagawa, Japan, Central Research Institute of Electric Power Industry, 31 pp (2011)

CSIR Strategic Communication (2013) *To contribute to the improvement of the quality of life of the people. 2012/13 annual report*. Pretoria, South Africa, CSIR Strategic Communication, 164 pp (2013)

CURC, EPRI (2012) *The CURC-EPRI coal technology roadmap. August 2012: update*. Available from: www.coal.org/roadmap/ Washington, DC, USA, Coal Utilization Research Council, 30 pp (Aug 2012)

Delegation of the European Union in China (2011) *Full translation of China's 12th Five-Year Plan*. Available at: www.cbichina.org.cn/cbichina/upload/fckeditor/Full%20Translation%20of%20the%2012th%20Five-Year%20Plan.pdf Beijing, China, Confederation of British Industry, 62 pp (2011)

Department of Energy (2011) Integrated Resource Plan for Electricity 2010–2030. *Government Gazette*; (34263); 3-71 (6 May 2011)

Department of Energy (2013a) Draft 2012 Integrated Energy Planning report. *Government Gazette*; (36690); 27-160 (24 Jul 2013)

Department of Energy (2013b) *Integrated Resource Plan for Electricity (IRP) 2010–2030. Update report 2013*. Available at: www.doe-irp.co.za/content/IRP2010_updatea.pdf Pretoria, South Africa, Department of Energy, 114 pp (21 Nov 2013)

Department of Environmental Affairs (2011) *National climate change response. White paper*. Available at: www.climateaction.org.za/docs/climate-action/white-paper-ver-1.pdf Pretoria, South Africa, Department of Environmental Affairs, 56 pp (2011)

Department of Mineral Resources (2011) *A beneficiation strategy for the minerals industry of South Africa*. Available at: www.gov.za/documents/download.php?f=147564 Pretoria, South Africa, Department of Mineral Resources, 30 pp (Jun 2011)

Department of Resources, Energy and Tourism (2012) *Energy White Paper 2012*. Canberra, ACT, Australia, Department of Resources, Energy and Tourism, 257 pp (2012)

Department of Science and Technology (2002) *South Africa's national research and development strategy*. Available at: www.dst.gov.za/index.php/resource-center/strategies-and-reports/174-national-research-a-development-strategy-2002 Pretoria, South Africa, Department of Science and Technology, 82 pp (Aug 2002)

Department of Science and Technology (2007) *Ten-Year Innovation Plan*. Available at: www.dst.gov.za/index.php/resource-center/strategies-and-reports/143-the-ten-year-plan-for-science-and-technology Pretoria, South Africa, Department of Science and Technology, 42 pp (2007)

Department of Science and Technology (2013a) *Research & development statistics at a glance 2011–12*. Available at: www.nstmis-dst.org/pdf/finalrndstatisticsataglance2011121.pdf New Delhi, India, Department of Science and Technology, 17 pp (Sep 2013)

Department of Science and Technology (2013b) *R&D statistics 2011–12. S&T indicators tables*. Available from: www.nstmis-dst.org/snt-indicators2011-12.aspx New Delhi, India, Department of Science and Technology, vp (Sep 2013)

DI Energy (2011) *'Green Energy Strategic Roadmap 2011' by Ministry of Knowledge and Economy of Republic of Korea*. Available at: http://energi.di.dk/sitecollectiondocuments/foreningssites/energi.di.dk/downloadboks/2011/koreas%20green%20energy%20strategic%20roadmap%202011.pdf Denmark, DI Energy, 15 pp (2011)

DOE (2012) *Department of Energy FY 2013 congressional budget request*. Available from: http://energy.gov/oe/downloads/details-fy-2013-congressional-budget-request-oe DOE/CF-0073, Washington, DC, USA, Department of Energy, vol 3, 556 pp (Feb 2012)

DOE (2013a) *Department of Energy FY 2014 congressional budget request*. Available from: http://energy.gov/oe/downloads/details-fy-2014-congressional-budget-request-oe-0 DOE/CF-0086, Washington, DC, USA, Department of Energy, vol 3, 633 pp (Apr 2013)

DOE (2013b) *Major demonstration programs: program update 2013*. Available from: http://seca.doe.gov/technologies/coalpower/cctc/program_updates.html DOE/FE-0565, Washington, DC, USA, Department of Energy, 99 pp (Sep 2013)

DOE (2014) *Department of Energy FY 2015 congressional budget request*. Available from: http://energy.gov/sites/prod/files/2014/04/f14/Volume%203.pdf DOE/CF-0098, Washington, DC, USA, Department of Energy, vol 3, 752 pp (Mar 2014)

Dubey D K (2013) NTPC plan for improvement of power plant efficiency. Presentation at: *International conference on advanced technologies and best practices for supercritical thermal power plants*, New Delhi, India, 21-22 Nov 2013. Available from: www.pace-d.com/advanced-technologies-and-best-practices-for-supercritical-thermal-power-plants 17 pp (2013)

EC (2007a) *An energy policy for Europe. COM(2007) 1 final*. Available at: http://ec.europa.eu/energy/energy_policy/doc/01_energy_policy_for_europe_en.pdf Brussels, Belgium, European Commission, 28 pp (10 Jan 2007)

EC (2007b) *Sustainable power generation from fossil fuels: aiming for near-zero emissions from coal after 2020. COM(2006) 843 final*. Available at: http://ec.europa.eu/energy/energy_policy/doc/16_communication_fossil_fuels_en.pdf Brussels, Belgium, European Commission, 15 pp (10 Jan 2007)

EC (2008) *Supporting early demonstration of sustainable power generation from fossil fuels. COM(2008) 13 final*. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1397743122123&uri=CELEX:52008DC0013 Brussels, Belgium, European Commission, 11 pp (23 Jan 2008)

EC (2009) *A technology roadmap. SEC(2009) 1295*. Available at: http://setis.ec.europa.eu/system/files/Complete%20report.pdf Brussels, Belgium, European Commission, 57 pp (7 Oct 2009)

EC (2010) *Energy 2020. A strategy for competitive, sustainable and secure energy. COM(2010) 639 final*. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1397743786081&uri=CELEX:52010DC0639 Brussels, Belgium, European Commission, 21 pp (10 Nov 2010)

EC (2011a) *A roadmap for moving to a competitive low carbon economy in 2050. COM(2011) 112 final*. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1397743972640&uri=CELEX:52011DC0112 Brussels, Belgium, European Commission, 16 pp (8 Mar 2011)

EC (2011b) *Energy Roadmap 2050. COM(2011) 885 final*. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52011DC0885 Brussels, Belgium, European Commission, 20 pp (15 Dec 2011)

EC (2011c) *Materials roadmap enabling low carbon energy technologies. SEC(2011) 1609 final*. Available at: http://setis.ec.europa.eu/activities/materials-roadmap/Materials_Roadmap_EN.pdf/view Brussels, Belgium, European Commission, 113 pp (13 Dec 2011)

EC (2013a) *EU energy in figures – statistical pocketbook 2013*. Available at: http://ec.europa.eu/energy/publications/doc/2013_pocketbook.pdf Luxembourg, Publications Office of the European Union, 252 pp (2013)

EC (2013b) *Energy technologies and innovation. COM(2013) 253 final*. Available at: http://ec.europa.eu/energy/technology/strategy/doc/comm_2013_0253_en.pdf Brussels, Belgium, European Commission, 13 pp (2 May 2013)

EC (2013c) *JRC scientific and policy reports R & D investment in the technologies of the European Strategic Energy Technology Plan. SWD(2013) 157 final*. Available at:

http://ec.europa.eu/energy/technology/strategy/doc/swf_2013_0157_en.pdf Brussels, Belgium, European Commission, 57 pp (2 May 2013)

EC (2013d) *Monitoring & assessment report of the research programme for the Research Fund for Coal and Steel*. Available at: http://ec.europa.eu/research/industrial_technologies/pdf/monitoring-assessment-report_en.pdf Luxembourg, Publications Office of the European Union, 104 pp (2013)

EC (2013e) *Summaries of RFCS projects 2003–2013*. Available from: http://cordis.europa.eu/coal-steel-rtd/home_en.html Brussels, Belgium, European Commission, Directorate-General for Research and Innovation, Research Fund for Coal and Steel, 598 pp (22 Aug 2013)

EC (2013f) *Report from the Commission to the European Parliament and the Council on the implementation of the European Energy Programme for Recovery. COM(2013) 791 final*. Available at: http://ec.europa.eu/energy/eepr/eeef/doc/com_2013_791_en.pdf Brussels, Belgium, European Commission, 14 pp (18 Nov 2013)

EC (2014a) *Communication from the Commission to the European Parliament and the Council. European energy security strategy. COM(2014) 330 final*. Available at: http://ec.europa.eu/energy/security_of_supply_en.htm Brussels, Belgium, European Commission, 24 pp (28 May 2014)

EC (2014b) *A policy framework for climate and energy in the period from 2020 to 2030. COM(2014) 15 final*. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1397745039222&uri=COM:2014:15:FIN Brussels, Belgium, European Commission, 18 pp (22 Jan 2014)

EIA (2013a) *AEO2014 early release overview*. Available at: www.eia.gov/forecasts/aeo/er/pdf/0383er(2014).pdf Washington, DC, USA, Energy Information Administration, 18 pp (Dec 2013)

EIA (2013b) *International energy outlook 2013, with projections to 2040*. Available at: www.eia.gov/forecasts/ieo/pdf/0484(2013).pdf DOE/EIA-0484(2013), Washington, DC, USA, Energy Information Administration, 312 pp (Jul 2013)

EIA (2014a) *Monthly energy review January 2014*. Available from: www.eia.gov/totalenergy/data/monthly/ DOE/EIA-0035(2014/01), Washington, DC, USA, Energy Information Administration, 211 pp (2014)

EIA (2014b) *Short-Term Energy Outlook (STEO)*. Available at: www.eia.gov/forecasts/steo/archives/Jan14.pdf Washington, DC, USA, Energy Information Administration, 47 pp (Jan 2014)

Energy Research Knowledge Centre (2013) *Energy research in Europe*. EUR 25927, Luxembourg, Publications Office of the European Union, 212 pp (2013)

Energy Supply and Demand Policy Office (2014) *Strategic Energy Plan*. Available at: www.enecho.meti.go.jp/en/category/others/basic_plan/pdf/4th_strategic_energy_plan.pdf Tokyo, Japan, Agency for Natural Resources and Energy, Energy Supply and Demand Policy Office, 91 pp (Apr 2014)

EPRI (2012) *2012 integrated-gasification combined-cycle (IGCC) research and development roadmap. Technology development for improved performance and economics. Public version*. Available from: www.epri.com Report 1026868, Palo Alto, CA, USA, Electric Power Research Institute, 76 pp (Dec 2012)

EPRI (2014) *2015 research portfolio*. Available at: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002003195 Palo Alto, CA, USA, Electric Power Research Institute, 16 pp (2014)

ESI Africa (2013) *Third generation UCG design for project in South Africa*. Available at: www.esi-africa.com/third-generation-ucg-design-for-project-in-south-africa 1 pp (15 Oct 2013)

Eskom Holdings Ltd (2011) *The Eskom factor 2011*. Johannesburg, South Africa, Eskom Holdings Ltd, 88 pp (2011)

Executive Office of the President (2013) *The President's climate action plan*. Available at: www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf Washington, DC, USA, The White House, 21 pp (Jun 2013)

Expert Group on Low Carbon Strategies for Inclusive Growth (2011) *Low carbon strategies for inclusive growth. An interim report*. Available at: http://planningcommission.nic.in/reports/genrep/Inter_Exp.pdf New Delhi, India, Planning Commission, 124 pp (May 2011)

Expert Group on Low Carbon Strategies for Inclusive Growth (2014) *The final report of the Expert Group on Low Carbon Strategies for Inclusive Growth*. Available at: http://planningcommission.nic.in/reports/genrep/rep_carbon2005.pdf New Delhi, India, Planning Commission, 144 pp (Apr 2014)

FENCO-NET (2013) *FENCO-NET's joint call within CO_2 capture, transport and storage*. Available at: www.fenco-era.net/home-fenco-era/ 1 pp (2013)

Feron P (2012) Post-combustion capture technology development for Australian coal fired power plants. Presentation at: *International advanced coal technologies conference*, Xi'an, China, 4-7 Jun 2012. Available at: www.uwyo.edu/ser/_files/docs/conferences/2013/china/paul%20feron.pdf Laramie, WY, USA, University of Wyoming, 25 pp (2012)

Fisher N (2013) Energy security and low carbon economies. *World Coal*; **22**(8); 14 (Aug 2013)

Fletcher J J, Zhang C (2013) US-China Advanced Coal Technology Consortium, US-China Clean Energy Research Center: research direction and program overview. Paper presented at: *2013 international Pittsburgh coal conference*, Beijing, China, 15-18 Sep 2013. 12 pp (2013)

Froggatt A (2013) A declining role for coal. *Modern Power Systems*; **22**(9); 12-14 (Sep 2013)

Fukuda M (2012a) Advanced USC technology development in Japan. Paper presented at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/my-event London, UK, IEA Clean Coal Centre, 16 pp (2012)

Fukuda Y (2012b) High temperature corrosion and steam oxidation of candidate materials for 700C class A-USC. Presentation at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/my-event London, UK, IEA Clean Coal Centre, 15 pp (2012)

Global CCS Institute (2013) *The global status of CCS: 2013*. Melbourne, Vic, Australia, Global CCS Institute, 204 pp (2013)

Global CCS Institute (2014) *The global status of CCS: February 2014*. Melbourne, Vic, Australia, Global CCS Institute, 24 pp (2014)

Goel M (2010) Chapter 13. Implementing clean coal technology in India. Barriers and prospects. In: *India infrastructure report 2010. Infrastructure development in a low carbon economy*. New Delhi, India, Oxford University Press, pp 208-221 (2010)

Gomez-Briceño D, De Jong M, Drage T, Falzetti M, Hedin N, Snijkers F (2011) *SET-Plan – scientific assessment in support of the materials roadmap enabling low carbon energy technologies – fossil fuel energies sector, including carbon capture and storage*. Available at: http://publications.jrc.ec.europa.eu/repository/handle/111111111/23967 EUR 25104, Luxembourg, Publications Office of the European Union, 48 pp (2011)

Green M (2014) Underground coal gasification: on the road to commercialisation. *Modern Power Systems*; **34**(1); 22-24 (Jan 2014)

Gross C, Van der Riet M (2011) Eskom UCG strategic intent. Presentation at: *1st workshop on underground coal gasification*, Johannesburg, South Africa, 13-15 Jul 2011. Available at: www.iea-coal.org.uk/site/2010/conferences/conference-papers/underground-coal-gasification-workshop 31 pp (2011)

Hall I (2013) Mapping the future of South Africa's coal industry. Presentation at: *GeoForum 2013*, Johannesburg, South Africa, 3-5 Jul 2013. 34 pp (2013)

Hannan S (2013) Update on Australia's CCS policy and engagement with China. Presentation at: *CAGSII workshop*, Melbourne, Vic, Australia, 8 May 2013. Available at: www.cagsinfo.net/pdfs/cags2-workshop1/2-1SeanHennan.pdf Canberra, ACT, Australia, Geoscience Australia, CAGS, 18 pp (2013)

Harada M (2005) The strategy for CCT R&D and its promotion towards zero-emission in Japan. Paper presented at: *Clean fossil energy technical and policy seminar, meeting today's challenges to supply tomorrow's energy*, Cebu, Philippines, 25-28 Jan 2005. Available at: www.egcfe.ewg.apec.org/publications/proceedings/CFE/Cebu_2005/session_6/6.4_Harada.pdf Asia Pacific Economic Cooperation (APEC), Expert Group on Clean Fossil Energy (EGCFE), 12 pp (2005)

Henderson C, Baruya P (2012) *CO_2 reductions from CCTs and CO_2 capture*. CCC/200, London, UK, IEA Clean Coal Centre, 49 pp (Jul 2012)

Henderson C, Mills S J (2009) *Clean coal roadmaps to 2030*. CCC/152, London, UK, IEA Clean Coal Centre, 105 pp (Sep 2009)

Hill T L (2006) *International funding sources for major coal investment projects*. CCC/109, London, UK, IEA Clean Coal Centre, 50 pp (Feb 2006)

Hooper B N (2009) The Latrobe Valley Post Combustion Capture Project. *Energy Procedia*; **1**; 1367-1372 (2009)

Huang S, Cousins A, Cottrell A, Feron P H M (2013) *Tarong post combustion pilot plant*. Available at: www.carboncapturejournal.com/news/tarong-post-combustion-pilot-plant/3375.aspx?Category=all London, UK, Carbon Capture Journal Ltd, vp (29 Sep 2013)

IANS (2013) *Boiler for coal-fired power plants to get R&D funding boost*. Available at: www.business-standard.com/article/news-ians/boiler-for-coal-fired-power-plants-to-get-r-d-funding-boost-113062100318_1.html 2 pp (21Jun 2013)

IEA (2008a) *Energy policies of IEA countries. Japan 2008 review*. Available at: http://www.iea.org/publications/freepublications/publication/Japan2008.pdf Paris, France, OECD/IEA, 220 pp (2008)

IEA (2008b) *Energy policies of IEA countries. The United States 2007 review*. Available at: http://www.iea.org/publications/freepublications/publication/us2007.pdf Paris, France, OECD/IEA, 200 pp (2008)

IEA (2009) *Cleaner coal in China*. Available at: http://www.iea.org/publications/freepublications/publication/coal_china2009.pdf Paris, France, OECD/IEA, 322 pp (2009)

IEA (2012a) *Energy policies of IEA countries: Australia. 2012 review. Summary*. Available at: www.iea.org/Textbase/npsum/australia2012SUM.pdf Paris, France, OECD/IEA, 5 pp (2012)

IEA (2012b) *Energy policies of IEA countries: the Republic of Korea. 2012 review*. Available at: www.iea.org/publications/freepublications/publication/Korea2012_free.pdf Paris, France, OECD/IEA, 140 pp (2012)

IEA (2012c) *CO_2 emissions from fuel combustion. Highlights. 2012 edition*. Available at: www.iea.org/co2highlights/co2highlights.pdf Paris, France, OECD/IEA, 138 pp (2012)

IEA (2012d) *Technology roadmap high-efficiency, low-emissions coal-fired power generation*. Available at: www.iea.org/publications/freepublications/publication/name,32869,en.html Paris, France, OECD/IEA, 48 pp (2012)

IEA (2013a) *World energy outlook 2013*. Paris, France, OECD/IEA, 687 pp (2013)

IEA (2013b) *CO_2 emissions from fuel combustion. Highlights. 2013 edition*. Available at: www.iea.org/publications/freepublications/publication/CO2EmissionsFromFuelCombustionHighlights2013.pdf Paris, France, OECD/IEA, 158 pp (2013)

IEA (2013c) *Coal information 2013*. Paris, France, OECD/IEA, vp (2013)

IEA (2013d) *Database on RD&D budgets*. Available at: www.iea.org/stats/rd.asp Paris, France, IEA (2013)

IEA (2013e) *Tracking clean energy progress 2013*. Paris, France, OECD/IEA, 154 pp (2013)

Interagency Task Force on Carbon Capture and Storage (2010) *Report of the Interagency Task Force on Carbon Capture and Storage*. Available at: www.epa.gov/climatechange/Downloads/ccs/CCS-Task-Force-Report-2010.pdf USA, Environmental Protection Agency, 233 pp (Aug 2010)

International Power (2012) *Carbon capture and storage plant at Hazelwood. Media statement*. Available at: www.gdfsuezau.com/news/210212-carbon-capture-and-storage-plant-at-hazelwood/ Melbourne, Vic, Australia, GDF SUEZ Australian Energy, 2 pp (21 Feb 2012)

InvestKorea (2013) *Korea will invest KRW 11.7 TN in science and technology*. Available from: www.investkorea.org Seoul, South Korea, Invest Korea, 2 pp (8 Aug 2013)

Ishihara N (2013) *Statement by Nobuteru Ishihara, Japanese Minister of the Environment, at COP19/CMP9*. Available at: http://www.env.go.jp/en/earth/cc/statement131120.pdf Tokyo, Japan, Ministry of the Environment, 3 pp (Nov 2013)

Jaeger H (2012) *Greengen - China's first IGCC demo project 'inaugurated'*. Available at: http://gasification-igcc.blogspot.co.uk/ 1 pp (21 Dec 2012)

Japan Coal Energy Center (2007) *Clean coal technologies in Japan. Technology innovation in the coal industry*. Available from: www.jcoal.or.jp/cctinjapan_en/cctinjapan_en.html Tokyo, Japan, Japan Coal Energy Center, 116 pp (Jan 2007)

Japanese Cabinet (2013) *Comprehensive strategy on science, technology and innovation. A challenge for creating Japan in a new dimension*. Available at: www8.cao.go.jp/cstp/english/doc/20130607cao_sti_strategy_provisional.pdf Tokyo, Japan, Cabinet Office, Council for Science and Technology Policy, 79 pp (7 Jun 2013)

Jegarl S (2013) *The status and prospects of CO_2 capture technologies in Korea*. Presentation at: *IEA Clean Coal Centre meeting*, London, UK, Aug 2013. London, UK, IEA Clean Coal Centre, 39 pp (2013)

Jones R S, Yoo B (2011) *Korea's green growth strategy. Mitigating climate change and developing new growth engines*. Available from: www.oecd.org/workingpapers OECD Economics Department Working Papers no. 798, Paris, France, OECD Publishing, 32 pp (2011)

Kastmann P A, Peng G, Lund P C (2013) *Carbon capture, utilisation and storage. R&D activities in China and Japan*. Available at: www.gassnova.no/en/Documents/Gassnova%20CCS%20report_China_Japan_byIN-v01.pdf Porsgrunn, Norway, Gassnova, 47 pp (2013)

Kather A, Rafailidis S, Hermsdorf C (and others) (2008) *Research and development needs for clean coal deployment*. CCC/130, London, UK, IEA Clean Coal Centre, 70 pp (Jan 2008)

KCRC (2012) *Korea CCS 2020 project. Subproject guide*. Available at: www.kcrc.re.kr/eng_introduction_04_02/articles/view/tableid/eng_brochure/id/380 Daejeon, South Korea, Korea Carbon Capture & Sequestration R&D Center, 48 pp (2012)

Kempener R, Anadon L D, Condor J (2010) *Governmental energy innovation investments, policies, and institutions in the major emerging economies: Brazil, Russia, India, Mexico, China, and South Africa*. Available at: http://belfercenter.ksg.harvard.edu/publication/20517/governmental_energy_innovation_investments_policies_and_institutions_in_the_major_emerging_economies.html Energy technology innovation policy discussion paper no. 2010–16, Cambridge, MA, USA, Harvard University, Harvard Kennedy School, Belfer Center for Science and International Affairs, 64 pp (Nov 2010)

Kim J-N (2009) Keynote address: Current status of CCT & CCS R&D in KIER. Presentation at: *APEC clean fossil energy technical and policy seminar*, Incheon, Korea, 12-14 Oct 2009. Available at: www.egcfe.ewg.apec.org/publications/proceedings/CFE/Korea_2009/index.html Asia Pacific Economic Cooperation (APEC), Expert Group on Clean Fossil Energy (EGCFE), 24 pp (2009)

Kim S C (2011) Overview of IGCC R&D project in Korea. Presentation at: *Gasification technologies conference*, San Francisco, CA, USA, 9-12 Oct 2011. Available at: www.gasification.org/uploads/downloads/Conferences/2011/45KIM.pdf Arlington, VA, USA, Gasification Technologies Council, 24 pp (2011)

Kim Y, Seo S, Kim J (2011) The Korean activities of oxy-fuel combustion. Presentation at: *2nd oxyfuel combustion conference*, Yeppoon, Qld, Australia, 12-16 Sep 2011. 34 pp (2011)

Kolver L (2013) *Underground coal gasification holds significant opportunity for SA – Lennon*. Available at: www.miningweekly.com/article/underground-coal-gasification-holds-significant-opportunity-for-sa-lennon-2013-10-10 1 pp (10 Oct 2013)

Korea Energy Economics Institute (2012) *2012 yearbook of energy statistics*. Available at: www.keei.re.kr/keei/download/YES2012.pdf Gyeonggi-do, Korea, Korea Energy Economics Institute, 380 pp (Dec 2012)

Lee E (2013) *China sets new energy goals*. Available at: www.chadbourne.com/files/Publication/7c3523d7-2dbc-4d30-a536-74c647ff9550/Presentation/PublicationAttachment/83fd9f67-b8e2-45cf-a349-7b373ace79a9/ChinaSetsNewGoals_Apr13.pdf Beijing, China, Chadbourne & Parke LLP, 5 pp (Apr 2013)

Luo Z, Zhang J, Burnard K (2009) Near Zero Emissions Coal: A China-UK initiative to develop CCS in China. *Energy Procedia*; **1**; 3909-3916 (2009)

Mathews J P, Miller B G, Song C, Schobert H H, Botha F, Finkleman R B (2013) The EBB and flow of US coal research 1970–2010 with a focus on academic institutions. *Fuel*; **105**; 1-12 (2013)

METI (2008) *Cool Earth-Innovative Energy Technology Program (Summary)*. Available at: www.meti.go.jp/english/newtopics/data/pdf/CoolEarth_E_revised.pdf Tokyo, Japan, Ministry of Economy, Trade and Industry, 23 pp (5 Mar 2008)

METI (2013a) *FY2013 budget request*. Available at: www.meti.go.jp/english/aboutmeti/policy/fy2013/pdf/130129budget.pdf Tokyo, Japan, Ministry of Economy, Trade and Industry, 44 pp (29 Jan 2013)

METI (2013b) *FY2014. Points of economic and industrial policies*. Available at: www.meti.go.jp/english/aboutmeti/policy/fy2014/pdf/0906_001a.pdf Tokyo, Japan, Ministry of Economy, Trade and Industry, 45 pp (Aug 2013)

Mills S J (2007) *Prospects for coal and clean coal technologies in India*. CCC/129, London, UK, IEA Clean Coal Centre, 73 pp (Dec 2007)

Mills S J (2010) *Prospects for coal, CCTs and CCS in the European Union*. CCC/173, London, UK, IEA Clean Coal Centre, 77 pp (Aug 2010)

Minchener A (2010) *Developments in China's coal-fired power sector*. CCC/163, London, UK, IEA Clean Coal Centre, 55 pp (Jan 2010)

Minchener A (2011) *CCS challenges and opportunities for China*. CCC/190, London, UK, IEA Clean Coal Centre, 95 pp (Dec 2011)

Minchener A (2012a) *Carbon mitigation technologies for emerging economies*. CCC/198, London, UK, IEA Clean Coal Centre, 65 pp (May 2012)

Minchener A (2012b) *Non-greenhouse gas emissions from coal-fired power plants in China*. CCC/196, London, UK, IEA Clean Coal Centre, 53 pp (Apr 2012)

Ministry of Environment (2014) *National Greenhouse Gas Emissions Reduction Roadmap 2020*. Available at: http://eng.me.go.kr/eng/web/board/read.do?menuId=21&boardMasterId=522&boardId=339283 Sejong, Republic of Korea, Ministry of Environment, 3 pp (28 Jan 2014)

Ministry of the Environment (2014) *Japan's climate change policies*. Available at: www.env.go.jp/en/focus/docs/files/20140318-83.pdf Tokyo, Japan, Ministry of the Environment, 74 pp (18 Mar 2014)

Ministry of Finance (2011) *Office memorandum. Subject: Guidelines for appraisal and approval of projects/schemes eligible for financing under the National Clean Energy Fund*. Available at: http://finmin.nic.in/the_ministry/dept_expenditure/plan_finance2/Guidelines_proj_NCEF.pdf New Delhi, India, Ministry of Finance, 3 pp (18 Apr 2011)

Ministry of Power (2012) *Report of The Working Group on Power for Twelfth Plan (2012–17)*. Available at: http://planningcommission.gov.in/aboutus/committee/wrkgrp12/wg_power1904.pdf New Delhi, India, Planning Commission, 466 pp (Jan 2012)

Ministry of Power (2013) *Outcome budget of Ministry of Power 2013-14*. Available at: www.powermin.nic.in/funds_for_power_sector/pdf/OUTCOME_BUDGET_2013-14.pdf New Delhi, India, Ministry of Power, 227 pp (2013)

MOST (2013) Chapter 3. National Key Basic Research and Development Programme. In: *National Science and Technology Programme 2012 annual report*. Available at: www.most.gov.cn/mostinfo/xinxifenlei/gjkjjh/201303/t20130325_100414.htm Beijing, China, Ministry of Science and Technology, pp 26-44 (5 Mar 2013) (In Chinese)

Nagasaki N, Sasaki K, Suzuki T, Dodo S, Nagaremori F (2013) Near-zero-emission IGCC power plant technology. *Hitachi Review*; **62**(1); 39-47 (2013)

National Low Emissions Coal Council (2009) *National Low Emissions Coal Strategy: accelerating carbon capture and storage in Australia*. Canberra, ACT, Australia, Department of Resources, Energy and Tourism, 92 pp (Sep 2009)

National Low Emissions Coal Council (2010) *National Low Emissions Coal Strategy: accelerating carbon capture and storage in Australia - update*. Canberra, ACT, Australia, Department of Resources, Energy and Tourism, 14 pp (Nov 2010)

National Planning Commission (2012) *National Development Plan 2030. Our future – make it work*. Available from: www.npconline.co.za Pretoria, South Africa, National Planning Commission, 489 pp (2012)

National Treasury (2014a) *Budget 2014. Estimates of national expenditure. Vote 29. Energy*. Available at: www.treasury.gov.za/documents/national%20budget/2014/enebooklets/Vote%2029%20Energy.pdf Pretoria, South Africa, National Treasury, 58 pp (26 Feb 2014)

National Treasury (2014b) *Budget 2014. Estimates of national expenditure. Vote 34. Science and technology*. Available at: www.treasury.gov.za/documents/national%20budget/2014/enebooklets/Vote%2034%20Science%20and%20Technology.pdf Pretoria, South Africa, National Treasury, 62 pp (26 Feb 2014)

NDRC (2013) *Notice of National Development and Reform Commission on promoting carbon capture, utilisation and storage pilot and demonstration*. NDRC Climate [2013] Document No. 849, Beijing, China, National Development and Reform Commission, vp (Apr 2013) (In Chinese, English translation available at: www.globalccsinstitute.com/publications/notice-national-development-and-reform-commission-ndrc-promoting-carbon-capture)

NETL (2010) *DOE/NETL carbon dioxide capture and storage RD&D roadmap*. Available at: www.netl.doe.gov/File%20Library/Research/Carbon%20Seq/Reference%20Shelf/CCSRoadmap.pdf Pittsburgh, PA, USA, National Energy Technology Laboratory, 78 pp (Dec 2010)

NETL (2012) *2012 technology readiness assessment - Clean Coal Research Program. Pathway for readying the next generation of affordable clean energy technology - Carbon Capture, Utilization, and Storage (CCUS)*. Available at: www.netl.doe.gov/File%20Library/Research/Coal/Reference%20Shelf/TRL-Comprehensive-Report_121112_FINAL_1.pdf Pittsburgh, PA, USA, National Energy Technology Laboratory, 130 pp (Dec 2012)

NETL (2013a) *Hydrogen Energy California Project*. Available at: www.alrc.doe.gov/publications/factsheets/project/FE0000663.pdf Morgantown, WV, USA, National Energy Technology Laboratory, 2 pp (May 2013)

NETL (2013b) *Demonstration of a coal-based transport gasifier*. Available at: www.alrc.doe.gov/publications/factsheets/project/NT42391.pdf Pittsburgh, PA, USA, National Energy Technology Laboratory, 2 pp (Mar 2013)

NETL (2013c) *Summit Texas Clean Energy, LLC: Texas Clean Energy Project: Pre-combustion CO_2 capture and sequestration*. Available at: www.alrc.doe.gov/publications/factsheets/project/FE0002650.pdf Morgantown, WV, USA, National Energy Technology Laboratory, 2 pp (Sep 2013)

NETL (2013d) *NRG Energy: W.A. Parish Post-Combustion CO_2 Capture and Sequestration Project*. Available at: www.alrc.doe.gov/publications/factsheets/project/FE0003311.pdf Morgantown, WV, USA, National Energy Technology Laboratory, 2 pp (Sep 2013)

NETL (2013e) *W.A. Parish Post-Combustion CO_2 Capture and Sequestration Project final environmental impact statement. Volume I*. Available at: http://energy.gov/sites/prod/files/EIS-0473-FEIS-Vol_I-2013_1.pdf DOE/EIS-0473, Morgantown, WV, USA, National Energy Technology Laboratory, 532 pp (Feb 2013)

Nicol K (2013) *Status of advanced ultra-supercritical coal-fired power plant*. CCC/229, London, UK, IEA Clean Coal Centre, 57 pp (2013)

NSFC (2013) *Programs of Joint Funds*. Available at: www.nsfc.gov.cn/Portals/0/fj/english/fj/pdf/2013/131.pdf Beijing, China, National Natural Science Foundation of China, 39 pp (2013)

Official Journal of the European Union (2010) Supporting early demonstration of sustainable power generation from fossil fuels. *Official Journal of the European Union*; C 16 E; 28-32 (22 Jan 2010)

Panda G R, Jena N (2012) Evaluating the performance of the National Clean Energy Fund. *Economic & Political Weekly*; **47**(37); 18-21 (15 Sep 2012)

Park Y C, Jo S-H, Ryu H-J, Yi C-K, Yun Y, Baek J-I (2013) Current status of the development for the pilot-scale syngas clean-up system using solid sorbents integrated with a coal gasifier. Poster presented at: *International conference on clean coal technologies: CCT2013*, Thessaloniki, Greece, 12-16 May 2013. London, UK, IEA Clean Coal Centre, 10 pp (2013)

Pinkston T (2013) Kemper County IGCC project update. Presentation at: *2013 Gasification technologies conference*, Colorado Springs, CO, USA, 13-16 Oct 2013. Available at: www.gasification.org/uploads/downloads/Conferences/2013/3-4-Pinkston-Southern.pdf Arlington, VA, USA, Gasification Technologies Council, 13 pp (2013)

Planning Commission (2006) *Integrated energy policy. Report of the Expert Committee*. Available at: http://planningcommission.nic.in/reports/genrep/rep_intengy.pdf New Delhi, India, Planning Commission, 182 pp (Aug 2006)

Planning Commission (2008) *Eleventh Five Year Plan (2007–2012). Volume 3: Agriculture, rural development, industry, services and physical infrastructure*. Available at: http://planningcommission.nic.in/plans/planrel/fiveyr/11th/11_v3/11th_vol3.pdf New Delhi, India, Oxford University Press, 537 pp (2008)

Planning Commission (2013a) *Twelfth Five Year Plan (2012–2017). Faster, more inclusive and sustainable growth. Volume 1*. Available at: http://planningcommission.nic.in/plans/planrel/fiveyr/welcome.html New Delhi, India, SAGE Publications India Pvt Ltd, 370 pp (2013)

Planning Commission (2013b) *Twelfth Five Year Plan (2012–2017). Economic sectors. Volume 2*. Available at: http://planningcommission.nic.in/plans/planrel/fiveyr/welcome.html New Delhi, India, SAGE Publications India Pvt Ltd, 438 pp (2013)

Prasad D N (2014) Status of development of low rank coals in India. Presentation at: *3rd international low rank coal industry symposium*, Melbourne, Vic, Australia, 28-30 Apr 2014. 43 pp (2014)

Prime Minister's Council on Climate Change (2008) *National action plan for climate change*. Available at: http://pmindia.gov.in/climate_change_english.pdf New Delhi, India, Government of India, 54 pp (2008)

Ramesh M (2013a) *A symbol of collective apathy*. Available at: www.thehindubusinessline.com/opinion/a-symbol-of-collective-apathy/article4591441.ece 2 pp (7 Apr 2013)

Ramesh M (2013b) *BHEL-NTPC joint venture for power project in the offing*. Available at: www.thehindubusinessline.com/companies/bhelntpc-joint-venture-for-power-project-in-the-offing/article4598924.ece 1 pp (9 Apr 2013)

Reitenbach G (2013) R&D projects target cheaper carbon capture, use, and storage. *Power (NY)*; **157**(8); 60, 62, 64 (Aug 2013)

RITE (2013) Annual report. *RITE Today*; **8**; 1-59 (2013)

Ryan B (2014) *Coal reserves study gives lie to Eskom supply scare*. Available at: www.bdlive.co.za/business/mining/2014/04/17/coal-reserves-study-gives-lie-to-eskom-supply-scare Rosebank, South Africa, BDFM Publishers (Pty) Ltd, vp (17 Apr 2014)

Ryu C K (2011) KEPCO's CCS activities and demonstration plan. Presentation at: *2nd Australia-Korea green growth workshop*, Melbourne, Vic, Australia, 17-18 Mar 2011. Available at: www.atse.org.au/Documents/International%20Colloboration/Workshops/AKGG%20March%202011/Ryu.pdf Melbourne, Vic, Australia, Australian Academy of Technological Sciences and Engineering, 26 pp (2011)

SACCCS (2014) *Roadmap*. Available at: http://www.sacccs.org.za/roadmap/ South Africa, South African Centre for Carbon Capture and Storage, 1 pp (accessed Aug 2014)

Sachdev R K (2007) Clean coal technologies – Indian scenario. Presentation at: *Third international conference on clean coal technologies for our future*, Cagliari, Italy, 15-17 May 2007. Available from: www.iea-coal.org.uk/site/2010/publications-section/cct2007? London, UK, IEA Clean Coal Centre, 15 pp (2007)

Sagara N (2013) Overview of high-efficiency clean coal technology in Japan. Presentation at: *Hungary-Japan energy seminar*, Budapest, Hungary, 14 Oct 2013. 33 pp (2013)

Sahu H B (2013) Implementing clean coal technology through gasification and liquefaction – the Indian perspective. *International Journal of ChemTech Research*; **5**(2); 824-830 (Apr-Jun 2013)

SANEDI (2011) *Strategic Plan 2012/13 – 2016/17. Final*. Available at: www.sanedi.org.za/archived/wp-content/uploads/2013/04/2012-17_sanedi_strategic_plan_v9.pdf Sandton, South Africa, South African National Energy Development Institute, 98 pp (Aug 2011)

SANEDI (2013) *SANEDI annual report 2012/13*. Available at: www.sanedi.org.za/wp-content/uploads/2013/10/sanedi_annual_report_2013.pdf Sandton, South Africa, South African National Energy Development Institute, 112 pp (2013)

Schuppers J (2013) *EC support to CCS RTD*. Presentation at: *9th coal dialogue*, Brussels, Belgium, 9 Jun 2013. Available at: http://www.euracoal.org/pages/medien.php?idpage=1307 Brussels, Belgium, European Association for Coal and Lignite - EURACOAL, 17 pp (2013)

Smouse S M, Fapohunda B O, Krishnan R P (and others) (2010) *Clean energy research and deployment initiative. Assessment report on cleaner coal technology*. Available at: www.pace-d.com/wp-content/uploads/2012/08/Annexure%202%20-%20Cleaner%20Coal%20Assessment%20Report.pdf United States Agency for International Development (USAID), 36 pp (25 Feb 2010)

State Council (2012) *China's energy policy 2012*. Available at: www.gov.cn/english/official/2012-10/24/content_2250497.htm Beijing, China, State Council, Information Office, vp (Oct 2012)

State Statistics Bureau, MOST, Ministry of Finance (2013) *Statistical report on national science and technology funding*. Available at: www.mof.gov.cn/zhengwuxinxi/caizhengshuju/201309/t20130926_993359.html Beijing, China, Ministry of Finance, 7 pp (26 Sep 2013) (In Chinese)

Sun R, Cui Z, Tao Y (2012) Development of 700°C USC coal-fired power generation technology in China. Paper presented at: *Advanced ultrasupercritical coal-fired power plants workshop*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home London, UK, IEA Clean Coal Centre, 10 pp (2012)

Swedish Agency for Growth Policy Analysis (2013) *Policies for a sustainable energy system – South Korea. Background report to PM 2014:05*. Available at: www.tillvaxtanalys.se/download/18.752e3f4c144bb4af26811e/1394806211360/Energisystem+bortom+2020+Sydkorea.pdf Östersund, Sweden, Myndigheten för tillväxtpolitiska utvärderingar och analyser, 24 pp (2013)

Tan X (2010) Clean technology R&D and innovation in emerging countries – experience from China. *Energy Policy*; **38**(6); 2916-2926 (Jun 2010)

The Green House (2011) *Overview of the South African coal value chain. Prepared as a basis for the development of the South African Coal Roadmap*. Available from: www.fossilfuel.co.za/initiatives1 or www.sanedi.org.za/coal-roadmap 231 pp (Oct 2011)

The Green House (2013) *The South African Coal Roadmap*. Available from: www.fossilfuel.co.za/initiatives1 or www.sanedi.org.za/coal-roadmap 52 pp (Jul 2013)

Tzimas E, Moss R L, Ntagia P (2011) *2011 technology map of the European Strategic Energy Technology Plan (SET-Plan)*. Available at: http://setis.ec.europa.eu/system/files/Technology_Map_2011.pdf EUR 24979, Luxembourg, Publications Office of the European Union, 178 pp (2011)

Van Puyvelde D (2013) *Capture demonstration at Korea's Boryeong thermal power station*. Available at: www.globalccsinstitute.com/insights/authors/dennisvanpuyvelde/2013/07/23/capture-demonstration-koreas-boryeong-thermal-power Docklands, Vic, Australia, Global CCS Institute, 3 pp (23 Jul 2013)

Wiesenthal T, Mercier A, Schade B, Petriè H, Szabó L (2010) *Quantitative assessment of the impact of the Strategic Energy Technology Plan on the European power sector*. EUR 24566, Luxembourg, Publications Office of the European Union, 48 pp (2010)

Williams D (2013) *South Korea plans gas and coal development to meet demand*. Available at: www.powerengineeringint.com/articles/2013/01/South-Korea-plans-gas-and-coal-development-to-meet-demand.html Tulsa, OK, USA, PennWell Publishing, 1 pp (23 Jan 2013)

Xu S (2013) GreenGen and CCS demonstration projects. Presentation at: *2013 US-China clean energy workshop*, Birmingham, AL, USA, 16-18 Apr 2013. Available at: http://uschinacleanenergy.wvu.edu/wp-content/uploads/2013/03/Session-2-1300-GreenGen-Update-Xu-Shisen.pdf 31 pp (2013)

Yoshimura U, Matsuda T (2014) The global need for clean coal technologies and J-COAL's roadmap to get there. *Cornerstone*; **2**(2); 72-77 (Sum 2014)

ZEP (2013) *Recommendations for research to support CCS deployment in Europe beyond 2020. Update on CO_2 capture*. Available at: www.zeroemissionsplatform.eu/library.html European Technology Platform for Zero Emission Fossil Fuel Power Plants, 36 pp (Sep 2013)

Zhang X, Fan J-L, Wei Y-M (2013) Technology roadmap study on carbon capture, utilization and storage in China. *Energy Policy*; **59**; 536-550 (2013)

Zhang J (2014) Beijing, China, Administrative Centre for China's Agenda 21, *personal communication* (May 2014)