Prospects for coal, CCTs and CCS in the European Union

Stephen J Mills

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Abstract

Since the EU enlargements of 2004 and 2007, the economic importance of coal for many Member States has continued. In a significant number, coal maintains an important role for power generation and in major industrial sectors such as iron and steel and cement production. The use of hard coal and lignite remains crucial in the commercial and industrial life of the EU. In 2008, between them, EU Member States produced around 146 Mt of hard coal (43% of total EU hard coal consumption) and 434 Mt of lignite (99% of total EU lignite consumption). A further 211 Mt of hard coal was imported. Thus, total EU coal consumption amounted to 783 Mt. At the moment, around 30% of electricity generation in the EU-27 is coal-based although in some countries, coal accounts for more than 50% of total power generation; for instance, 59% in the Czech Republic and 53% in Greece. In Poland, it is over 90%. Some countries produce most of the coal and/or lignite consumed, whereas others rely almost exclusively on imports. Many others fall some way between these extremes. This report includes a general review and update of the situation in the EU, and considers CCT- and CCS-related initiatives and activities. The scope and status of major EU clean coal and carbon capture and storage programmes are examined. These include such initiatives as the creation in 2006 of the Zero Emission Platform (ZEP), plus related major national (both government and private sector) RD&D CCT and CCS programmes under way or planned. The different technological options being pursued such as supercritical PCC, IGCC + CCS, oxyfuel combustion, and post-combustion CO_2 capture, are addressed and the status of each reviewed. The second part of the report comprises more detailed examination of CCT and CCS activities in EU Member States that have an annual coal consumption of around 10 Mt or more. For each country, coal use and clean coal- and CCS-related activities are examined.

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Acronyms and abbreviations

ASU	air separation unit
BGL	British Gas/Lurgi
BOFA	boosted overfire air
CBM	coalbed methane
CCC	(IEA) Clean Coal Centre
CCT	Clean Coal Technology
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CFBC	Circulating Fluidised Bed Combustion
CSLF	Carbon Sequestration Leadership Forum
CEE	Central and Eastern Europe
CHP	combined heat and power
CFBC	Circulating Fluidised Bed Combustion
COE	cost of electricity
CV	calorific value
EBRD	European bank for reconstruction and development
EC	European Commission
ECSC	European Coal and Steel Community
EERA	European Energy Research Alliance
EERP	European Economic Recovery Plan
EGR	enhanced gas recovery
EOR	enhanced oil recovery
EPC	Engineering, Procurement and Construction
ESP	electrostatic precipitator
EU	European Union
FBC	Fluidised Bed Combustion
FEED	front end engineering and design
FT	Fischer Tropsch
FGD	Flue Gas Desulphurisation
GE	General Electric
HP	high pressure
HRSG	heat recovery steam generator
IEA	International Energy Agency
IEA GHG R&D	The IEA Greenhouse Gas R&D Programme
IGCC	Integrated Gasification Combined Cycle
IP	intermediate pressure
IPPCD	integrated pollution prevention and control directive
LCPD	large combustion plant directive
LHV	lower heating value
LP	low pressure
MBM	meat and bone meal
MEA	monoethanolamine
MHI	Mitsubishi Heavy Industries
MoU	Memorandum of Understanding
MSW	municipal solid waste
OFA	overfire air
PCC	pulverised coal combustion
PCI	pulverised coal injection
PFBC	Pressurised Fluidised Bed Combustion
RD&D	Research, Development and Demonstration
RFCS	Research Fund for Coal and Steel
RO	(UK) renewables obligation
SC	supercritical
SCR	selective catalytic reduction
SNCR	selective non catalytic reduction
US DOE	United States Department of Energy
UNFCC	United Nations Framework Convention on Climate Change
USC	ultra-supercritical
ZEP	Zero Emissions Platform

Contents

1 Introduction

About 80% of Europe's fossil fuel reserves comprise hard coal and lignite and most EU Member States have access to reserves of one or both. Several countries, having joined the EU since 2004, have brought with them significant coal and lignite resources, adding considerably to the EU's total. In particular, in 2004, Bulgaria, the Czech Republic, Hungary and Poland were still Accession Countries; they are now full members. Each has a coal industry based on domestic coal reserves, and in each case, coal forms a major component of the respective energy mix. Despite reductions in production and consumption in recent years, for each, coal will remain important for the foreseeable future. As with many older EU Member States, it will continue to be particularly important for power generation. However, in the case of Belgium, coal use has fallen from the 2004 level of ~12 Mt to 8 Mt, hence the country is not considered in detail in the present report.

Several revisions of estimates for proved reserves and resources of major coal-producing Member States have been made in recent years. A recent estimate is presented in Table 1.

Despite a general decline in coal production and consumption in recent years, coal continues to play a significant role in the energy mix of many EU countries and the EU in general. Coal remains a major contributor to EU energy supply, with a share of around 22% of the EU-27 total energy consumption (Figure 1). A third of the EU's power generation is coal based. Data for coal production and consumption in the twelve largest coal-consuming Member States is presented in Table 2. Since 2004, coal production in most coal-producing states has reduced, although in some cases, this reduced production has been replaced with increased imports of coal.

Since the most recent European Union enlargements of 2004 and 2007, the economic importance of coal for the Union as a whole has been maintained. In a significant number of Member States, coal has retained an important role for power generation and in major industrial sectors such as iron and steel manufacture and cement production. Within the EU-27, hard coal and lignite have a 22% share of Primary Energy Consumption and is used to generate roughly a third of all electricity. The use of hard coal and lignite remains crucial to the commercial and industrial life of the EU, currently the world's third biggest coal consumer. In 2008, between them, EU Member States produced around 146 Mt of hard coal (43% of total EU hard coal consumption) and 434 Mt of

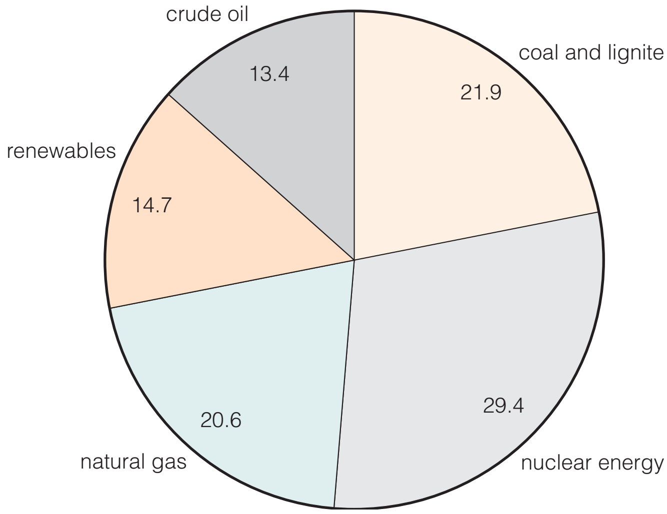


Figure 1 Primary energy production for the EU-27, 2008, %

Table 1 Proved coal reserves and resources for major coal-producing EU Member States, (Mt, 2009) (Pudil, 2009)

Country	Hard coal		Lignite	
	Reserves	Resources	Reserves	Resources
Bulgaria	–	–	1928	4194
Czech Republic	3112	21,108	185	772
Germany	118	82,947	40,818	36,760
Greece	–	–	2876	3554
Hungary	276	5075	2633	2704
Poland	12,459	167,000	3870	41,000
Romania	14	2373	408	7947
Spain	868	3363	–	–
UK	432	186,700	–	–
Other EU	770	7468	757	2368
Total EU	18,049	476,032	53,475	99,299

Table 2 Coal production and consumption in the twelve largest coal-consuming EU Member States (OECD/IEA, 2008; Euracoal, 2009)

Country	Hard coal production, Mt		Lignite production, Mt		Total coal production, Mt	Hard coal imports, Mt	Total coal consumption, Mtce
	2004	2008	2004	2008	2008	2007	2008
Bulgaria	–	–	26.4	28.7	26.0	4.9 (2008)	11.1
Czech Republic	7.3	7.5	56.8	52.7	60.2	2.5	29.3
France	–	–	–	–	–	18.2	18.1
Germany	29.2	19.1	181.9	175.3	194.4	45.9	114.0
Greece	–	–	70.0	65.7	65.7	0.8	15.0
Hungary	–	–	11.2	9.4	9.4	2.0	38.2 (2007)
Italy	–	–	–	–	–	24.6	24.1
Netherlands	–	–	–	–	–	13.0	11.4
Poland	101.2	84.3	61.2	59.5	143.8	5.8	84.8
Romania	–	3.0	–	36.0	39.0	4.0	12.8
Spain	8.9	7.3	11.6	2.9	10.2	24.9	20.2
UK	25.1	16.5	–	–	16.5	42.8	49.7
Total EU-27		146		434	580	211	438.5

lignite (99% of total EU lignite consumption). A further 211 Mt of hard coal was imported. Thus, total EU coal consumption amounted to 783 Mt (Wilde, 2009a). Around two thirds of this combined total was used by the power generation sector. Currently, around 30% of electricity generation in the EU-27 is coal-based although in some countries coal accounts for more than 50% of total power generation; for instance, 59% in the Czech Republic and 53% in Greece. In Poland, it is more than 90%. Some countries produce most of the coal and/or lignite consumed, whereas others rely almost exclusively on imports. Many others fall some way between these extremes.

1.1 European Union CCT and CCS activities

In 2007, the *Communication on Sustainable Power Generation from Fossil Fuels* was adopted as part of the EU's energy package (Europa, nd). This examined how best to improve energy security and reduce greenhouse gas emissions such that a 2ºC temperature rise (from pre-industrial levels) is not exceeded. It also outlined the EU's general strategy on CCS and the CCS-related work programme for the next few years. Major tasks identified were the development of an enabling legal framework and economic incentives for CCS within the EU, and encouragement of a network of demonstration plants across Europe and in key third countries.

The future of coal in Europe depends on the growing use of high-efficiency power plants coupled with the widespread deployment of CCS (Wilde, 2009b). In order to reduce global greenhouse gas emission levels by at least half of 1990 levels by 2050, developed countries need to cut their collective emissions to 25–40% below 1990 levels by 2020, and by 80–95% by 2050. In 2007, a commitment was made that the EU will cut its emissions to 30% below 1990 levels by 2020; at the same time, EU leaders committed to transforming Europe into a highly energy-efficient, low-carbon economy. These emissions reduction targets are underpinned by several energy-related objectives that include a 20% reduction in energy consumption through greater energy efficiency, and an increased market share for renewables (up to 20% from current level of 9%). A major package of legislative measures aimed at implementing these climate and renewable energy targets was agreed in December 2008 and became law during 2009. They complement ongoing work to improve energy efficiency.

Within the present context, Clean Coal Technologies are regarded as referring primarily to two main areas:

- reduction of the traditional pollutants emitted by coal combustion, such as SOx, NOx and particulates. In most cases, suitable clean-up technology has been developed and applied (or is being applied) to coal-fired power plants in most Member States;
- improvement of coal-to-electricity conversion efficiency. Today's best available technology allows efficiency up to 46% (LHV) for hard coal plants and 43% for lignite-fired plants. Through further R&D and better integration of components, the FP7 Clean Coal activity aims to increase this to >50%. This area encompasses USC PCC, IGCC, FBC and oxy-fuel technologies.

Alongside efficiency improvements, CCS is seen as one of the key technologies for cutting CO_2 emissions from coal-fired power plants. The EU is co-operating closely with industries and Member States to support its development and application. The aim is to make coal-fired power generation effectively zero emission by 2020. Both CCT and CCS activities feature highly in the FP7 programme (*see below*).

There are strong incentives for Europe to pursue the creation of a low-carbon economy and to achieve its environmental and energy goals. However, it will be impossible to reduce EU or world CO_2 emissions by 50% by 2050 (2ºC rise limit) by these measures alone. Greater use of technologies that enable the sustainable use of fossil fuels (such as coal + CCS) are also needed. Without this, it appears unlikely that current climate goals will be achievable. By 2030, CCS could contribute ~14% of all reductions needed. Various studies suggest that parts of Europe have significant CO_2 storage potential (technical potential likely to exceed 2000 Gt). Current total EU CO_2 emissions are ~24 Gt/y (Brockett, 2007).

In 2007, the European Council endorsed the Commission's intention to stimulate the construction and operation of a set of CCS demonstration projects by 2015, viewed as crucial for widespread commercial application of the technology. To support these, in Autumn 2009, the *European Carbon Dioxide Capture and Storage (CCS) Demonstration Project Network* was launched. Its main aim is to enhance co-ordination between the organisations involved with the development of the first demonstration projects. The network will provide these initial entrants in the field with a means of co-ordination, exchange of 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 (Wilde, 2009b). There will also be a focus on identifying best practices, thereby ensuring that the best technologies available in Europe are utilised to their full potential. In December 2009, the knowledge-sharing network, co-ordinated by the Norwegian DNV Group (Det Norske Veritas) held its first event. This meeting gathered over 60 delegates representing 20 projects in 13 European countries, engaged in the challenge of implementing large-scale CCS demonstration projects. Issues such as the membership basis (Qualification Criteria and Knowledge Sharing Protocol), international co-operation, and the Network agenda for 2010 onwards, were discussed (CCSN Network, 2010). The Network plans to work closely with other national and international initiatives.

For 2007-13, the EU has substantially increased its R&D budget for environment, energy and transport; this is helping to support the development and deployment of CCT and CCS technologies (European Commission, 2009). An important element of EU policy is *The European Strategic Energy Technology Plan* (SET-Plan) aimed at optimising and co-ordinating the EU's efforts to develop these technologies. The Plan aims to accelerate the development and deployment of cost-effective low carbon technologies and encompasses measures relating to planning, implementation, resources and international co-operation in the field of energy technology. It highlights the necessity of decarbonising EU electricity supply by 2050 and refers to the need for, among other technologies, carbon capture and storage. The Plan is the technology component of the EU's energy and climate policy and forms part (via co-ordinated research) of European efforts to develop a portfolio of affordable, clean, efficient, low emission energy technologies. It incorporates EU strategy to accelerate their development and application. The Plan provides guidelines for building a coherent and effective European energy research landscape, aimed at the selection of technologies with the greatest potential. It also brings together the research capabilities of a number of major European institutes and universities that, in 2008, joined the European Energy Research Alliance (EERA). There is also industrial involvement, through the creation of a number of European Industrial Initiatives/technology avenues. These initiatives have been identified as ones where most value will be added by working at Community level – the focus is on technologies for which the barriers, the scale of the investment, and risks involved can be better tackled collectively.

For some areas, technology roadmaps have been produced for the development of key low carbon technologies (up to 2020) with strong potential at EU level. One of these is for CCS. This presents the technology objectives needed to make it fully cost-competitive, more efficient, and proven at a scale appropriate for market deployment. The European Energy Programme for Recovery (EEPR) is helping to rejuvenate the European economy and as part of this, €1.6 billion has been allocated towards the first CCS demonstration plants (€1035 million)and offshore wind projects (€565 million).

In June 2010, the *CCS EII Implementation Plan 2010-2012* was launched. A component of this is the *CCS Project Network*, an industry-led collaboration between the EC and Member States. This aims to enhance co-operation between governments and industry with a view to delivering cost-competitive deployment of CCS post-2020, and to further develop the technologies to allow application in all carbon-intensive industrial sectors. The SET-Plan recognises that these objectives can be best delivered through a coherent overall effort by industry, the EC and Member States, and various activities for the achievement of these objectives are ongoing. As part of these activities, the CCS EII Technology Roadmap has been published. It is anticipated that the added value of the CCS EII Plan will be to drive forward and accelerate the necessary changes in policy, technology and financing at all levels of governance, and to ensure delivery in an efficient manner and on time. There are a number of major objectives that will build on the comparative strengths of each of the partners, namely:

- **Industry**: to manage technology and market risk; to deliver on technology and cost objectives;
- **Member States**: to ensure regulatory compliance by providing a clear regulatory framework at national level; to provide financial support as needed, taking into account the favourable State Aid rules for CCS; to take into account the agreed CCS EII R,D&D priorities in their national programmes;
- **EC**: to provide guidance as necessary in relation to regulatory framework; to provide clarity over applicable EU law and policy and how these may affect business decisions; to co-ordinate CCS demonstration at EU level through the Project Network and provide support through the EEPR and the NER, etc;

- **Research organisations and EERA**: to undertake necessary research activities complementing those of industry, and therefore deliver required breakthrough research at least cost and on time;
- **NGOs**: to promote understanding and raise awareness of the advantages of CCS in civil society and to advise on actions as appropriate.

In October 2009, the European Commission proposed that an additional €50 billion (over the next decade) should be invested in the further development of low carbon technologies. This would mean almost tripling the annual investment in the EU from €3 to €8 billion and would represent a step forward in the implementation of the SET-Plan. Different sources of funding have been considered (public and private sectors, and at national and EU level).

Capacity building involving major overseas coal-consuming countries in the areas of CCT and CCS also features in key European Commission proposals. In 2010, the Commission (within the context of its *Thematic Programme for Environment and Sustainable Management of Natural Resources, including Energy*, via its EuropeAid Co-operation Office) launched an open call for proposals (EuropeAid/129199/C/ACT/TPS) on 'Co-operation on Clean Coal Technologies (CCT) and Carbon Capture and Storage (CCS)'. This is concentrating on CCT and CCS capacity building and studies in India, Indonesia, Kazakhstan, the Russian Federation, South Africa and Ukraine. These activities will support and promote the use of these technologies and will contribute towards the strengthening of international expert networks and knowledge exchange. Possible topic areas include co-operation between organisations in emerging countries and CCT/CCS plants in Europe, studies relating to the demonstration, diffusion and deployment of CCT and CCS, energy efficiency financing mechanisms, and awareness-raising activities, internships, training and seminars. Grants of between €150,000 and €500,000 will be made available in the beneficiary countries (European Commission, 2010). The total available is €3 million.

1.2 EU Framework Programmes

Since 1984, EU-wide R&D activities have been implemented predominantly under large research, technological development and demonstration (RTD) framework programmes (FP). These are implemented mainly through calls for proposals. Based on the treaty establishing the EU, the framework programme serves two main strategic objectives, namely strengthening the scientific and technological bases of industry, and encouraging its international competitiveness while promoting research activities in support of other EU policies. All projects involve several EU member countries. Technology Platforms, consisting of stakeholders, led by industry, define priorities, time-frames and action plans. Often, work has tended to build on that of preceding FPs.

The current Seventh Framework (FP7) covers the period from 2007 to 2013. The broad objectives of FP7 have been grouped into four categories: *Co-operation, Ideas, People and Capacities*. For each type of objective, there is a specific programme corresponding to the main areas of EU research policy (Cordis, nd). This has a budget for energy of €2.35 billion over the duration of the programme. It is an important element in meeting the Lisbon strategy aim of making the EU economy the most dynamic, competitive, knowledge-based economy in the world by 2010. Compared to preceding Framework Programmes, the seventh benefits from an improved structure, a larger budget, more flexible funding schemes, and a longer duration (seven years instead of four). Recognising that, alone, no single technology being developed can make a sufficient difference, and that their commercialisation will take place over differing time horizons, a broad technology portfolio approach has been adopted. In the event of failure, this strategy helps minimise risk and costs.

1.3 Energy research within the Co-operation Specific Programme of FP7

The Co-operation Specific Programme supports a range of research actions in trans-national co-operation in ten themes, that include energy. The energy research part of FP7 is, to some degree, a continuation of research activities that were supported under the previous, still on-going sixth Framework Programme (FP6). A major goal of research in the 'energy' thematic area is to aid the development of technologies necessary to make the current fossil fuel based energy system more sustainable and less dependent on imported fuels. To address issues of climate change and security of energy supply, emphasis is on a portfolio of energy sources and carriers, with particular focus on lower and non CO_2 emitting energy technologies. These will be combined with enhanced energy efficiency and conservation. The energy theme within FP7 is managed by the General Directorates of Research, Energy and Transport. Activities under the energy theme of the programme include:

CO_2 capture and storage technologies for zero emission power generation

RD&D of technologies aimed at significantly reducing the environmental impact of fossil fuel use via highly efficient, cost-effective power and/or co-generation plants with near-zero emissions, based on CCS, with particular emphasis on underground storage.

Clean coal technologies

RD&D of technologies to substantially increase plant efficiency, reliability and reduce associated costs through development and demonstration of clean coal and other solid fuel conversion technologies, also producing secondary energy carriers (including hydrogen) and liquid or gaseous fuels. Activities will be linked as appropriate to CCS technologies or co-utilisation of biomass.

The RD&D aims encompassed by FP7 are to improve energy efficiency throughout the energy system, to accelerate the uptake of renewable energy sources, to decarbonise power generation, to reduce greenhouse gas emissions, to diversify

Europe's energy mix, and to enhance the competitiveness of European industry (Cordis, 2009a). It therefore embraces the following areas:

- hydrogen and fuel cells (via the Fuel Cells and Hydrogen Joint Undertaking – FCH JU);
- renewable electricity generation (increased overall conversion efficiency, cost efficiency and reliability, driving down COE);
- renewable fuel production (fuel production systems and conversion technologies);
- renewables for heating and cooling (technologies for cheaper, more efficient active and passive heating and cooling);
- CO_2 capture and storage technologies for zero emission power generation;
- Clean Coal Technologies (improved power plant efficiency, reliability and reduce costs via RD&D of cleaner coal; also producing secondary energy carriers (including hydrogen) and liquid or gaseous fuels);
- smart energy networks;
- energy efficiency and savings;
- knowledge for energy policy making.

There is therefore a strong focus on CCT and CCS in recognition of the drive for greater efficiency whilst CCS is developed and deployed. Within this context, 'clean coal' is regarded as a sustainable solid hydrocarbon value chain, with a focus on efficient and clean coal utilisation – coal use aimed at zero (or significantly reduced) emissions by means of enhanced plant efficiency and CCS. A major aim is to improve the cost-effectiveness of zero emission CCT and other fossil fuel based power plants, enabling the use of fossil fuel reserves with a substantially reduced environmental impact. Thus, projects are addressing the necessary RD&D of conversion technologies required for solid hydrocarbons (such as hard coal and lignite) with a focus on advanced zero emission power generation. Mainstream systems, such as pulverised and other coal combustion systems, gasification, and fluidised bed technologies, are encompassed. Work in this area is expected to increase power plant efficiency and provide a foundation for the adoption of CCS. Safer storage, monitoring and verification techniques for geological storage will accompany this. Other areas are noted in Table 3. These include a number of cross cutting measures.

1.4 Clean Coal and CCS calls under FP7

Under FP7, CCT activities have been pursued via a series of annual calls. In 2007, the 1st Call focused on polygeneration, and gasification technologies suitable for CCS, plus the value chain for CCT and CCS. Major projects developed through this included *ECCO* – European value chain for CO_2, and *COMETH*. ECCO was initiated in 2008, with the objective of facilitating robust strategic decision

Table 3 Illustrative examples of Clean coal- and CCS-related topics selected under FP7 (Cordis, 2009b)

Topic area	Topic code	Topic title	Call identifier	Deadline
Clean coal technologies				
Clean coal	ENERGY.2010.6.1.1	Efficiency improvement of oxygen-based combustion	FP7-ENERGY-2010-2	4/3/2010
Carbon capture and storage technologies for zero emission power generation				
CCS	ENERGY.2010.5.1-1	Demonstration of advanced CO_2 capture concepts	FP7-ENERGY-2010-1	15/10/2009
CCS	ENERGY.2010.5.2-1	CCS – storage site characterisation	FP7-ENERGY-2010-1	15/10/2009
CCS	ENERGY.2010.5.2-2	Trans-national co-operation and networking in the field of geological storage of CO_2	FP7-ENERGY-2010-1	15/10/2009
CCS	ENERGY.2010.5.2-3	CCS – site abandonment	FP7-ENERGY-2010-1	15/10/2009
CCS	ENERGY.2010.3	Sub-seabed carbon storage and the marine environment	FP7 - OCEAN-2010	14/1/2010
CCS	ENV.2010.3.1.8-1	Development of technologies for long-term carbon sequestration	FP7 - ENV-2010	5/1/2010
Clean coal - CCS - cross cutting issues				
Zero emission power plant	ENERGY.2008.5 and 6.1.1	Feasibility and engineering study for development of an integrated solution for a large scale zero emission fossil fuel power plant	FP7 - ENERGY - 2008 - TREN	8/10/2008
GHG emissions	ENERGY.2010.5 and 6.2-1	Extending the value chain for GHG emissions other than CO_2	FP7 - ENERGY - 2010 - 2	4/3/2010

making regarding early and future implementation of CO_2 value chains in the face of uncertainty. The project budget is €5.35 million (~€3.9 million from European Commission), spread over three years. The project aims to identify strategies for early deployment of CCS and is the first EU-funded project with direct relevance to oil and gas production through the focus on EOR and EGR via CO_2 injection. ECCO will provide recommendations on how to stimulate deployment of CCS in Europe. There are 19 partners (including major electricity generators such as Vattenfall, DONG Energy, E.ON and RWE), with SINTEF Energy Research as co-ordinator.

The collaborative *COMETH* project, launched in November 2008, aims to extend the value chain for greenhouse gas emissions (other than CO_2) from coal production and use. It is examining new opportunities for using coal mine methane (CMM) in countries with large coal deposits through development of a viable strategy for its recovery and use as an energy source. Frauenhofer UMSICHT is project co-ordinator. The European Commission is also a member of the *Methane to Markets Partnership* (M2M). This international initiative advances cost-effective methane recovery and use as a clean energy source.

The 2nd FP7 Call (in 2008) focused on combustion and gasification. Topics include fluidised bed combustion, oxyfuel combustion, gas turbines for gasification-based systems, feasibility studies for CCT plants with integrated CCS, and recovery and use of methane. Two projects were funded under this call, namely *H_2-IGCC* and *FLEXI BURN CFB*. *H_2-IGCC* (H2-IGCC project, 2009) is a four-year project, co-ordinated by the European Turbine Network. It kicked off in November 2009 with 24 partners from ten countries. Its overall objective is to provide and demonstrate technical solutions for increasing gas turbine efficiency and fuel flexibility that will allow the opening up of the market for IGCC with carbon capture and storage by 2020. The *FLEXI BURN CFB* (2009-2012) consortium of thirteen partners is led by the VTT Technical Research Centre of Finland and aims to develop and demonstrate a power plant concept based on circulating fluidised bed (CFB) technology combined with CCS (VTT, 2009). The plant will be based on supercritical once-through technology and oxygen-firing, with carbon capture for higher efficiency and operational flexibility via the utilisation of indigenous fossil fuels with simultaneous cofiring of biomass.

The 3rd Call (in 2009) focused on combustion, particularly increasing the efficiency of pulverised coal combustion-based plants, and one project is currently being negotiated for funding under this topic. The 4th Call (closed in March 2010) concentrated further on combustion and methane recovery, and included demonstration projects for oxyfuel combustion, and the recovery and use of methane (Wilde, 2009b). The evaluation of submitted proposals is currently ongoing (Filiou, 2010).

CCS Calls under FP 7 have followed a similar pattern to those for CCTs. The focus under the 1st Call (2007) was on CO_2 capture (advanced capture techniques), the 2nd Call (2008) concentrated on CO_2 storage (storage capacity in emerging economies and deep saline aquifers, transport infrastructure, and public acceptance), and the 3rd Call (2009) focused on both capture and storage. The 4th Call (2010) will focus on storage (advanced capture techniques, storage site characterisation and decommissioning, co-operation network on geological storage). This Call closed in March 2010.

1.5 European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP)

The Platform is a coalition of industry and other stakeholders (comprising science, environmental NGOs and academia) set up in 2006 by the European Commission to improve competitiveness, growth and sustainability within the EU, by supporting and driving forward the development and deployment of CCS technologies. There are three main goals:
- enable CCS as a key technology for combating climate change;
- make CCS commercially viable by 2020 via an EU-backed demonstration programme;
- accelerate R&D into next-generation CCS technology and its wide deployment post-2020.

The Platform fulfils several roles in that it provides expert advice on all technical, policy, commercial and other related issues; provides input on all related technology issues; and acts as an important communicator.

In 2006, the ZEP published its *Strategic Deployment Document* (SDD) and *Strategic Research Agenda* (SRA). The SDD considered how to accelerate technology deployment, whilst the SRA described a collaborative programme of technology development for reducing costs and risks. These two provided the roadmap necessary to commercialise CCS by 2020 – this included ten to twelve demonstration projects. In 2008, ZEP carried out an in-depth study into how such a demonstration programme could work in practice. The subsequent report described what the programme needed to cover to ensure that it was fully functional by 2015, with a view to commercialisation of CCS by 2020. In late 2008, the EU established both a legal framework for CO_2 storage and funding to support, via its *Flagship Programme*, up to twelve CCS demonstration projects. The intention is that by the end of the demonstration phase in 2020, there should be widescale uptake of CCS technology. The main objectives of the Flagship Programme include the scaling up and demonstration of selected technologies (based on different fuel and plant technologies), their improved cost-effectiveness and availability, the assessment of European CO_2 storage potential, and full-scale commercial technology deployment post-2020 (Thorvik, 2007).

The ZEP coalition published a proposal for the way forward to achieve the ten to twelve CCS demonstrations recommended in its (2006) Strategic Research Agenda. The need for ten to twelve demonstrations was subsequently taken up as policy by the EU. The coalition defined those technical aspects of the full CCS value chain that require validation in the demonstrations. It confirmed the need for ten to twelve projects to cover an adequate proportion (80%) of the technical validation gaps in order to allow CCS to become commercially proven for all important applications, and so commercially deployable from 2020.

All three of the major capture technologies (post-combustion, oxyfuel and pre-combustion) were deemed ready for large-scale demonstration, pending some existing validation initiatives for the first two (ZEP, 2008). Pre-combustion technology blocks were viewed as more advanced than those for post-combustion and oxyfuel. Common to all was the need to demonstrate overall integration, and to enhance plant performance of the non-capture sub-systems to ease integration of the CO_2 capture systems.

ZEP concluded that public funding would be needed for the cost of the highest risk parts of the demonstration, namely the CCS systems. Industry would fund the conventional systems, at an estimated €7–12 billion. The cost calculations were based on information from the recent report by McKinsey (McKinsey, 2008).

1.5.1 Demonstration projects selected under the EERP (December 2009)

The European Economic Recovery Plan (EERP) was endorsed by the European Council in December 2008, to fund initiatives to increase Union spending in strategic sectors for containing the impact of the economic crisis, and to provide new stimulus to the European economy. Under this umbrella, a number of proposals were received for CCS demonstration (11 proposals) and offshore wind projects. Funding of between €7 and €12 billion was proposed for ten to twelve projects (Sweeney, 2009). In December 2009, as part of the list of selected energy projects for European economic recovery, the CCS projects selected were announced (Table 4). These include a post-combustion scrubber at the Belchatow site in Poland (Figure 2). With the exception of the Italian and French schemes, each project will receive €180 million of stimulus funding from a €5 billion budget surplus, to be matched by national governments. ENEL's project will receive €100 million and that of ArcelorMittal, €50 million.

Table 4 CCS projects* selected under the EERP (December 2009)

Project	Technology	Comments
Vattenfall, Jaenschwalde in Germany	Oxyfuel and post combustion capture	385 MWe demonstration Capture of up to 2.7 Mt/y Plant grid connection by 2015 Two storage and transport option will be analysed
Rotterdam Hub scheme, the Netherlands (Maasvlakte J.V./E.ON Benelux, Electrabel)	Post-combustion capture	Demonstration of full CCS chain (250 MWe) Storage in depleted offshore gas field Project forms part of Rotterdam Climate Initiative
Belchatow, Poland (PGE EBSA)	Post-combustion amine scrubber	Demonstration of full CCS chain (250 MWe) on new SC PCC lignite-fired unit Three nearby saline aquifers will be explored
ENDESA, Compostilla, Spain	Oxyfuel + CFBC	Demonstration of full CCS chain using 30 MW oxy-fuel/CFBC pilot project. Project to be enlarged to demo by 2015 Storage in an aquifer nearby
Powerfuel, Hatfield, UK	IGCC + CCS	Demonstration of CCS on new 900 MW IGCC plant Storage in an offshore gas field Project forms part of the Yorkshire Forward initiative
ENEL, Porto Tolle, Italy	Post-combustion	Installation of CCS technology on new 660 MW coal-fired power plant Capture part will treat equivalent of 250 MWe output Storage in nearby saline aquifer
ArcelorMittal steel plant, Florange, France	Blast furnace-based with Top Gas Recycling (TGR-BF) and CCS	

* Abstracted from the list of 15 energy projects for European economic recovery. Europa press release. Ref: MEMO/09/542. 9 Dec 2009; these are considered further in the appropriate country case studies in the present report

Figure 2 The Belchatow power plant site in Poland (photograph courtesy of Elektrownia Belchatow)

Figure 3 Artists impression of E.ON's Wilhelmshaven 50+ power plant (photograph courtesy of E.ON)

1.6 Other major European initiatives

1.6.1 Advanced 700ºC PF Power Plant research project (AD700)

Funding for this project has come from several EU Framework programmes. Its aim is the construction and operation of a 500 MW ultra-supercritical PCC demonstration plant (Project 50+) with a net efficiency of over 50% (LHV). A major aim is the development of superalloys for ultra-supercritical steam conditions of >37.5 MPa/700ºC. Funding has been provided by the European Commission and the Governments of the UK and Switzerland, with substantial contributions also coming from power generators in France, Belgium, Germany, Denmark, Greece and Sweden.

The project extends over a period of 15 years – it started in 1998 with a feasibility study and a materials development programme. There is a strong focus on the development of nickel-based alloys. The project pathway to the 700ºC power plant is via four main stages (Folke and others, 2007):

- Materials development;
- COMTES 700 test facility;
- NRWPP700 power plant specification;
- 50+ demonstration power project

The materials test programme is centred on the COMTES 700 (AD700-3) Component Test Facility, located at the Scholven F power plant in Germany. Candidate alloys are being tested for applications that include furnace walls, superheaters, thick walled tubes, and turbine valves. The facility has achieved >20,000 hours of successful operation, with data being fed into the feasibility study focusing on the development of the specification for a 700ºC power plant (NRWPP700); this was undertaken between 2006 and 2009.

A materials test rig is also installed in the boiler of Elsam's Esbjerg power plant under the auspices of VGB's E-max power plant initiative. It is being run in parallel with, and complements the work of, the Scholven programme and has operated for four years at steam temperatures up to 720ºC. VGB initiated activities in collaboration with a number of major European utilities, including ENEL, EdF, Electrabel, E.ON Energie, Vattenfall, EnBW, Elsam, RWE, and Energie E2. A major goal is to have the AD700 technology commercially available as soon as possible after 2010, and the E-max project is directed towards the demonstration of a power plant using AD700 technology.

Between 2006 and 2014, the 50+ demonstration plant will be will be designed and engineered (Figure 3). The site for the 500 MW demonstration plant will be at Wilhelmshaven, on the North Sea coast of Germany. This €1 billion coastal plant will use cold seawater for cooling, helping it to achieve its high efficiency. It is likely to use imported bituminous coals. Steam parameters will be 35 MPa/700ºC/720ºC. Planning of the plant was due for completion in 2008, with construction scheduled to begin in 2010. However, the plant's commissioning date has been pushed back to allow greater development of manufacturing and repair concepts of thick walled components produced from nickel-based alloys (Boillot, 2010). E.ON has announced that it will build the plant CO_2 capture-ready.

1.6.2 European COST Actions

Founded in 1971, COST is a framework for *European Co-operation in Scientific and Technical Research*. It covers basic and pre-competitive research. The Materials, Physical and Nanosciences domain of the COST Actions have enabled funding of work on higher temperature turbine components. New materials, particularly of the 9–12% Cr steel class, were developed as part of the COST 501, 522 and 536 Actions. Materials generated from the first two of these have already been introduced into SC PCC plants. COST 536 (completed mid 2009) concentrated on 9–12% Cr steels (suitable for critical components such as turbine rotors, casings for turbines and valves, headers and main steam pipes) with increased high temperature strength, intended for the manufacture of components for steam conditions up to 650ºC.

1.6.3 Research Programme of the Research Fund for Coal and Steel (RFCS)

The Research Fund for Coal and Steel is a separate, complementary programme to the Research Framework Programme, with the aim of supporting the competitiveness of the steel and coal industries. It covers all aspects of research, from production processes to applications, and follows a clear 'bottom up' approach with a strong industrial focus. Created in February 2003 further to a protocol annexed to the EU Treaty, it is the successor to the European Coal and Steel Treaty research programme (ECSC). Its annual budget of around €55 million is based on the interest accrued from the assets of the now-expired ECSC Treaty. Respectively, 27.2% and 72.8% of the annual budget are devoted to the coal and steel sectors. Since its creation, the RFCS has supported 378 research projects in the fields of coal and steel, with total funding of €379 million.

As noted, the RFCS supports industrial research projects in the areas of coal and steel. It covers the entire spectrum from production processes to applications, encompassing the utilisation and conversion of resources, environmental improvements, and safety at work. Regarding coal, the research objectives include the management of external dependence concerning energy supply, the efficient protection of the environment and improvements in the use of coal as a clean energy source, health and safety in mines, and improvement of the competitive position of coal in the European Community. The research projects supported are wide-ranging and, in the fields of CCT and CCS, include:

- performance improvement of pulverised coal fired plants;
- reduction of slagging and fouling impacts;
- improved environmental control;
- co-combustion and fluidised bed applications;
- control of CO_2 emissions

The RFCS is providing funds towards a number of coal-based projects (Table 5).

Coal-fired power generation projects engaged in during the period 2002-06 are listed in Minchener and McMullen, 2007 (Appendix B).

A completed project of particular note was *CCTPROM* – Clean Coal Technology RD&D Promotion and Dissemination (18 months duration, 2006-07). This reported on the technical achievements of the CCT power generation RD&D activities arising from the ECSC and RFCS coal utilisation programmes. It focused primarily on major coal-consuming nation states that had recently joined the EU, namely Poland, the Czech Republic and Romania. The project was co-ordinated by IEA Coal Research Ltd through the IEA Clean Coal Centre. Partners comprised SEVEn-Stredisko Pro Efektivni Vyuzivani Energie of the Czech Republic, the Silesian University of Technology in Poland, and the Institutul de Studii si Proiectari Energetice in Romania (CCTPROM, 2009). Major common interests included:

- improvement of PCC-fired power plant performance, both efficiency and environmental control (dust, NOx, SOx and heavy metals), when using various coal types;
- co-combustion using coal (particularly lignite) and biomass, mostly within fluidised bed applications, including supercritical boilers.

The project report was disseminated widely and workshops were held in each nation state to promote the findings of the review and to determine primary interests in future R&D. Associated information was made available to appropriate stakeholders in other countries via various networks and associations. The expectation is that this will lead to more

Table 5 Research Fund for Coal and Steel-funded projects (since 2009)

Project title	Partners	Timescale	Description
COALSWAD	seven partners, led by Frauenhofer Gesellschaft eV	July 2008 start. 36 months	Estimation of CO_2 sequestration capacity and CH_4 production rate in coal Investigation of adsorption and swelling behaviour of coal to determine the feasibility of CO_2 sequestration and CH_4 production enhancement
HUGE	eleven partners led by GIG of Poland	2007-10	Hydrogen oriented underground coal gasification in Europe Underground gasificiation of coal in a dynamic geo-reactor, CBM usage and CO_2 sequestration in coal deposits
CO2freeSNG project	four partners led by Technical University of Graz (Austria)	2009 start. 36 months	Substitute natural gas from coal and internal sequestration of CO_2 Scale up of gasification, methanation, and sequestration technologies previously developed for biomass Evaluation of technical and economic application of the concept for coal Test programme in existing gasification plant

informed co-operation between R&D organisations in different EU Member States. A comprehensive review of the CCTPROM programme and the scope and achievements of the ECSC and RFCS projects on coal-fired power generation RD&D is available (Minchener and McMullen, 2007).

As noted, the RFCS is currently engaged in a range of projects, one of which is aimed at the development of advanced steel-making processes, leading to reduced CO_2 emissions – the *Ultra-Low Carbon Dioxide (CO2) Steelmaking Project* (ULCOS). Many iron and steel production processes rely heavily on the use of coal. Globally, CO_2 emissions from the sector are significant and efforts are under way to reduce this impact. The *ULCOS* project is a co-operative R&D initiative aimed at reducing CO_2 emissions by at least 50% from current best (iron ore-based) steel-making processes by 2050. The project consortium consists of 48 partners from 13 European countries that include all major EU steel companies, energy and engineering partners, research institutes and universities, plus Rio Tinto. It is supported by the European Commission. Co-ordinated by ArcelorMittal, it is the world's largest steel industry project on climate change. There are nine core partners (ArcelorMittal plus Corus, TKSE, Riva, Voestalpine, LKAB, Dillingen Hutte, Saarstahl, SSAB, and Ruukki). The project budget is ~€75 million (funded by industrial partners and the European Commission via FP6 and the RFCS). One of the major ULCOS technical themes is carbon capture and storage. The project is being taken forward via a number of steps, namely process concept-building (ULCOS-I; 2004-09), large-scale demonstration (ULCOS-II; 2009-14), commercial-scale demonstration (2015–20), followed by global deployment of the technology from 2020.

Various breakthrough technologies have been investigated and the most advanced are being implemented at appropriate scale. One technology comprises a blast furnace-based system with Top Gas Recycling (TGR-BF) and CCS. A pilot plant will be set up at Eisenhüttenstadt in Germany between 2010 and 2014. This will validate the TGR-BF concept on a small sized blast furnace. Between 2011 and 2015, an industrial-scale demonstration will be developed in Florange (France); this will incorporate CCS, with underground CO_2 storage in the Lorraine region. Both project sites belong to ArcelorMittal. The aim is to lead to large-scale commercial deployment within existing steel-making facilities post-2020.

The ULCOS consortium has also been pursuing development of the *Isarna* process. This is a highly energy-efficient iron making process based on direct smelting of iron ore fines using a smelt cyclone (developed by Corus) in combination with a coal-based smelter. All process steps are directly hot-coupled, avoiding energy losses from intermediate treatment of materials and process gases. Rio Tinto is now involved via the licensing of its *HIsmelt* direct smelting technology. The new project is developing a process that combines the Isarna smelt cyclone with the HIsmelt smelter, the combination operating on pure oxygen. This is known as *HIsarna*. The process is both compact and highly efficient. It will produce less CO_2 emissions than other coal-based processes, while the use of pure oxygen is expected to ease CO_2 capture and storage. A 65 kt/y pilot plant is to be built at Corus IJmuiden, in The Netherlands. This is due to start operations in 2010, followed by a three-year pilot testing phase. Scale-up to commercial size and subsequent proliferation through the global steel industry is expected to follow in due course.

1.6.4 EU-China Partnership on Climate Change and Energy & Environment Programme

The *EU-China Energy Environment Programme* (EEP) was established in 2002 to further strengthen EU-China co-operation on sustainable energy use by securing supply under improved economic, social and environmental conditions. The aim is to contribute to improved environmental quality and health conditions in China. Under this programme, the EU-China project on CBM was funded (EU China, nd); this ended in 2008. The study examined CBM resources in China, the available technology for its extraction, technical barriers, and economic assessment of CBM resources within the country.

As part of the actions under the *EU-China Partnership on Climate Change*, designed to strengthen practical co-operation on the development, deployment and transfer of clean fossil fuel technologies, in order to improve energy efficiency and move towards a low carbon economy, co-operation on carbon capture and storage was agreed. This is the *Near Zero Emissions Coal* (NZEC) project, aimed at developing and demonstrating advanced near-zero emission coal technology through carbon dioxide capture from coal-fired power plants and its subsequent storage underground in exploited oil or gas fields or in sealed geological strata.

1.6.5 Biomass cofiring in Europe

The importance of cofiring biomass with coal (particularly in large coal-fired power stations) has increased considerably in recent years. Many EU Member States with coal-fired generating capacity now regularly cofire a range of biomass and waste-derived materials; these are examined in greater detail in the individual country reviews later in the present report.

In recent years, several major pan-European programmes have focused on cofiring. The Integrated European network for biomass cofiring (NETBIOCOF – 2005-07) was a Coordinated Action funded by the EU under the sixth Framework Programme. The Action's main objective was to promote co-operation between European research organisations engaged in biomass cofiring, and the promotion of innovative technologies to expand its use, with particular emphasis in the new Member States. Motives included a desire to reduce reliance on imported energy sources through the increased use of indigenous biomass, providing a cost-effective means of minimising CO_2 emissions from power generation and other industrial applications. Many Member States were involved in the project.

Cofiring efforts have continued under FP7 with the launch in 2008 of the four-year collaborative project entitled *Demonstration of Large Scale Biomass Cofiring and Supply*

Chain Integration (DEBCO). This is concerned with the development and demonstration of innovative approaches to the co-utilisation of biomass with coal, characterised by cost-effectiveness and/or increased energy efficiency, for large-scale electricity production and/or co-generation. Part of this aims, wherever feasible, to increase the share of biomass cofired in large-scale PCC power plants from current levels of 3–10%, to 50+% (on a thermal basis) depending on the fuel type and plant-related limitations. Countries represented are Italy, Belgium, Greece, Hungary, Germany, The Netherlands, UK and Poland. Demonstration plants are being developed in Belgium, Italy and Greece.

Cofiring is also encouraged and promoted via Task 32 of the IEA *Bioenergy Agreement*. This is focused on biomass combustion and co-combustion, particularly in the area of small-medium scale co-generation plants and cofiring at a larger scale in conventional coal-fired boilers. There is also interaction between Task 32 and other IEA Implementing Agreements, such as the Clean Coal Centre, Clean Coal Science, and Fluidised Bed Conversion. The Operating Agent is the Netherlands Agency for Energy and the Environment (NOVEM) and the Task Leader is the TNO Institute of Environmental Sciences, Energy Research and Process Innovation. European participation includes the European Commission, Austria, Belgium, Denmark, Germany, Netherlands, Norway, Sweden, Switzerland, and UK.

1.6.6 Summary

The EC has put in place a number of crucial regulatory and financial instruments for CCT and CCS demonstration and deployment, although there remain significant challenges to ensure that, in particular, CCS will be able to compete with other low carbon technologies. As part of this, it is intended that support will be continued for the CCS demonstration projects selected. The impetus towards the development and application of a range of policies and technologies will be maintained.

1.7 Introduction to case studies

In the present report, twelve EU Member States have been selected and examined. Each consumes ⩾10 Mt of hard coal and/or lignite a year. Of these, nine rely to varying degrees on coal and/or lignite produced from indigenous reserves. The remaining three (France, Italy and The Netherlands) rely almost entirely on imported supplies.

In the following section, the energy situation, with particular respect to coal, is examined for those Member States selected. Thus, short case studies are presented for Bulgaria, the Czech Republic, France, Greece, Germany, Hungary, Poland, Italy, The Netherlands, Romania, Spain and the UK. Within each study, the current and possible future use of coal is considered. Major applications for coal are examined and activities in related areas addressed.

For each country, the use of coal and clean coal technologies is examined. Carbon capture and storage (where associated with coal use) is also covered. CCS-related activities were not considered in detail in the 2004 report as at the time, development and application of the various technologies was not well advanced. However, efforts to mitigate and control greenhouse gas emissions have increased significantly during the past six years, hence it is appropriate that the present report reflects the increasing activities ongoing in most coal-consuming Member States.

Despite moves in recent years to increase the use of alternatives sources of energy, in the Member States considered, there are often strong commercial and strategic incentives to continue using hard coal and/or lignite as a component of the national energy mix. This is especially so in the power generation sector. Many of the reasons are self-evident and focus on the continued provision of a secure, affordable national energy supply. Most of the reasons cited remain similar to those noted in the 2004 report and include:

- security of supply and minimisation of dependence on imported energy. Particular concerns include the stability of some major oil- and gas-supplying regions. In contrast, coal, despite recent price rises, is viewed as forming a reliable, widely available energy source. The price of coal is more stable than that of oil and gas and less susceptible to large fluctuations in market price. The stability of coal price also helps impart a stabilising effect on the price of electricity;
- economic impact of imports on national trade balance. Importing sizeable quantities of oil and gas is an expensive option. Indigenous energy supplies such as opencast-sourced lignite are much cheaper;
- limited indigenous energy resources. In some countries, there are few (if any) affordable alternative sources of energy;
- maintaining an indigenous coal industry provides employment in national mining and power generation industries. In some regions, coal mining remains the prime employer, hence the social consequences of closure could be significant;
- there may be opportunities for cofiring various biomass and waste feedstocks in existing coal-fired power plant. This can provide a route for the disposal of such materials in a cost-effective, environmentally-friendly manner, whilst helping to maintain the viability of the coal-fired facility.

In the following section, the energy situation, with particular respect to coal, is examined for the EU Member States noted above.

2 Bulgaria

Bulgaria has limited reserves of fossil fuels, its indigenous energy resources consisting mainly of low rank lignite and brown coal. These play a significant role in the country's energy security, being used mostly for power generation. Some bituminous coal and anthracite is also imported for steel making and power generation. In 2008, the country imported 4.91 Mt of hard coal (4.49 Mt of steam coal) (OECD/IEA, 2008). Most came from Russia and parts of the former USSR.

Most of Bulgaria's lignite reserves are in the central and western parts of the country. Annually, 25–26 Mt is produced, since 2002, exclusively by opencast mining. The bulk of production comes from the three Maritsa Iztok mines belonging to Mini Maritsa Iztok EAD, and is supplied to three minemouth power plants (total of 2.24 GW). Much of the country's brown coal deposits are located in the western part of the country, near the Black Sea. Annually, around 3 Mt is supplied to the 630 MW Bobov Dol power plant. Overall, national coal output comprises 88.7% lignite, 10.9% brown coal and 0.4% hard coal (Euracoal, 2009).

2.1 Power generation

The country has a total installed generating capacity of 11.4 GW. This includes 1475 MW of hard coal fired plants, and 3370 MW fired on lignite and brown coal. Indigenous lignite and hard coal play a major role in Bulgaria's power sector. In 2007, lignite/brown coal and hard coal generated 41.7% of the national total of 45.8 TWh (Euracoal, 2009). Nuclear power supplied much of the balance (42.6%), with smaller contributions from oil (0.9%), natural gas (5%), and other systems such as hydro (10%).

Bulgaria's nuclear capacity comprises two units. Two others, at the Kozloduy site, were closed at the end of 2006 as a condition of the country's entry into the EU in 2007. To compensate for the loss of this nuclear capacity and to improve overall sector performance, emphasis on coal-fired plant has grown. A number of existing units are in the process of being modernised and their output increased. There are also several new projects being developed. However, there is strong government commitment to nuclear energy, and two new units are planned for the Belene nuclear site. The first is scheduled to start up in 2014 (WNA, 2009).

2.1.1 Power plant modernisation programmes

Bulgarian coal-fired power plants are all conventional PCC subcritical facilities. In many cases, average unit capacity is small, with most of the larger units of only around ~210–220 MW. Some are fired on indigenous lignite/brown coal, while others fire imported bituminous coal or anthracite. Recent years have seen a number of projects undertaken, aimed at reducing the environmental impact of coal-fired plants. Several have now been equipped with limestone gypsum FGD units: an Alstom unit on Maritsa East (New) I, units from Schumacher and IHI on Maritsa II, plus a unit from RWE Solutions on Maritsa III (CoalPower).

At some plants, a series of upgrades has been applied. For instance, in May 2009, ENEL completed a long-running project to upgrade Maritza East III, the company's Bulgarian thermal power plant (ENEL has a 73% stake in the plant, NEK the remainder). The environmental upgrades (two FGD units and low NOx burners) now allow the plant to comply with EU environmental standards; it is currently one of the few lignite-fired power plants in the Balkans fully compliant with the latest EU standards. In addition, plant capacity was increased from 840 to 908 MW. Upgrades included boiler and air pre-heater revamping, new flue gas fans, new superheater, reheater and water wall elements, and upgraded steam turbines. The plant's operational lifespan has been extended by 15 years. This was the first major energy sector investment project in South Eastern Europe financed without state guarantees. In early 2010, it was announced that GE had been selected to rebuild and modernise the ESP units at Maritza East III. This forms part six of ENEL's on-going eight-phase modernisation project.

Some other Bulgarian plants are also in the process of being upgraded and modernised. Such a project was launched in June 2008, with the purchase by Consortium Energia MK (a group of Bulgarian coal producers) of the 630 MW Bobov Dol thermal power plant. The new owners intend to invest €60 million in environmental upgrades to bring the plant up to EU standards. The plant has three 210 MW units; one is currently shut down and will require modernising and equipping with FGD before it can be restarted (Coal Trans, 2008). There are also proposals for the construction of two new 200 MW units at the site, although no time frame has yet been announced (Ivanova, 2008).

Most environmental control systems applied in Bulgaria are similar to those used widely elsewhere. However, following the successful operation of a combined SO_2/NOx electron beam irradiation treatment pilot project at the Maritza East II power plant, a commercial-scale unit is under construction at the 120 MW coal-fired Svishtov power plant. This should be capable of transforming 85% of SO_2 and 40% of the NOx present in the plant's flue gas into dry ammonium compounds, suitable for use as fertilisers (Kim and others, 2009).

There has only been one major coal-fired power plant built in recent years, the 670 MW AES Maritsa East (New) I lignite-fired plant. This was constructed (at a cost of €700 million) on a turnkey basis by Alstom. It operates at subcritical steam conditions and was equipped with Alstom advanced pulverised lignite-firing boilers using state-of-the-art low NOx burners. Alstom also supplied the limestone-gypsum FGD system (98% removal efficiency) and an ESP. Emission levels are fully compliant with the latest EU standards. The plant was the first large-scale power project to be built in Bulgaria for the last twenty years. Commercial operation begin during 2009.

2.2 IGCC

There are no IGCC plants currently operating in Bulgaria although several initiatives have been proposed. In 2008, a competition was inaugurated to encourage proposals for IGCC developments. TET proposed the Maritsa East 4 power plant site for a ~600 MW lignite-fired IGCC plant (CSLF, 2009). No further information has yet been made public.

In 2009, the Government announced its willingness to pursue a demonstration project entitled the *Low Energy Lignite Project* (installed capacity of 400–600 MW) using IGCC and CCS technologies. The project cost is estimated at €750–850 million (Bellona, 2009).

2.3 Cofiring

In 2008, the Bulgarian Council of Ministers approved a national long-term programme encouraging the use of biomass as a means of generating cheap energy and reducing CO_2 emissions. Biomass accounts for some 40% of the renewable energy sources potential in Bulgaria. The principal sources are sawmill waste and lumber tailings that could, potentially, be used to generate up to 13.5 TWh/y.

Although, currently, cofiring is not used commercially, there is Bulgarian involvement in the EU-funded NETBIOCOF project. Bulgaria is represented by the Technical University of Sofia.

2.4 CCS activities

The official position on CCS is that the country supports technological developments leading to its commercial introduction, and will follow EU requirements, within the country's economic capabilities. However, it still needs to develop a regulatory framework for CCS deployment. In 2008, the Bulgarian Government announced its support for the development of a CCS project in the country. It also stated its willingness to support a demonstration project at the Maritsa East power plant site as part of the EU programme of building ten to twelve pilot plants with CCS by 2015 (Bellona, 2009). However, it is presently unclear if the Bulgarian Government will commit funding for a major CCS project, although reportedly, discussions have been held with potential overseas investors.

A CCS project has since been suggested for the Maritsa East II power plant site. A contract notice has been issued for consultancy services relating to a CCS study to be completed by the end of 2010. A total CO_2 emission of 3.26 Mt/y is to be considered. The project leader will be TETs Maritsa Iztok 2 EAD (MIT, 2009).

To date, only limited study has been made to assess CO_2 geological storage options in Bulgaria. However, the Ministry of Environment and Water intends to engage in a large-scale research project in order to identify geological formations that could potentially be used as CO_2 storage sites. The EBRD is assisting the Ministry of Economy and Energy to assess the technical and economic feasibility for CO_2 transport and storage in Bulgaria; this study began mid 2009.

In 2007 Enemona, a private energy company, and the Ministry of Economy and Energy, signed an agreement licensing the company for lignite exploration in the Momin Dol area, along with the development of a power plant and energy centre. As part of this, Enemona intends to investigate potential geological storage sites within the locale. Funding options are currently being explored.

Bulgaria was involved in the EU GeoCapacity project, represented by the University of Sofia

3 Czech Republic

Coal (both brown and black) is the Czech Republic's only significant indigenous energy resource and it remains the core fuel within the country's energy sector. Total coal reserves have been estimated at ~2 Gt. Lignite/brown coal accounts for more than two thirds of these, being produced mainly from opencast operations in North Bohemia, and used predominantly for power generation. Annual lignite and brown coal production has remained at around 49–50 Mt/y for some years. Hard coal is extracted in North Moravia, near the cities of Ostrava and Karviná. Around 13 Mt is produced each year, around half of which is used in the metallurgical and chemical industries. Most of the Republic's electricity is generated by coal-fired stations located close to coal mines. These produce nearly two thirds of the country's output. Much of the balance is provided by the Republic's two nuclear plants at Temelín and Dukovany.

3.1 Power generation

In terms of power generation, the country is currently more than self sufficient and is able to export as much as 25% of its overall production. In a typical year, around 60% of the Republic's total electricity output (88.4 TWh in 2007) is provided by coal-fired stations, with a further 30% being generated by nuclear power plants. Some 6% is produced by other thermal stations. Hydro and other renewable systems make only small contributions. The combined capacity of the country's conventional coal-fired power plants is ~10.6 GW. Many of these comprise conventional PCC plants using subcritical steam conditions, although in recent years, a number have been repowered using CFBC technology (*see below*). Conventional PCC plants fired on brown coal (the least expensive option) produce most of the electricity generated by thermal stations (47 TWh in 2007), with hard coal-fired units producing only 7.7 TWh.

3.1.1 Power plant modernisation

The biggest individual Czech power generator is the ČEZ Group. The company generates nearly three-quarters of the Republic's electricity from 15 coal-fired power plants, and also operates nuclear and renewable capacity. During the 1990s, ČEZ began an extensive programme of modernisation and environmental improvement of its coal-fired power plants in order to improve efficiency and achieve environmental compliance. Obsolete plants were closed and the remainder modernised and upgraded in various ways such that they were able to meet new emissions limits. Several outdated brown coal and lignite-fired units were closed and 6.5 GW of remaining capacity equipped with FGD systems. A total of 28 FGD units were installed. Overall, the ČEZ desulphurisation programme on its PCC and CFBC units (total of 4810 MW and 442 MW respectively) has reduced total SO_2 emissions by over 90%. Other measures have reduced NOx and particulate emissions. As a result, NOx emissions have fallen by 50%, particulates by 95%, and CO by 78%. Increasingly, station ash is now used as structural fill and for land reclamation, slag used in construction materials production (such as cement and concrete), and gypsum from FGD operations utilised for wall board manufacture. ČEZ's programme of modernising and upgrading its coal-fired stations continues.

Improving the efficiency of existing power plants has reduced coal requirement and CO_2 emissions per unit of electricity. And to this aim, for several years, ČEZ has maintained an extensive on-going programme to upgrade its coal-fired power plants. For the period up to 2012, a number of scheduled renewal activities have been brought forward. These include those at the Tušimice power plant (accelerated by three years, from 2011), the Ledvice power plant (by four years, post-2012), and the Prunérov II power plant (by three years, post-2012) (ČEZ, 2008). A number of other similar activities have also been approved.

3.2 Supercritical PCC plants and proposals

In the Republic, the power plant equipment supplier Skoda Power is active in the development and manufacture of supercritical steam turbines for use in thermal power plants, capable of operation at 28 MPa/>600ºC. These units are being deployed in two new power plants under construction within the country. Skoda is also developing steam turbines (using specialised nickel alloys) for operation at temperatures in excess of 700ºC. There are currently two commercial SC PCC projects being developed by ČEZ:

Ledvice

The existing plant has three PCC units, two of which have been decommissioned; a new SC PCC unit is relacing these. Unit 3 is an FBC plant and will remain in operation. Start-up of the new brown coal-fired 660 MW supercritical unit is scheduled for 2012. This is using an Alstom tower-type steam generator operating with steam parameters of 28 MPa/600ºC/610ºC. It will produce around 1678 t/h of steam. The plant's planned lifetime is 40 years. Table 6 compares the main parameters of the new SC unit and those of the site's existing subcritical PCC units.

The plant is adopting primary measures for NOx control and a wet limestone FGD scrubber to reduce SO_2 emissions. Combustion products (fly ash and clinker) and FGD gypsum will be mixed with water and lime to produce a certified product (additive granulate) which will be used for opencast mine reclamation purposes in the Bilina region. Coal for the new plant will come from Doly Bilina mine (Mills, 2007a).

Pocerady

A second brown coal-fired 660 MW SC PCC project, similar to the Ledvice plant, is planned for development in the period 2010-15. In April 2006, a business plan was submitted by

Table 6 Main parameters of Ledvice subcritical and supercritical PCC units (Creslar, 2008)		
	New supercritical unit	Existing subcritical units
Output	660 MWe	2 x 110 MWe
Superheated steam parameters	28 MPa/600°C/610°C	12.8 MPa/540°C
Reheat steam parameters	4.9 MPa/610°C	3.6 MPa/540°C
NOx emission limits	200 mg/m^3	650 mg/m^3
SO_2 emission limits	150 mg/m^3	1700 mg/m^3
Total Suspended Particulates	20 mg/m^3	100 mg/m^3
Unit efficiency (gross, LHV)	~47% (42% net)	~37%
Coal consumption	656 kg/MWh	1130 kg/MWh
CO_2 emissions	735 kg/MWh	1356 kg/MWh
NOx emissions	0.55 kg/MWh	2.11 kg/MWh
SO_2 emissions	0.41 kg/MWh	5.01 kg/MWh
Total Suspended Particulate emissions	0.06 kg/MWh	0.08 kg/MWh

Figure 4 Part of the Pocerady power plant site in the Czech Republic (photograph courtesy of ČEZ)

ČEZ for the plant (Mills, 2007a). Part of the existing plant is shown in Figure 4.

3.3 CFBC plants

Although there has been some deployment of bubbling fluidised bed technology within the country, most larger installations (power plants, co-generation plants, and heat-only facilities) have opted for circulating fluidised bed systems. In the power generation sector, new CFB capacity has been used regularly to replace outdated, inefficient PCC plant, providing a cost-effective solution to meeting increasingly stringent emission limits and/or the need for increased capacity. In many situations, it has been less expensive to repower using CFB technology than to equip old plant with modern FGD and other clean-up systems. Advantageously, repowering with CFB technology has often

Table 7 Czech CFB-based facilities		
Plant	Technology	Fuel
ČEZ Tisová	Two CFB boilers (86 and 100 MWe)	Sokolov brown coal. Up to 20% wood cofired
ČEZ Pořici	Two CFB boilers (2 x 55 MWe)	Brown coal, biomass
ČEZ Hodonin	Two FBC boilers (60 MWe and 45 MWe)	Local lignite, biomass
Ledvice 3	CFB boiler (110 MWe)	Bilina lignite, biomass
TW Trinec	Two CFB boilers (2 x 160 t/h steam)	Ostrava middlings, steam coal, coal sludges and blast furnace gas
Mlada Boleslav (Skoda)	Two CFB boilers (2 x 70 MWe)	Local hard coal
Kladno	Two CFB boilers (2 x 124 MWe)	Local hard coal
Zlin	Two CFB boilers (25 MWe and 30 MWe)	Local hard coal/brown coal

resulted in increased generating capacity from a particular site. Major CFB projects are in place at a number of power/co-generation plants (Table 7).

3.4 IGCC

The Czech Republic's only coal-based IGCC is the Vresova power plant (Figure 5), located at the former gas works belonging to Sokolovska uhelná (SUAS). Here, two 200 MWe gas turbines are fired on syngas produced by 26 old fixed-bed gasifiers. These consume ~2000 t/d of coal and can produce ~200,000 m^3/h (~4,700,000 m^3/d) of raw gas. However, this is equivalent to only around 70% of the plant's total electrical output, and natural gas is sometimes added in order to help meet peak load demand. The system is regarded as highly flexible; for example, coal gas input can be increased from 70% to 100% of its maximum contribution in only five minutes (Collot, 2002).

Figure 5 The Vresova IGCC plant in the Czech Republic (photograph courtesy of Sokolovska uhelná)

Following cleaning, syngas produced is fed to the two combined cycle units, each with a net output of 185 MWe; 128 MWe is produced by a dedicated GE 9E gas turbine, and 57 MWe by a steam turbine. Plant emissions of SO_2 and NOx are controlled using a SNOX combined control system. In 2006, a new 140 MWth entrained flow gasifier was added to the site by Siemens. This was installed to gasify some of the by-products generated by the Lurgi gasifiers. The new gasifier is of the full quench, cooling wall design, and operates at 28 MPa pressure and a temperature of 1400ºC. It started operations in June 2007 (Mills, 2007a). For several years, there have been suggestions of a switch to HTW gasification technology at Vresova, although to date, there has been no progress. Coal gasification continues to be carried out in Lurgi dry ash gasifiers. Trials co-gasifying coal and biomass are planned (Svoboda and Puncochár, 2008).

3.5 Cofiring activities

ČEZ aims to reduce its overall CO_2 emissions by replacing part of its coal burn with biomass. There are a number of projects in hand. These include cofiring biomass (such as wood chips) in its CFBC-based power plants at Hodonín, Porící, Ledvice and Tisová. For instance, since 2004, the CFB boilers of the latter have been fired on combinations of lignite and up to 20% (by weight) of wood chips.

There are also two projects being developed, fired solely on biomass (partial conversion of Dvur Králové heating plant, and a 5 MWe facility at the Hodonín power plant). It is anticipated that these activities will serve to stimulate development of the biomass market and help create a reliable and stable supply chain. ČEZ intends to increase its consumption of biomass to ~500 kt/y by 2012. In 2008, 360 kt of woody biomass (wood chips, saw dust) were co-combusted; overall production of electric power produced via co-combustion of coal and biomass in the country was more than 330 GWh (Svoboda and Puncochár, 2008).

3.6 CCT and CCS activities

Czech research is currently focused mainly on the activities of ČEZ, now a member of European Technology Platform on Zero Emission Fossil Fuel Power Plants. ČEZ plans both short-term and longer-term CCT projects based on use of indigenous lignite/brown coal and aims to adopt best available technologies in order to improve plant efficiency. It also intends to invest in the development of CCS and near-zero emission technologies, initially via pilot-scale activities. A commercial-scale project is expected post-2020.

The company aims to have a CCS pilot plant operating within the next decade (Voosen, 2007). In 2007, ČEZ proposed that the Republic use some of its Kyoto (AAU – Assigned Amount Units) emission credits to help develop a carbon capture project that incorporated geological storage; possible options are reportedly being discussed with state administration authorities. However, the company is currently involved in an on-going initiative to build the country's first CCS demonstration plant. Two post-combustion carbon capture options are being considered, namely:

The North Bohemia Clean Coal demonstration project

This will be located at the new 660 MW brown coal fired SC PCC unit at the Ledvice site. An amine scrubber will capture CO_2 from plant flue gases. This will then be piped for storage in deep sedimentary aquifers in the Central Bohemian Permocarboniferous Basin. A start-up of 2015 has been suggested.

The Hodonín CO2 Separation Project

The Hodonin co-generation plant has a capacity of 105 MWe + 250 MWth, produced by two CFBC units (60 MW and 45 MW). Fuel is a combination of local lignite and biomass. An amine scrubber has been proposed, with CO_2 storage in depleted oil/gas reservoirs or deep sedimentary aquifers. A potential start-up date of 2015 has been suggested (Budinsky, 2008). There appears to be potential for EOR application in the Hodonin area (AF Power, 2008).

In the area of CO_2 storage, the Czech Republic has been involved as a partner in the EU GeoCapacity project, represented by the Czech Geological Survey and ČEZ Group. The latter is examining the feasibility for geological storage as part of the North Bohemia Clean Coal post-combustion capture project. The company is capitalising on its mineral exploration activities (such as core drilling) as a mechanism for collecting and analysing information useful for the characterisation of sub-surface geology (Budinsky, 2007). Although the country has several areas potentially suitable for CO_2 storage, CEZ is reportedly interested primarily in the depleted South Moravian oil fields surrounding Hodonín.

4 France

There is no longer any deep coal mining in France, although in 2006, a new opencast site and 1 GW coal-fired power plant was proposed; it was suggested that this was could be operational by 2011. Coal continues to make a contribution in several industrial sectors (such as iron and steel manufacture) and power generation, although most of France's coal requirement is met via imports. In 2008, this amounted to 21.4 Mt of hard coal, sourced primarily from countries such as the USA, Colombia, South Africa and Australia (Euracoal, 2009). However, as France relies heavily on nuclear power for much of its electricity, coal generates only 4% of the country's total. France is the world's second largest generator of nuclear energy (after the USA). Typically, recent annual generation has amounted to ~574 TWh of which, nuclear generally provides 78–80%, natural gas 4%, oil 1%, coal 4%, and other systems ~12%. EdF relies on its nuclear capacity for baseload operation, using its thermal plants to meet peak requirements. Hydropower is used for both.

The largest generators are EdF and E.ON AG; in 2008, E.ON acquired a 65% stake in Endesa France/SNET. France's total generating capacity is 116 GW, the bulk of which is nuclear based; EdF operates 59 nuclear reactors with a total capacity in excess 63 GW. The balance comprises mainly 25 GW hydro and 26 GW fossil fuel. As a result of its relatively low generating costs, the country exports a considerable amount of electricity from its nuclear plants. Annually, EdF exports 65–70 TWh to Belgium, Germany, Italy, Spain, Switzerland and the UK. Much of the nuclear fleet is nearing the end of its operational life. However, the French Government plans a significant expansion of the sector; this will include the upgrading of some existing facilities and the construction of a series of third generation reactors. For instance, EdF is currently building a new 1650 MW nuclear unit at Flamanville, Normandy, alongside two existing 1300 MW units, scheduled for completion in 2012.

Considerable manufacturing expertise has been developed by the French manufacturer Framatone, responsible for the supply of much of the country's nuclear infrastructure. Thus, reactors, fuel products and services also form a major export. Several major French technology suppliers are also becoming increasingly involved with technology transfer to developing nations. For instance, during 2009, collaborative links were created between France and India in the area of CCT knowledge sharing. As part of this, the Indian Government foresees a significant role for French companies (such as Alstom and Areva) in the country's energy sector. Alstom, as a major international technology developer and supplier (and already having a tie-up with BHEL in India) is expected to become increasingly involved in the transition of the Indian power sector from subcritical to SC PCC technology. Alstom has also become increasingly involved with developments in China's growing markets and has formed a joint venture company with Beijing Heavy-duty Electric Machinery Plant, creating Alstom Beizhong Power (Beijing) Co Ltd. This is claimed to be the only company in northern China capable of designing and producing 600 MW subcritical, supercritical and ultra-supercritical steam turbine power generation units. This new venture was followed by acquisition of a 51% stake in the Chinese Wuhan Boiler Company. Alstom is supplying Wuhan with several technologies that include SC PCC, CFB and low NOx burners. The joint venture is producing 600 MW and 1000 MW SC and USC boiler sets. Alstom also manufactures 600 MW steam turbines in a facility near Beijing (Mills, 2008).

4.1 Coal-fired power plants

France has a total of ~11 GW of coal-fired plants. These comprise mainly conventional PCC plant using subcritical steam conditions, although there are also two CFB-based power plants (*see below*). PCC unit capacity varies between 60 and 600 MW with many plants using combinations of differently sized units. For instance, EdF's coal- and oil-fired Cordemais station uses a combination of 585, 600 and 700 MW units and the Le Havre station uses units of 250 and 585 MW.

Some coal-fired plants have been upgraded and fitted with modern emission control systems. EdF is in the process of reducing atmospheric emissions of its coal-fired stations by 30–40% through the use of low ash coals, fitting FGD units, and adopting NOx control measures (for instance, the Cordemais and Le Havre stations are being equipped). Some major stations such as Cordemais, Emile Huchet, Le Havre and Provence have already been equipped with FGD systems. NOx control measures have also been applied at some stations. Cordemais, Emile Huchet and Provence now operate SCR systems, overfire air is used at Blenod, and low NOx burners have been fitted to stations such as Vitry en Seine (CoalPower).

Despite the country's heavy reliance on nuclear power, recent years have seen several new coal-fired plants proposed. In 2008, Endesa France announced plans for a zero-emission 700 MW plant based on clean coal technology at Le Havre; no details have been revealed about the type of technology proposed.

There has also been a proposal by French energy company Seren to re-open an opencast mine in Lucenay-les-Aix in the Nievre area. This would provide coal for a proposed 1 GW power station. The cost for the mine and power plant would reportedly be around €1.4 billion. A notional commissioning date of 2011 has been suggested. However, the current status of both projects is unclear. This is set against a background of reports (mid 2009) that France intends to close half of the coal-fired capacity operated by EdF and E.ON France by 2015. This forms part of a plan to reduce national energy consumption, cut CO_2 emissions, and more than double the share of energy from renewable resources by 2020. Closed capacity would be replaced with gas-fired and other plant. Reportedly, the French Government will not sanction the construction of any new coal-fired plants that do not include CCS capabilities.

4.1.1 Supercritical PCC plants and proposals

Although there are no SC power plants operating in France, in 2009, EdF became involved with the use of the technology for power generation in China. The company received the approval from the Chinese authorities to acquire a 35% holding in a joint venture with Chinese partners to operate two 600 MW units of a SC coal-fired power station at Sanmenxia in Henan, brought on line in 2007.

There is also considerable experience in all forms of coal-fired power generation technologies (including SC systems) in France through the presence of the major international supplier Alstom. The company is one of the biggest global suppliers of power plant equipment and has supplied more than a quarter of the world's installed generating capacity (Mills, 2008).

4.2 CFBC plants

For some years, there have been two major CFB-based power plants operating in France:

Emile-Huchet Unit 4, Carling, Lorraine

This 125 MWe (285 MWth) plant has been operating since 1990 when it was handed over to Charbonnage de France. At the time, it was the largest of its type in Europe. It is fired on high ash lump coal combined with tailings produced from coal washing operations. This is fed as a coal-water mixture comprising ~30% water and >40% ash. The CFBC was used to repower the site's existing PCC Unit 4. Steam conditions are 15.5 MPa/540ºC/540ºC.

Gardanne, Provence

In 1992, Alstom was awarded an EPC contract for a new CFB boiler to re-power one of the Gardanne power plant's units. When commercial operations began in 1995, at 250 MWe (557 MWth) capacity, this was the largest CFB in the world. Lurgi CFB technology was used. Originally fired on local lignite, more recently, the plant has also operated using imported hard coals and petcoke.

Other units

There are also several small coal-fired CFBC plants operating (Table 8) and several others use bubbling fluidised bed technology, firing predominantly municipal waste and biomass.

4.3 IGCC

None operating or planned.

4.4 Cofiring

In France, the use of cofiring is limited. The City of Grenoble operates the second largest district heating network after Paris. Five thermal plants, two of which are FBC-based (La Poterne plant – 72.5 MWth CFB; and the Villeneuve plant – 62 MWth, Ignifuid) supply heat to 75,000 dwellings. Some animal wastes ('flours') have also been utilised along with coal.

An industrial company (Nestlé/SOPAD) reportedly continues to operate a cofired Ignifluid unit in the north of country. This cofires coal with agricultural wastes for steam and heat production. In the French overseas territory of Guadeloupe, two 32 MWe FBC units cofire coal and bagasse (165 kt/y coal + 180 kt/y bagasse).

In 2007, EdF Trading, the subsidiary of utility EdF responsible for wholesale market activity, acquired biomass company Renewable Fuel Supply Limited (RFSL). RFSL provides a biomass procurement service and logistical and technical support to coal-fired power generation companies wishing to cofire biomass.

4.5 CCS activities

As more than 90% of France's electricity is produced by nuclear or hydro plants, the country has a very low level of CO_2 emissions per capita from electricity generation. However, efforts are under way to cut national carbon emissions. A target recently announced by the French Government aims to reduce carbon emissions by 22% (based on 2005 levels) by 2020. Part of this will be achieved by reductions in energy consumption, energy saving measures, and the greater use of renewable technologies.

A number of French organisations have been involved in recent major (coal and non-coal based) CCS-related programmes (Table 9).

Table 8 French CFBC plants (IEA-FBC, 2002)

Operator	Date of installation	Supplier	Output	Fuel(s)
City of Grenoble	(2 plants)	Foster Wheeler, Ignifluid	72.5 MWth, 63 MWth	Coal, wood
Cofreth/Massy	1990	Foster Wheeler/CNIM	2 x 10 MWe co-gen	Coal, oil
Somedith/Marseilles	1988	na	50 MWth	Coal
Nestlé France (SOPAD)	na	Ignifluid	na	Coal, biomass (coffee grounds and pods)

Table 9 French involvement in major EU programmes and projects

Project/programme	Organisation(s)
EU GeoCapacity	Bureau de Recherches Géologiques et Miniéres (BRGM),
Institute Francaise du Petrole (IFP)	
Snohvit (Snow White) LNG Project	Gaz de France
Lacq pilot project CO_2 storage/oxy-fuel	Air Liquide, IFP, BRGM, TOTAL
GESTCO	CGF (as subcontractor)
RECOPOL	IFP, Gaz de France
NASCENT	Bureau de Researches Geologiques et Minerales (BRGM)
Coal Bed Methane Recovery ICBM	IFP
Underground Disposal of Carbon Dioxide (JOULE II)	BRGM
Weyburn CO_2 Monitoring Project	BRGM
EC-Weyburn	BRGM
PICOR	IFP, BRGM, TOTAL-FINA-ELF, Universities of Bordeaux, Grenoble, Montpellier, and Toulouse
CO2STORE	Total, BRGM, IFP
CASTOR,	IFP, GDF, Alstom Power
CRUST (ORC-PROJECT)	Gaz de France
PICOREF	Air Liquide, Alstom, CGG, Gaz de France, SNET, Total, BRGM, IFP, INERIS, LAEGO, School of Mines (Saint-Etienne), ICMCB-CNRS, Universities of Toulouse, Grenoble and Montpellier

4.5.1 Oxyfuel combustion

In mid 2009, what was claimed to be the world's first retrofit of a power plant with CCS technology began operating at Total's gas-fired Lacq plant in the south of France. The Lacq pilot was the first CCS project in Europe to incorporate CO_2 pipeline transport and storage. The €60 million project has entailed converting one of the five steam boilers of the Lacq field's steam generating plant to oxyfuel combustion (Aimnard, 2007). Alstom was responsible for retrofitting the 30 MWth conventional gas-fired boiler for oxyfiring combustion via the installation of four special 8 MW burners. CO_2 captured is compressed then transported through a 27 km gas pipeline and injected at a depth of 4500 m in the nearly-depleted Rousse natural gas reservoir in the Lacq area. The pilot plant produces 40 t/h steam for use by the industries of the Lacq complex, and will generate up to150 kt of CO_2 over a two-year period. Construction work was completed in January 2009 and the plant was inaugurated in January 2010. A two-year test period is now under way. The project partnership comprises Total, Air Liquide, the French Petroleum Institute, the French Bureau of Geological and Mining Research (BRGM) and Alstom.

5 Germany

Even though its share has declined over the past decade, hard coal and lignite remain Germany's main fuels for power generation. In 2007, the country's reserves of hard coal were estimated to be 118 Gt and its lignite reserves, 40.8 Gt. The country meets a significant proportion of its energy needs from these reserves. In 2008, 19.1 Mt of hard coal and 175.3 Mt of lignite was produced from deep and opencast mines. The hard coal industry is in the process of being restructured and there are currently seven operational deep mines in three areas (Ruhr, Saar and Ibbenbüren coalfields). The Ruhr is the most productive, producing ~75% of the country's output. Lignite production is centred in four mining regions, all of which rely exclusively on opencast techniques. As a result of its availability and cost, lignite is of critical importance to the country's energy supply. It is used mainly for power generation (~165 Mt/y, around 92% of total lignite production). Overall, lignite accounts for around a quarter of Germany's electricity generation.

Even though German coal output remains considerable, the country still imports hard coal. In recent years, this has amounted to >40 Mt/y. Imports have come from many countries, although the biggest suppliers are currently Poland, Colombia, South Africa, Australia and Russia.

5.1 Power generation sector

Total installed generating capacity is currently ~143.3 GW. This includes 27.7 GW of hard coal-fired plants, and 20.4 GW of lignite-fired. In 2007, total power supply amounted to 633.8 TWh; of this, hard coal-fired capacity generated 142.3 TWh and lignite-fired plants, 156 TWh. Annually, the amount of coal used by individual stations varies between 500 kt and >2 Mt. Most German coal-fired stations are based on variants of pulverised coal technology, many using subcritical steam conditions. However, there is a growing a number that have adopted supercritical conditions. There is also a sizeable level of capacity based on fluidised bed technology.

5.1.1 Power plant modernisation

Around a quarter of Germany's power plants will require modernisation in the near future. It is estimated that the German electricity industry needs to spend some €40 billion over the next 10 to 20 years in order to replace its outdated generating plant. For more than a decade, many German coal-fired (both lignite and hard coal) generators have been engaged in programmes to modernise their respective power plants. Generally, these efforts have increased plant efficiency, extended plant lifetime and reduced CO_2 emissions.

Depending on the particular plant, a number of modernisation and upgrading measures may have been applied. In many cases, several have been undertaken simultaneously. For instance, typical of many, efficiency of E.ON's 30-year old (>200,000 hours operation) 350 MW Farge Power Plant in Bremen was improved by a series of measures that included:

- new IP/LP steam turbines (rotors and inner casings);
- new upgraded condenser;
- maintenance/overhaul of HP turbine;
- flow optimisation of FGD unit;
- flow optimisation of superheater;
- soot blower optimisation.

This has extended plant lifetime and advantageously, increased output by 27 MW. Efficiency has been boosted to 42% (LHV) (Bednorz, 2006). Many similar upgrades have also been undertaken at other coal-fired stations.

All major German coal-fired power plants are well equipped with emission control systems. To reduce SO_2 emissions and meet stricter requirements, many were retrofitted with FGD systems during the 1980s and 90s. The most widely applied process is wet scrubbing using lime/limestone, with gypsum as a by-product. However, there is also some use of other systems such as spray dry scrubbers. NOx emissions are generally controlled using a range of techniques that include the use of primary measures, low NOx burners, SCR, SNCR, overfire air and reburning with natural gas. Particulates are captured using mainly ESPs, with a few fabric filters.

5.2 Supercritical PCC plants and proposals

Germany has a number of SC power plants operating, the first having being completed during the 1990s. These use 500 MW units with main steam conditions of 26.2 to 26.8 MPa and temperatures of between 545ºC and 554ºC. Reheat temperatures are all about 580ºC. The country is currently investing in over 10 GW of new advanced supercritical coal-fired power stations.

In 2002-03, RWE Power's 1000 MW lignite-fired **Niederaussem K** unit went commercial (Figure 6), one of the largest supercritical units operating in the world. Lignite is fired in a SC tangential wall fired sliding pressure tower boiler, using main steam conditions of 27.5 MPa and 580ºC, with reheat to 600ºC. It is the world's most efficient lignite-fired plant. Through the use of various innovative plant design features, Niederaussem K successfully fires lignite of over 50% moisture content, whilst achieving a net efficiency of more than 43% (LHV, net). This is achieved through the use of high steam conditions and advanced steam turbine, elaborate feedwater heating circuit with final feedwater temperature of 295ºC, heat capture for feedwater heating from the by-pass economiser, low turbine exhaust pressure through use of a high cooling tower for a cooling water temperature of <15ºC, effective low temperature heat recovery from the flue gas through the flue gas cooler, and low plant power consumption by using high efficiency electrical drives and minimising fan power demand through reducing combustion air requirement (Henderson, 2008).

Figure 6 The lignite-fired Niederaussem power plant in Germany (photograph courtesy of RWE Power)

A further important feature is the large-scale demonstration plant that dries 25% of the lignite fuel feed (a flow equivalent to 250 MW) enabling higher efficiency. Moisture is reduced from >50% to12%. This reduces the energy penalty of drying and raises efficiency further. The drying process (the WTA process) uses a fluidised bed system to dry incoming lignite. Only low grade (110–120ºC) heat in the form of low pressure steam is used to dry the lignite; much of the latent heat in the issuing stream is recovered in a feedwater heater. When fully operational, the WTA system will increase efficiency by around one percentage point and reduce CO_2 emissions by more than 250 kt/y. On a 1 GW lignite-fired plant, CO_2 emissions could be reduced by ~1 Mt/y. Applied to the full fuel flow of a lignite plant, the WTA system would raise efficiency by ~4 percentage points (Henderson, 2008).

There are currently several other SC/USC PCC plants at various stages in their respective development (Blue Wave/IEA CCC, 2007). Most are due on line between 2009 and 2011 (Table 10). These include the proposal by E.ON to construct a 500 MW plant on the North Sea coast at Wilhelmshaven (*see below*), with an efficiency of 50% (LHV). Typically, expected SC plant efficiencies range between 40% and 45%. Several other projects are at the planning stage or in early development. From 2010, construction of new RWE power plants, as well as modernisation of existing units, will be undertaken by the newly-formed Essen-based company RWE Technology GmbH. The advanced USC PCC 500 MW 700ºC **Wilhelmshaven 50+ project** is planned by E.ON, at a cost of €1 billon, on the German North Sea coast. This aims to achieve an efficiency of at least 50% (LHV), primarily through the use of very high steam conditions (35 MPa/700ºC/720ºC) coupled with the use of cold cooling water from the North Sea. Advanced new materials of construction, capable of withstanding such high steam conditions, are being developed and tested as part of the COMTES 700 project in the Scholven power plant. Nickel-based materials will be used for the manufacture of many of the plant's critical components. Globally, state-of-the-art coal-fired plants can currently achieve efficiencies of ~46%, although the overall German average is 38%. Increasing plant efficiency from 38% to >50% would reduce coal requirement and significantly reduce CO_2 emissions (roughly a third less). Imported bituminous coals will be used in the new plant. Planning of the Wilhelmshaven plant has been completed and construction was scheduled to begin in 2010, with commissioning and operation planned for 2014. However, reports (in May 2010) suggest that the project will be delayed and the commissioning date pushed back.

Several major German and EU programmes have been instrumental in the development of advanced alloys and other materials suitable for use in very high steam conditions. Some activities remain on-going. Major projects have included the German COORETEC initiative, which examined the use of existing materials for temperatures between 620ºC and 700ºC, and the European Thermie Advanced 700ºC PF Power Plant research project (AD700), a major aim of which is the development of superalloys for USC steam conditions of >37.5 MPa/700ºC. The 15-year project involves more than thirty manufacturers, power generators and other organisations. Funding has been provided by the European Commission and a number of national governments. The project is progressing via several main stages (materials development, COMTES 700 test facility; and NRWPP700 power plant specification), culminating in the construction and operation of the 50+ Wilhelshaven plant.

Materials-related work is also being carried out under the German MARKCO programme. There has been strong national investment in this and VGB is funding the long-term characterisation of advanced 9–12% Cr steel components under its VGB 158 project. As an extension of the EU COST activities, several projects have been initiated to determine the oxidation behaviour of 9–12% Cr steels through exposure of samples at 30 MPa/650ºC in an operating power plant (Komet 650 project) and the extent to which coatings may be able to improve them (EU project 'Supercoat').

Siemens currently produces steam turbines in Germany capable of operating at ultra-supercritical conditions of up to 30 MPa/600ºC/620ºC.

5.3 CFBC

Atmospheric pressure CFBC technology has been well established in Germany for many years, operated by various industrial companies and power generators. There are around 40 plants that generate electricity, operate as co-generation plants, or raise steam for industrial purposes. Some are fired on bituminous coal, some on lignite and others on combinations of coal and biomass and/or wastes. A typical example of a bituminous coal-fired plant is that of Energieversorgung Offenbach, where two 25 MW units supplied by Lurgi generate power and supply heat to a district heating scheme. Stadwerke Duisburg operates a CFB-based co-generation plant in a similar manner; here, various biomass materials are cofired with coal. Historically, CFB units have been supplied by a number of technology suppliers that have included Lurgi/LLB, Foster Wheeler, Riley Stoker, Deutsche Babcock, Steinmueller, Alstom, and EVT.

Table 10 German supercritical PCC power plant projects

Client	Location	Capacity, MWe	Schedule	Coal type	Comments
Vattenfall	Boxberg R	675	Start-up 2011	Lignite	Rafako supplying boiler Steam conditions of 28.5 MPa, 600/545/581°C Expected efficiency >43% (LHV)
Vattenfall Europe Generation/ Hitachi Power Europe	Moorburg	2 x 820	Start-up 2010	Lignite	Rafako of Poland contracted with Hitachi for supply of pressure parts Steam conditions of 30.5 MPa/600°C, reheat 6.5 MPa/610°C
RWE Power	Neurath BoA project	2 x 1100	Start-up 2009-10	Lignite	Units 2 and 3 Hitachi boiler Steam conditions of 27.2 MPa, 600/605°C Alstom Brno is supplying pressure parts and steam turbine islands and carrying out overall plant engineering Incorporates lignite drying unit
RWE Power	Westfalen, Hamm	1600	Construction started in 2008 Start-up 2011 and 2012	Hard coal	Joint ownership of RWE + 23 municipal authorities (350 W share) Estimated cost €2 billion Steam conditions 31.4 MPa/610°C/625°C 46% efficiency Alstom will supply complete boiler islands and other equipment Will save 2.5 Mt/y CO_2 cf to conventional PCC plant Being built capture ready
Vattenfall	Walsum 10, Duisburg	750	Commission 2009-10 Start-up 2011	Lignite or hard coal	Turnkey contract awarded to Hitachi Power Europe in 2006. Hitachi turbine Steam conditions of 29 MPa/603°C, reheat 7.5MPa/621°C Rafako supplying boiler
E.ON	Datteln Unit 4	1100	Construction 2007 onwards Start-up 2011	Imported hard coal	Hitachi supplying boiler ABB supplying plant control system. Steam conditions of 28.5 MPa/600°C, reheat 7.8 MPa/620°C 3000 t/h steam Total project cost €1.2 billion (in 2006)
E.ON	Wilhelms-haven	500	Start-up 2014	Traded hard coals	Steam conditions 700°C Anticipated 50% efficiency Cost €1 billion Located on North Sea coast to use cold sea cooling water – will help achieve 50%
EnBW (EDF)	Karlsruhe	890	Start-up 2011	Hard coal	Alstom supplying once-through SC tower boiler – 31 MPa, 603/621°C. 2347 t/h steam Alstom steam turbine
STEAG	Herne Unit 5	750	Start-up 2011	Hard coal	Project on hold

5.4 Pressurised Fluidised Bed Combustion (PFBC)

In Cottbus, Stadtwerke Cottbus GmbH operates a lignite-fired (bubbling bed) PFBC co-generation plant. This has a total nominal output of 71 MWe (17 MWe from the gas turbine) plus 220 MW of steam and hot water for use by local industry and in a district heating scheme. Efficiency is around ~46–47% (LHV). The plant, based on a P200 module, was supplied by ABB during the late 1990s at a cost of US$230 million. The P200 boiler delivers steam at 14.2 MPa /537ºC to the high pressure turbine. After expansion, the steam is reheated and supplied, also at 537ºC, to the IP/LP steam turbine. Two oil/gas-fired peak load boilers are also available at periods of high demand. Commercial operations began in 1999. In 2002, a project team was formed to improve plant operation and increase availability. The plant was one of the last built using the technology as, in 2000-01, ABB Carbon abandoned its PFBC technology as a result of poor commercial prospects and corporate restructuring.

5.5 IGCC plants and proposals

There are two German IGCC projects, one operational and one proposed. The first is the Schwarze Pumpe plant where coal and various feedstocks (such as wastes, biomass and lignite) have been gasified for some years. The waste materials have included demolition wood, used plastics, sewage sludge, auto-fluff, MSW, waste oil, paint and varnish sludge, mixed solvents, tars, and on-site process waste streams. These have been gasified in the site's three different gasifiers. These three units operate in an integrated fashion, producing syngas that is converted to methanol and used to generate electricity. They comprise:

- an oxygen-blown, 25 MPa, 14 t/h FDV rotating grate unit;
- an oxygen-blown, 25 MPa, 35 t/h BGL slagging gasifier;
- an oxygen-blown GSP 15 t/h entrained flow gasifier.

Recent years have seen the plant suffer from a number of financial problems and resultant changes of ownership.

In late 2008, RWE AG (with partners BASF and the Linde Group) confirmed its intention of developing a 450 MW (gross) lignite-fuelled IGCC + CCS power plant to be built at the Goldenbergwerk site in Huerth near Cologne. A 1000 MWth entrained flow quench gasifier operating at 40 MPa pressure is proposed. A 295 MW F-class gas turbine and a 160 MW steam turbine will be used. The IGCC plant will incorporate a lignite drying process (WTA – developed by RWE) prior to gasification. The plant will be fuelled on Rhenish lignite. Net plant efficiency is expected to be 34% (LHV). About 90% CO_2 capture is envisaged (total of 2.3–2.6 Mt/y). Storage options in Schleswig-Holstein are currently being investigated – these are focusing on the potential of deep saline formations and explorative drilling is under way in the region. A suitable storage formation could also be used to accept CO_2 from other power stations in the locality.

An estimated €2.12 billion will be required for the IGCC plant, CO_2 pipeline and storage facility. RWE has so far committed €1 billion towards this (€800 million for the power plant and €200 million for the pipeline and storage operations). Initial plant construction activities reportedly began in late 2008 and RWE suggested plant commissioning by the end of 2014, with a start-up date in 2015. However, in November 2009, the project was reportedly put on hold.

5.6 Cofiring activities

In Germany, more than 20 plants have cofired various biomass and wastes with coal for power and co-generation purposes. A number have been cofiring continuously since the mid 1990s, whereas others have so far carried out test programmes. Around 20 plants cofire dried/dewatered sewage sludge. The largest cofiring capacity is that of the Weisweiller RWE plant, capable of firing 140 kt of dewatered sewage sludge with brown coal. Sludge represents 7.5% (wt) of the fuel feed (Fernando, 2007). Various other feedstocks are also cofired with hard coal or lignite in PCC stations, these including refuse-derived fuel, wood and straw (IEA Bioenergy, nd).

Cofiring activities are not limited to conventional PCC plants, as a number of CFBC units also cofire. For instance, meat and bone meal (MBM) has been cofired at Rethmann Lipperwerke's (78 MWth) CFB plant at Lünen where it provided up to 50–60% of the thermal input.

5.6.1 Oxyfuel combustion

Vattenfall 30 MW pilot project

Since mid 2008, Vattenfall has been operating a 30 MWth oxyfuel pilot plant near the 1600 MW coal-fired Schwarze

Figure 7 The oxyfuel boiler assembly of the Schwarze Pumpe pilot plant in Germany (photograph courtesy of Vattenfall)

Pumpe power plant at Spremberg, Brandenburg, to the south of Berlin (Figure 7). This forms part of Vattenfall's programme to develop and commercialise oxyfuel technology and is viewed as a crucial stage in scaling up the technology for a 250–350 MW near-zero emission demonstration. The main objectives of the Schwarze Pumpe project include validation of engineering techniques, improved understanding of oxyfuel combustion dynamics, and a demonstration of the capture technology. The initial test programme will run for three years although the plant has a planned lifetime of at least a decade. The programme will focus predominantly on the optimisation of oxyfuel technology within the plant's major components. The pilot plant incorporates the complete process chain, as required for a full-scale power generation plant. This includes steam generator, ASU, ESP, FGD, flue gas clean-up system, and CO_2 treatment plant. This approach allows the testing of each component of the full capture chain and the interaction of the different components in terms of start-up, shut-down, load change behaviour, and switch from air to oxyfuel combustion. However, as already well-established technology, no steam turbine is used.

The plant's steam generator produces ~40 t/h of steam at 330ºC and 25 MPa; this requires 5.2 t/h of pulverised lignite and 10 t/h of oxygen. At full load, ~9 t/h of liquefied CO_2 is produced. Alstom supplied the plant's steam generator and ESP. In 2009, Air Products joined the project; they are concentrating on installation of their CO_2 capture technology and the purification and compression of the oxyfuel coal gas. During the course of the programme, a range of lignites and hard coals will be tested. Other factors to be addressed include coal moisture content, variation of excess oxygen content (1–5%), variation of flue gas recirculation rate, and variation of oxygen content at different burner registers. CO_2

Table 11 Major German post-combustion capture projects and proposals (Santos, 2009; Henderson and Mills, 2009)

Participants	Location	CO_2 capture	Status/Comments
RWE Power AG, BASF, Linde Group	Niederaussem pilot, Bergheim	Pilot start-up 2009 ~7 t/d CO_2 capture	Lignite-fired plant Testing of new developments and new BASF solvents Estimated cost of project €80 million
E.ON, Cansolv Technologies	Heyden power plant pilot (7.5 MW)	Amine-based scrubber to treat 1% of plant's flue gas (for 2–3 years)	Optimisation of CO_2 capture and minimisation of energy consumption Also investigation of various plant construction methods
E.ON, Fluor	Wilhelshaven pilot (5 MW)	Econamine FG+ MEA scrubber Start-up 2010 (for 2 years)	Investigation of various plant construction methods
E.ON, MHI	Unnamed German power plant (7.5 MW)	100 t/d CO_2 capture using KS-1 Start-up 2010 (for 2 years)	Investigation of various plant construction methods
E.ON, Siemens	Staudinger Power Plant, Unit 5	Solvent testing on 1 MW slipstream.	To operate between 2009 and 2010 Further developments up to 2014
E.ON, Electrabel, Hitachi Power Europe	Pilot – on E.ON and Electrabel power plants	na	Moveable test unit Solvent development and testing at different locations
Vattenfall	Jänschwalde power plant (lignite)	Joint oxy-fuel and post-combustion project Several potential storage/pipeline options being evaluated	Construction due to begin in 2011 Plant operation in 2015
DONG Energy	Greifswald	na	Hard coal fired Proposal Up to 8 Mt/y CO_2 capture and storage Pipeline transport

captured from the plant (90% capture target) will be transported by truck to the Altmark natural gas field in Northern Germany, Europe's largest on-shore field. During the three-year trial, CO_2 will be injected into depleted gas reservoirs to determine if the field's lifetime can be extended.

During the pilot plant's first year of operation, CO_2 capture rate exceeded 90% (estimated 98% achievable) and purity was ~99.7%. A total of 1700 t was captured. There are plans to inject a total of ~100 kt CO_2, although the Altmark formation has an estimated storage capacity of 600 Mt. In addition, Vattenfall and the Linde Group are co-operating to develop further possible applications for some of the CO_2 from the plant. Linde will take delivery of ~4000 t/y of liquefied CO_2 and market it. If the pilot trials confirm that the Altmark field is suitable for large-scale operation, it will be used to store CO_2 from a large-scale oxyfuel demonstration plant, expected to be operational by 2015. From this time, around 1.5–2 Mt/y CO_2 will be transported to the field by pipeline for storage.

Vattenfall Jänschwalde 'double demonstration' project

Data produced by the Schwarze Pumpe pilot plant will be directed towards a scaled-up demonstration project at the 3 GW lignite-fired Jänschwalde power plant. Construction of this is scheduled to begin in 2011. Commissioning of the flue gas scrubbing plant, oxyfuel plant, pipeline and storage site is planned for 2013-14. A new oxyfuel boiler of ~600 MWth, equivalent to 250 MWe (gross) will replace one of the site's existing boilers. It will be fired on pre-dried local lignite. Both oxyfuel and post-combustion capture concepts will be investigated and the block's other boiler will be suitably retrofitted. This twin demonstration unit will begin supplying CO_2-lean electricity to the grid in 2015. Feasibility studies for the Jänschwalde demonstration plant are under way, along with planning and permitting activities.

CO_2 captured from the plant will be piped to a suitable storage location, several of which are currently under consideration. These include the Birkholz-Beeskow and Neutrebbin areas, where sedimentary rock formations were screened between 2004 and 2008, and several possible (aquifer) sites in Brandenburg. Verbundnetz Gas and Schlumberger are also involved with these investigations that are due to be completed in 2010. Around 1.5–2 Mt/y CO_2 is expected to be captured and stored. Several possible routes for the CO_2 pipelines have been considered.

Since 2004, Vattenfall has also been considering its Boxberg IV station for an oxyfuel project (Santos, 2009).

5.6.2 Post-combustion capture

There are a number of post-combustion CO_2 capture projects being developed in Germany for application to coal-fired power plants, many based on derivatives of amine scrubbing. Most are treating flue gas from hard coal fired facilities, although some lignite-fired capacity is also being addressed. Major projects and proposals are summarised in Table 11.

6 Greece

Greece has only limited indigenous energy resources although the country does possess sizeable reserves of lignite. This is Greece's only significant fossil fuel source (6.8 Gt, of which 3.3 Gt are considered economically recoverable), representing more than 80% of the country's primary energy production. While Greece produces no hard coal, it is the second largest European producer of lignite after Germany. Since the 1950s, lignite has been mined exclusively by opencast methods. Most is used for power generation in minemouth power plants. Security of supply, low extraction costs and stable prices remain important factors in maintaining its strong position in the Greek energy market.

In 2008, Greek lignite production amounted to 66 Mt, produced mainly by the Government-owned Public Power Corporation (PPC) at the West Macedonia Lignite Centre (49.3 Mt) and the Megalopolis Lignite Centre (14.2 Mt). PPC produces ~ 95% of the country's lignite (OECD/IEA, 2006; OECD/IEA,2008). The quality of Greek lignite varies, depending on location, and ash content can range between 5% and >20%, and water content between 40% and 65%. To counteract these variations, different grades are sometimes blended in order to meet specified power plant requirements. Around 0.8 Mt/y of hard coal is also imported from South Africa, Russia, Venezuela and Colombia.

6.1 Power generation sector

Currently, around three-quarters of the country's electricity is generated by thermal power stations, predominantly lignite-fired. In 2008, total power generation (interconnected and Greek islands) amounted to 60.8 TWh. Lignite's share was 53.1%, with the balance coming mainly from oil (15.8%), gas (17.4%) and other systems (13.7%). Since the 1990s, Greek electricity demand has increased steadily and there is a projected need for an additional 6 GW of capacity by 2015; much of this is likely to be gas fired. It was recently announced that from 2013, PPC will need to spend up to €800 M/y on CO_2 emission rights. As a result, lignite use for power generation could reduce in the future.

6.1.1 Power plant modernisation programmes

In 2007, the Greek market for new thermal and renewable energy power plant projects and equipment was estimated to be US$1900 million. As a result of increased generating capacity and modernisation programmes, between 2005 and 2007, capacity grew at the rate of 10–12%/y, mainly via the construction of new units. According to the *2008-2012 Greek Energy Development Programme*, Greece plans to spend US$12 billion on the development and expansion of its energy sector during the period up to 2012, of which US$ 9 billion will be for new power plants. During this period, activity will focus mainly on the construction of new privately-owned thermal power plants, along with modernisation of several existing stations.

All existing lignite-fired power plants rely on PCC technology, mostly with units of ~300 MW. Many are now more than 30 years old and are the focus of modernisation efforts. PPC is engaged in modernising and/or enlarging a number of its coal-fired power plants (Table 12). It operates eight lignite-fired power stations, comprising 22 units, with a total installed capacity of 5.3 GW. The company plans to replace outdated lignite-fired capacity by 2020 (total of 2.5 GW). Average efficiency of older plants is low (<33%, LHV) although the country's two supercritical PCC plants are somewhat higher (*see below*).

A number of new privately-owned projects (some in conjunction with PPC) are also planned; some intend to use gas-firing, although a number of coal-based projects are also proposed. These include a lignite-fired plant by HELPE (Hellenic Petroleum, by 2012); a 600 MW unit in Astakos Aetoloakarnanias by Edison SpA; a 600 MW unit in Aspra Spitia, Viotias; and a 420–450 MW unit by TERNA in Madoudi, Evia region (Energy News, 2007; Export.gov, nd).

In recent years, several Greek plants have been equipped with limestone-gypsum FGD scrubbers (the 850 MW Megalopolis plant, the 330 MW Meliti-Achlada plant, and the Florina station). There are plans for several others to be similarly equipped. Greece currently produces ~1 Mt of FGD gypsum each year, utilised for wall board manufacture and as a cement additive.

6.2 Supercritical PCC plants and proposals

There are currently two SC PCC power plants in operation. The first to come on line (in 1997) was the 365 MW St Demetrious Ag Dimitrious lignite-fired facility; there are also

Table 12 Greek power plant enlargement and/or modernisation

Location	Fuel	Capacity, MW	Modernisation date
Megalopolis V	Gas/lignite	800	2011
Meliti II	Lignite	450	2012
Aliveri VI	Hard coal	700–800	2013
Kozani region	Lignite	250–400	na
Ptolemais	Lignite	450	2014
Larimna region	Hard coal	550–650	2014
Evia	Hard coal	na	2014-15

four subcritical units in operation at the site. In 2003, this was followed by the start-up of a new 330 MW lignite-fired SC unit at PPC's existing Florina plant. The SC boiler was supplied by LMZ of Russia and uses modest steam conditions of 24.2 MPa/543ºC/542ºC (CoalPower). Plant efficiency is reportedly ~38% (LHV). PPC is also considering a new 450 MW lignite-fired SC unit to be located in the Florina area and has also proposed new developments at Ptolemais, Larimna, Aliveri and Evia. Should these proceed, it is likely that SC PCC technology would be adopted.

An ENDESA-Mytilineos joint venture company (ENDESA Hellas) has proposed a clean coal 600 MW lignite-fired project at the Agios Nikolaus site in Viotia. The reported cost will be €890 million. In 2007, the company announced plans to have the new plant operational by 2013. However, it is unclear what impact the Government announcement (of February 2009) on the promotion of renewable technologies may have; this apparently ruled out investment in new coal-fired (or nuclear) power plants.

6.3 CFBC

Although not currently used in this way, Greek lignite has been evaluated as a suitable fuel for CFBC plants. Combustion tests have been carried out in three different CFBC facilities (in Athens and at RWE's Niederaussem power plant in Germany). Several co-combustion tests have also been undertaken using wood waste and other types of biomass. Results suggested that CFBC technology is well suited to the use of low rank Greek lignite (Kakaras and others, 2003). However, there is currently no commercial application.

6.4 IGCC

A number of studies have examined the suitability of Greek lignite for gasification and in IGCC cycles with CO_2 capture (for example, Elseviers and others, 1996, and Hatzilyberis and Androutspoulos, 2006). Kostas and others reported on two decades of experimental and theoretical work on the gasification of Greek lignite in a rotary kiln gasifier, with a view to scaling up to commercial-scale operation. Pilot plants operated by PPC and NTUA formed part of this programme. However, there are currently no major IGCC-related developments under way in the country.

6.5 Cofiring

Two Greek organisations are involved in the on-going EU seventh Framework Programme DEBCO project (Demonstration of large-scale biomass cofiring and supply chain integration). The project runs between 2008 and 2012 and aims to develop and demonstrate innovative and advanced technologies for cofiring biomass with lignite for large-scale electricity production and/or co-generation, at more competitive costs and/or increased energy efficiency. Goals are to increase current biomass utilisation levels (typically 3–10%) to 50% or more, in the process, reducing CO_2 emissions. Greek project partners include CERTH/ISFTHA and PPC. Co-combustion trials will be carried out during 2010 on one unit of PPC's Kardia lignite-fired power plant.

6.6 CCS-related activities

Fossil fuel-related CO_2 emissions account for ~55% of the Greek total. Levels have increased by around a quarter during the past decade, and by 2020 CO_2 emissions from the energy sector are projected to be 65% higher than in 1990. Compared to other European countries, Greek CO_2 emission intensity remains high. This results mainly from power generation, where lignite dominates and CCTs have yet to be adopted widely (ZEP Greece, 2007).

The Greek Energy R&D Administration is managed centrally by the General Secretariat for Research and Technology (GSRT), part of the Ministry of Development. This is the main authority responsible for the development and implementation of the overall framework for Greek R&D policy. Research for high-priority fields (such as energy) is conducted through different R&D consortia, helping to promote co-operation between partners and others. The Government sees a strong need to further support energy R&D in order to address issues associated with Kyoto commitments and domestic energy legislation. Energy-related activities are undertaken mainly by two Greek organisations: The Centre for Renewable Energy Sources (renewables, energy saving), and The Centre for Research and Technology Hellas (CERTH). The latter has two institutes active in energy, namely The Chemical Process Engineering Research Institute (energy conversion) and The Institute for Solid Fuels Technology and Applications – ISFTA (exploitation of solid

Table 13 Involvement of Greek organisations in major CCS-related programmes (Kakaras and Koukouzas, 2009; IEA GHG, nd)

Organisation	Project
Institute for Geology and Mineral Exploitation (IGME)	EU GeoCapacity
Institute for Geology and Mineral Exploitation (IGME)	NASCENT
Institute for Geology and Mineral Exploitation (IGME), PPC	GESTCO
Greek partnership (CERTH-NTUA-PPC)	ENCAP, CASTOR, CACHET, ISSC, C2H
CERTH/ISFTHA	CERCOT

fuels, implementation of CCTs, co-combustion and CCS) (OECD/IEA, 2006).

The Public Power Corporation is also active in the fields of CCT and CCS. PPC plans include a cofired coal/biomass combustion unit and there is also interest in coal bed methane production. PPC participates in the general assembly of the European Technology Platform for Zero Emissions Power Plants. The major national programme supporting CCS-related R&D is the Operational Programme *Competitiveness*, co-ordinated by GSRT (ZEP Greece, 2007). As well as PPC, there are several other Greek organisations that are, or have been, involved in major international CCS-related projects and programmes (Table 13).

With regard to CO_2 storage, several possible options (such as saline aquifers) have been assessed as part of the GESTCO project. Results suggested that the combination of one offshore and four onshore sites would provide a total capacity of 2345 Mt CO_2. The largest onshore sites were West Thessaloniki (459 Mt) and in the Mesohelleni Basin (360 Mt) (Kakaras and Koukouzas, 2009).

6.6.1 Oxyfuel and post-combustion activities

One of the Work Packages of the ENCAP CO2 project includes the investigation of concepts for a 380 MW Greek PCC oxyfuel (lignite-fired) power plant using advanced SC steam conditions (Anheden, 2008). Other studies have examined CO_2 control via the combination of partial oxyfuel firing coupled with post-combustion solvent scrubbing on a 330 MW lignite-fired Greek power plant (Doukelis and others, 2009). Further studies have determined the cost of electricity for a range of CO_2 mitigation technologies within a Greek context. These compared conventional lignite-fired PCC technology with amine scrubbing, oxyfuel firing, state-of-the-art SC PCC lignite firing, and lignite-fuelled IGCC (Kakaras and Koukouzas, 2009).

7 Hungary

Hungary's energy production structure is similar to that of many of the newer EU Member States, being based largely on the use of indigenous fossil fuels (lignite, brown coal, oil and natural gas). However, domestic oil and gas production has peaked and is expected to decline gradually. At present, the country imports around 80% of its oil and gas requirements, exclusively from Russia.

Total coal reserves are around 3.3 Gt (Euracoal, 2009). This comprises 2.9 Gt of lignite, along with both brown coal and hard coal of 0.2 Gt each (OECD/IEA, 2007). Lignite and brown coal reserves are concentrated mainly in the regions of Transdanubia and in the northern and northeastern areas. Typically, Hungarian lignite/brown coal has >40% water content and comprises ~20% ash. Annually, a total of around 10 Mt is produced, mainly for power generation purposes. Since 2005, the main production sites have been opencast mines in Vistona and Bukkabrany, and deep mines that supply the Vertes group of power plants. In 2008, a further 1.9 Mt of hard coal was also imported, mainly from Australia, Poland and Russia. Despite a reduction in the amount used since the political changes of 1990, coal retains a role for power generation and some industrial uses. The present level of coal use is forecast to be maintained until at least 2030.

7.1 Power generation sector

Hungary has a total installed capacity of 7.64 GW. A breakdown of larger units is given in Figure 8. Annually, ~40 TWh of electricity is produced, around 20% generated by coal-fired stations, four of which cofire biomass. Much of the balance comes from natural gas-fired stations (37%) and the Paks NPP nuclear power plant (37.6%). In recent years, the use of natural gas has also increased. There are a total of 18 individual generating units in operation (one nuclear, two gas/oil, four coal/biomass, seven gas, one coal, and three oil).

In the period up to 2020, around 6 GW of new generating capacity will be required to replace 4.5 GW of retired plant and to meet growing demand. Consequently, the Hungarian Government is encouraging the rapid construction of new plants. Many of these will be gas-fired, such as E.ON's new 433 MW combined-cycle power plant being built in Gönyü. However, it is envisaged that new coal- and renewable-based capacity will also be added. Any new coal-based plants are likely to adopt some form of CCT (Powermag-Hungary, 2009).

7.1.1 Power plant modernisation

Most of Hungary's power plants are now fairly old. The coal-fired units were built during the 1950s and 60s, most oil and gas plants during the 1970s, and the nuclear plant during the 1970s and 80s. The average age of the generation fleet is 21 years for larger stations, and 11 years for small-scale generators. Almost half of the generating capacity more than 25 years old, while over 21% is more than 30 years old. The advanced age of generating stations is the main reason for their relatively low efficiency (OECD/IEA, 2007).

Alongside plans for new power plants, efforts have been made to improve the performance and reduce the environmental impact of some of the existing PCC fleet. This has included RWE's 876 MW Matra co-generation plant, Hungary's largest thermal station. This comprises five PCC subcritical units (burning 8 Mt/y of lignite) plus two using natural gas. A major retrofit programme (boiler improvements, new burners, turbine upgrades) has increased plant output by 6%, extended its life by a decade, and assured compliance with EU environmental regulations. Emissions of NOx, SO_2, particulates and CO_2 have been reduced by the modernisation programme. SO_2 reductions were achieved by the installation of two wet limestone gypsum scrubbers, supplied by BBP Environment GmbH (CoalPower) and integrated into the interior of the two dry cooling towers (RWE, 2008). The Matra FGD units were the first to be built in Eastern Europe. These efforts allowed early compliance with EU emission standards and assured continued operation of the power station when Hungary became a member of the EU. A wet limestone-gypsum FGD plant (supplied by Lurgi Lentjes Bischoff GmbH) was also added in 2002 to the 240 MW Oroszlány power plant; this formed part of an environmental retrofit and was a precondition to comply with EU emissions limits and to allow continued operation after 2005.

Some oil and gas-fired plants have also been modernised. For instance, the US$126 million AES-Tisza Power II Plant refurbishment project has been completed, significantly reducing emissions of SO_2 and NOx, and extending the plant's life up to 2016. Similarly, the GDF-Suez Dunamenti plant is currently the focus for upgrading and modernisation. Alstom is in the process of installing a new steam turbine and

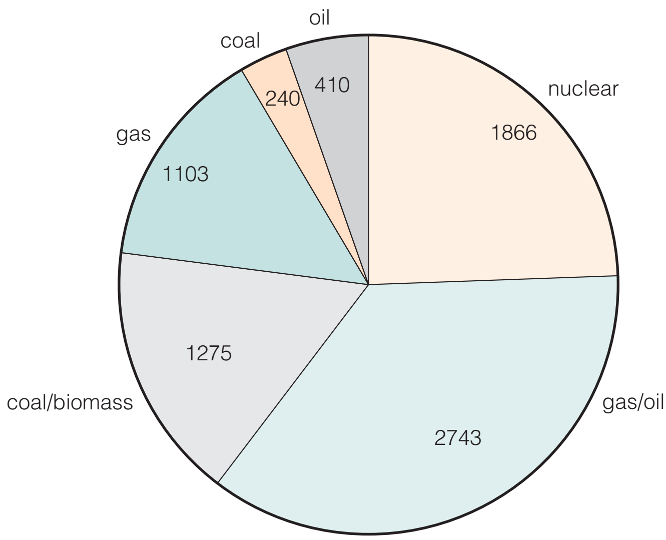


Figure 8 Larger-scale (>50 MW) generating capacity by fuel type (OECD/IEA, 2007)

upgrading others. A new gas turbine is also on order from Ansaldo. The various upgrades will result in a capacity increase of at least 200 MW.

7.2 CFBC

During the early 1990s, two units of the existing 102 MW brown coal fired Bakony co-generation/district heating plant were equipped with Hybrid-Fluid (HF) fluidised bed boiler technology. These remain operational.

7.3 Gasification and IGCC

There appear to be no significant Hungarian IGCC activities. However, an underground coal gasification project was announced recently (the Mecsek Hills Gas Project). Permitting for exploratory drilling has been granted for the site. There are coal reserves of between 1 and 1.25 Gt of coal, potentially suitable for UCG. The first prospective customer would probably be the nearby 183 MW Panon power station. An MoU is in place with the project developers, led by Wildhorse Energy.

7.4 Cofiring

Both the Oroszlány and Matra plants cofire biomass with coal. At the Oroszlány plant, in 2006 and 2008, two existing PCC boilers were modified to enable the cofiring of up to 30% biomass in the form of wood chips and agricultural by-products such as straw. There is a longer-term goal of achieving 50+% utilisation levels. At the Matra plant, RWE is engaged in on-going efforts to increase biomass levels (RWE, 2008).

A major programme (the Ajka Biomass Project) has also been undertaken at the Bakony co-generation plant where an FBC retrofit was carried out on two units of this conventional PCC plant; commercial cofiring operations began in 2004. Each 86 MWth FBC unit is now cofired. A programme of testing has evaluated a range of biomass feedstocks that have so far included agricultural (sunflower) wastes, bundled forest residues, rape seed pellets (biodiesel production by-product), different types of reeds, and materials from energy plantations. Most trials have been successful although there have been some operational difficulties (heating surface fouling) when using bran and straw (Kovács and Szics, 2007). In 2007, the plant consumed a total of 170 kt of wood, 40 kt of wood chips, and 30 kt of agricultural wastes.

Hungary is involved in the on-going EU NETBIOCOF cofiring project, being represented by NYME (Nyugat-Magyarországi Egyetem).

7.5 CCS activities

As elsewhere, a number of sectors are responsible for producing CO_2. However, the biggest is power generation. Major emitters are shown in Table 14.

Table 14 Major Hungarian CO_2 emitter allocations (under National Allocation Plan I) (OECD/IEA, 2007)

Operation	Sector	Annual allocation in Mt CO_2
Mátra lignite plant	Power generation	6.2
Dunaferr	Steel production	2.0
AES Tisza	Power generation	1.5
Százhalombatta	Refining	1.4
Dunamenti	Power generation	1.4
Vertes	Power generation	1.3
Total		13.8

Several government agencies are involved with CCS-related issues. The Ministry of Environment and Water deals with CO_2 emission permitting and the EU-ETS. Its Climate Protection and Energy Unit handles climate change policy and international reporting requirements for Hungary. This unit compiles the National Allocation Plan for the EU-ETS and is responsible for reporting to the UNFCCC. The Ministry of Economics and Transport is responsible for the formation of Hungarian energy policy. Reportedly, the general government policy with respect to CCT and CCS technologies is similar to that elsewhere in Europe. CCS has been nominated in the medium- and long-term energy strategy by the Ministry of Economy and Transport. However, Government funding for R&D remains limited. Some strategic research aimed at decreasing the country's overall CO_2 emissions is in hand (in 2009, this amounted to €25,000, 18 months duration). In the public sector, CCS-related topics are addressed by the Geophysical Institute of Hungary. No significant work appears to be being undertaken by Hungarian utilities or equipment manufacturers (ZEP Hungary, 2008).

Energy-related R&D in the private sector is limited to a handful of organisations that include Magyar Olaj-és Gázipari Rt (mapping, characterisation and estimating CO_2 storage options in Hungary, and clarification of technological requirements for its transport and storage), and Terra Humana Clean Technology Engineering Ltd. The latter develops clean solid multi-fuel uses for co-generation applications of less than 300 MWe through various routes such as biomass/clean coal cofiring. An estimated €100,000 is directed to energy R&D in the private sector.

7.5.1 CO_2 storage

As a landlocked country, Hungary is similar to some of its neighbours, in that it possesses three variants of geological formations potentially suitable for CO_2 storage. These comprise:

- depleted hydrocarbon fields. The Hungarian regulatory framework enables CO_2 storage in these. The estimated storage capacity of hydrocarbon fields is ~400 Mt CO_2, although some of the larger fields will remain dedicated to strategic underground gas storage. There may be some possibilities for EOR/EGR applications;

- unmineable coal seams. The geological and engineering information about unmineable coal seams is less comprehensive than that of hydrocarbon fields. Some potential locations are favourably situated close to coal-based power plants and there may also be the possibility of ECBM production. The estimated storage capacity of unmineable coal seams in Hungary is between 60 and 600 Mt CO_2;
- saline aquifers. These have not been well studied in Hungary. However, there are several formations that, potentially, could be used for the storage of CO_2. The preliminary estimates of storage potential in saline aquifers is 3000–5000 Mt CO_2 (ZEP Hungary, 2008).

Eötvös Loránd Geophysical Institute of Hungary (ELGI), the research institute of the Ministry of Economy and Transport, has participated in the CASTOR, EU GeoCapacity and CO2NET EAST projects. It is also a member of CO2NET and EneRG.

8 Italy

Coal is important for power generation although Italy currently relies almost entirely on imported supplies. In 2008, some 26.7 Mt of hard coal was imported from countries such as Indonesia, South Africa, and the USA. Overall, the country has a high energy import dependency of around 87%. Coal-fired power plants currently provide ~14% of the country's electricity. The balance is provided by gas-fired plant (52.3%), oil-fired stations (14.6%) and other systems such as renewables (19%) (Euracoal, 2009). Of a typical annual total of 314 TWh, coal-fired plants generate ~44 TWh.

8.1 Power generation sector

Italy has a total of 7.3 GW of coal-fired power generating capacity in operation. Until 2009, all was based on PCC technology using subcritical steam conditions (Table 15). However, since then, a CFB-based power plant has gone into commercial operation and several oil-fired plants have begun the process of switching to coal-fired supercritical operation (*see below*). In 2006, the coal-fired fleet average operating efficiency was ~39% (LHV), compared to the European average of 35% (Ruscito, 2006).

8.1.1 Power plant modernisation

During the 1980s and 90s, most coal-fired plants were rehabilitated in various ways, mainly by Ansaldo. ENEL plants thus treated were Bastardo, La Spezia, Turbigo, Fusina, Tavazzano, Monfalcone, San Filippo Mela and Vado Ligure. All received boiler modernisations and some had steam turbine and generator upgrades.

Table 15 Italian coal-fired power plants (2006)

Station	Capacity (MWe)
Brescia	70
Marghera	2 x 70
Vado Ligure	2 x 330
Genova	245
Fiumestanto	2 x 320
Sulcis *(see below)*	240
La Spezia	600
Fusina	2 x 170, 2 x 320
Monfalcone	2 x 170
Bastardo	2 x 75
Brindisi Nord	2 x 320
Brindisi Soud	4 x 660

All major coal-fired Italian power plants have had environmental upgrades. Since the 1990s, ENEL has invested more than €4 billion in emission reduction programmes. Between 2000 and 2005, emissions of SO_2 from ENEL plants fell by 64%, NOx fell by 33%, and particulates by 70% (Ruscito, 2006). SO_2 emissions are generally controlled by wet limestone FGD units or spray dry scrubbers. NOx is controlled using combinations of primary measures, low NOx burners, overfire air and SCR. Particulates are captured using ESPs. Recent years have seen further orders for FGD plants. In 2006, turnkey contracts were placed with MHI for multiple FGD units for the Torrevaldaliga Nord and Monfalcone power plants. These projects were completed in 2008. Several FGD-equipped plants have since been fitted with advanced wastewater (Zero Liquid Discharge Systems) control systems; these clean FGD purge wastewater prior to discharge. To date, five ENEL plants have been suitably equipped (Brindisi, Fusina, La Spezia, Sulcis and Torrevaldaliga).

8.2 Supercritical PCC plants and proposals

There are currently three Italian oil-fired power plants at different stages in their conversion to coal firing. These are installing PCC technology (total of 3.7 GW) and adopting SC steam conditions.

At ENEL's **Torrevaldaliga Nord** power plant in Lazia, three coal-fired 660 MW USC PCC units have been installed at a cost of €2 billion. Supercritical once-through Benson boilers were supplied by a consortium comprising Babcock Hitachi/Ansaldo Caldaie/Demont, and MHI supplied new steam turbines. Main steam conditions are ~25 MPa/604ºC with reheat at 612ºC. Initial firing took place in June 2008, and the first two units went on line in 2009, with the third due in 2010. South African and Indonesian coals are being used. Once fully operational, an efficiency of 44.7–45.0% (LHV) is expected. Emissions from the plant will be considerably lower than when oil-fired; SO_2 emissions will fall by 82% (FGD limestone-gypsum scrubber), NOx by 61% (advanced combustion system, SCR, and urea-to-ammonia unit), and particulates by 82%. CO_2 is expected to be 18% lower.

In a similar move to Torrevaldaliga Nord, at ENEL's **Porto Tolle (Phase I)** project, two 660 MW coal-fired USC PCC units are being installed. These are capable of cofiring biomass. There is a notional commissioning date of 2012-13. Following conversion, the plant's efficiency is expected to increase from 39% to 45% (LHV). As well as new coal boilers, ENEL is also installing SCR and FGD systems.

A third project is under way at E.ON's 1040 MW **Fiume Santo** plant in Sardinia. This comprises a combination of units fired on gas, coal, oil and Orimulsion. In 2003, an Orimulsion-to-coal conversion project on two units was started in order to reduce environmental impact and improve plant efficiency. In 2006, permission was sought for a new

410 MW coal-fired unit at the plant, based on USC PCC technology. This was to replace the two fuel oil-fired units. In December 2008, a favourable environmental impact assessment was received. The project is expected to be completed by 2014. E.ON is also considering co-combusting biomass in the existing coal-fired units.

The Italian manufacturer Ansaldo currently offers steam turbines for operation under supercritical or ultra-supercritical steam conditions (200–1200 MW, at up to 30 MPa/600ºC/610ºC).

8.3 CFBC

Sulcis 2

The original ENEL 240 MW Sulcis power plant used conventional PCC technology with subcritical steam conditions. However, its replacement, the new Sulcis 2 plant, uses a 340 MW Alstom CFBC unit that started commercial operation in 2006. Steam conditions are 16.9 MPa/ 565ºC/580ºC. Typically, the coal used is a blend of 20% Sulcis coal with 80% South African, cofired with biomass. Use of the latter (between 8% and 15% – equivalent of up to 47 MWe) avoids the production of 0.3 Mt/y of CO_2. Compared to the earlier PCC plant, efficiency has now been increased from 35% to ~40% (LHV). Ash produced from plant operations is disposed of in old mine workings. An FGD unit and fabric filter are used to minimise emissions of SO_2 and particulates.

8.4 IGCC

The ATI Sulcis power station at Portoscuso has been proposed as the site for a (Sulcis) coal-fuelled IGCC plant using Shell oxygen-blown, dry feed gasification technology. Sondel and Ansaldo are also involved. Two gasifier trains have been proposed; initially, the project would be of 450 MW capacity, possibly increasing to ~960 MW at a later date. The project is reportedly in the planning and development stage. Siemens steam and gas turbines have been suggested. Estimated project cost is around €1.3 billion.

ENEL is involved in several initiatives aimed at the development of zero emission IGCC technology. It is a partner in *DYNAMIS*, a project funded under the EU's FP6, for a pre-engineering study of a European zero emissions IGCC plant. It is also involved with *DECARBit*, a proposal to FP7 currently under negotiation, focused on high-potential, cost-efficient advanced capture techniques in pre-combustion schemes. ENEL is actively seeking co-operation opportunities for demonstrating zero emission IGCC technology. Other Italian organisations and their involvement in major CCS projects are shown in Table 16.

Italy also hosts a number of major oil refinery-based IGCC plants, fired on low value refinery by-products (Mills, 2006). These comprise the SARLUX plant in Sardinia, the ISAB Energy plant in Sicily, api Energia's Falconara plant, and the ENI Sannazzaro plant near Milan.

8.5 Cofiring activities

Cofiring is focused mainly on the use of biomass and RDF, with activities (involving several generators) currently limited to a relatively small number of plants. For instance, biomass cofiring is carried out at A2A Produzione's Monfalcone power plant and ENEL is also engaged in cofiring biomass and RDF. Two of the units of its on-going Porto Tolle USC PCC conversion will be capable of cofiring biomass. The Sulcis CFB-based plant also cofires combinations of coal and biomass.

Some plants, such as ENEL's coal-fired Fusina power plant near Venice, cofire RDF (Martelli, 2007). The nearby Veritas Vesta RDF production plant produces ~350 t/d of RDF pellets (about 80 kt/y), half of which are supplied to the Fusina station. The pellets have a calorific value similar to that of coal. The station has been equipped with pellet handling and preparation systems in order to make the RDF suitable for cofiring. Two of Fusina's PCC units (each of 330 MW) have been suitably modified to allow cofiring. In 2008, permission was granted by the Italian Ministry of the Environment allowing the Fusina plant to double the quantity of RDF burned from 35 to 70 kt/y.

8.6 CCS activities

Italy has a significant challenge in meeting its Kyoto Protocol commitments (existing gap 97 Mt CO_2/y) while satisfying an ever-increasing energy demand. To address this, Italian energy policy foresees a number of measures that include CCS. In 2003, the Ministry of Economic Development set up a National Committee to co-ordinate Italian participation in international initiatives on zero emissions. Italy is also active in the IEA, Carbon Sequestration Leadership Forum, and the European ZEP Technology Platform.

A number of national projects and programmes are being supported by National Government, Ministry of Economic Development, Ministry of Research, and regional governments. A three-year Energy R&D National Programme (funding of €150 million) includes funding for two CCS projects, namely quantifying existing potential CO_2 storage capacity over time, and ECBM site tests in Sardina (Sulcis Area). The CERSE Programme (fund for R&D on the electricity system) is an important national activity under the control of the Ministry of Economic Development. This focuses on technology innovation in electricity generation. A series of CCT- and CCS-related R&D activities are in hand; these comprise:

- efficiency improvement of SC PCC and IGCC systems;
- combined production of hydrogen and power incorporating CCS;
- identification of national potential CO_2 storage capacity;
- ECBM site tests in Sardinia (Sulcis area);
- CO_2 capture technologies (solid sorbents, membranes);
- 'Industry 2015' – an industry-oriented R&D programme;
- development of advanced mild combustion technology for oxycoal-fired power plants.

Table 16 Italian CCS activities and organisations (IEA GHG, nd; Gassnova, 2010; Girardi, 2009)

Organisation(s)	CCS-related involvement and activities
National Institute of Oceanography and Applied Geophysics, Eni Tecnologie	EU GeoCapacity
Universita 'La Spezienza' di Roma	NASCENT
INGV - National Institute for Geophysics and Vulcanology	CO2-EOR (Weyburn)
Instituto Nazionale di Geofisicia	EC-WEYBURN
National Research Council of Italy	GRACE
Sotacarbo Spa, Carbosulcis Spa, INGV, ENEA, University of Cagliari	PROMECAS
Universita di Roma 'La Sapienza', OGS, 11 other institutes	CO_2 GeoNet European Network of Excellence Studying underground CO_2 storage
OGS, INGV, ENI, ENEA, CESI, ENEL, Universities (La Sapienza, Roma 3, Padua, Polytechnic of Milan), private companies	CONFIGEOLIT- Italian site survey for geological storage of CO_2 from power generation and hydrogen production plants Currently being prepared
INGV, Independent Energy Solutions, ENEL, Edison, and API	SIBILLA feasibility study (CO_2 geological storage R&D) – part of CONFIGEOLIT
ENEL, INGV, OGS and other Italian geological institutes	Phase 3 of the ENEL CCS1 post-combustion capture project includes CO_2 geological storage project
ENEA - National Agency for New Technologies, Energy and the Environment	Department of Technologies for Energy, Renewable Sources and Energy Conservation - engaged in increasing energy efficiency and achieving a low carbon economy
ENI	CO_2 Capture Project (CCP). Has experience in all areas of CCS Conducting R&D work and short- and long-term engineering projects, such as feasibility studies on CO_2 injection into hydrocarbon fields
CNR - The National Research Council	Biological and environmental impact of CO_2 storage
Ansaldo, ENEA, Sotacarbo	Development of low CV fuel gas turbines and fuel cells in a CCS combined system. With Sotacarbo - the COHYGEN project (Sulcis coal syngas production with H_2 separation and CO_2 solvent capture
SOTACARBO	Aims to develop new and advanced CCTs Has represented Italy in the IEA Clean Coal Centre
CARBOSULCIS	Studies underground CO_2 storage and (ECBM) technology. Partner with Sotacarbo and INGV
ENEA (Italian National Agency for New Technologies, Energy and the Environment)	CCS activities include Clean coal/Zero emission coal technologies, and ZECOMIX test platform (coal gasification for H_2 and power generation with CO_2 separation) Also CARBOMICROGEN - small scale power generation systems using syngas and hydrogen from coal and/or biomass with CCS systems
TECHINT	Pre-combustion pilot plant at Sotacarbo Research Centre (PRATO Project). Optimised pre-combustion CO_2 capture technology
OGS, ENEA, ENI-Agip, Aquater, CNR, URS and 13 universities	Geological sequestration of CO_2 and development of the related technologies project. OGS is project co-ordinator
OGS (L'Istituto Nazionale di Oceanografia e di Geofisica Sperimentale)	National reference point for co-ordinating Italian participation in fields of oceanography and experimental geophysics Includes CO_2 storage issues
Assocarboni	Aim to improve the image of, and promote the consumption of solid fuels in Italy. Promotion of uptake of CCTs
SSC - Stazione sperimentale per i Combustibili (Fuel Experimental station)	Research institute operating within the framework of the Italian Department of Industry. Point of reference for Italian industrial fossil fuel sectors, and the Ministry of Economic Development

ENEA and SOTACARBO are both active in the CERSE programme and are undertaking work on coal-fired power plants for combined electricity and hydrogen production (ENEA), experimental and modelling activities on pre-combustion CO_2 capture and storage (via ECBM and saline aquifers), development of an Italian CCS road map, coal gasification with CCS (SOTACARBO), pilot plant testing, feasibility studies for a coal-fired demonstration power plant with CCS in Sardinia, oxycoal combustion (ENEA), and modelling and simulation studies (Girardi, 2009). Significant Italian CCS activities are summarised in Table 16.

There is also a further project currently at the preparation stage. This is the CONFIGEOLIT project (Italian site survey for geological storage of CO_2 from power generation and hydrogen production plants). This aims to create an interdisciplinary (geological-geophysical-geochemical) Italian work group with the intention of defining the feasibility of geological storage in Italy, and determining and characterising potential storage sites within the country. Project partners/participants comprise OGS, INGV, ENI, ENEA, CESI, ENEL, universities (La Sapienza, Roma 3, Padua, Polytechnic of Milan), institutes engaged in geological storage research, plus a consortium of private companies with expertise in geological assessment. The expected key deliverable will be a national report on possible CO_2 geological storage sites in Italy. Others will include an inventory of major industrial CO_2 sources, definition of the best sites for fossil-derived hydrogen plants, and an analysis on CO_2 pipeline costs and safety issues. The total duration of the project will be eight years.

As part of the CONFIGEOLIT project, the SIBILLA feasibility study (CO_2 Geological Storage R&D) was undertaken. The goal was a full evaluation of the storage capacity of CO_2 in Italy and the selection of suitable sites for initial experiments of large-scale CO_2 geological storage. The project included feasibility studies for possible storage in large capacity saline aquifers, or its use for EOR in the semi-depleted Santa Maria oil field. Sites considered were relatively close to ENEL hydrogen production or power generation plants in northeast Italy. Several off-shore and on-shore geological storage sites were shortlisted. The potential CO_2 storage capacity provided by sites within the study area is substantial. The project partners/participants were INGV, Independent Energy Solutions, ENEL, Edison, and API (the latter two only for EOR). Funding (€1 million) was provided by the Italian Ministry of Environment (MATT) and the project partners.

Phase 3 of the ENEL CCS1 post-combustion capture project will include the selection of a suitable geological storage site. Several potential areas are currently being studied by INGV, OGS and other Italian geological institutes.

As the major player in the Italian power sector, ENEL is at the forefront of Italian CCS activities, driving forward a number of initiatives. This includes measures to improve the efficiency of generation from existing power plants, introducing SC PCC technology to others (revamping oil-fired capacity), and increasing its use of renewable technologies. During the period 2003-06, ENEL invested €1.1 billion in such initiatives. The company target for 2009 was >4 Mt/y CO_2 avoided, with similar targets for future years. Major undertakings include the conversion of 5 GW of oil-fired plants to combined cycle gas firing (completed), conversion of 5 GW of oil-fired capacity to clean coal plants (under way), and replacement of old coal-fired units (1 GW) with new, more efficient units. ENEL regards the implementation of CCT/CCS technologies as crucial in making the continued use of coal compatible with the objective of reducing greenhouse gas emissions. It is pursuing the development of CCS technologies by various means.

In 2008-09, several major international CCT/CCS agreements were entered into. In May 2008, an MoU was signed between ENEL, the Ministry of Science and Technology of the People's Republic of China, and the Ministry for the Environment of Italy. This enables ENEL to co-operate in R&D activities aimed at promoting the use of CCTs in China, based on expertise developed at the Torrevaldaliga Nord power plant, as well as on CCS pilot projects currently under development. This accord forms part of the Sino-Italian Co-operation Program (SICP) launched in 2001 to identify opportunities for projects aimed at promoting a sustainable development path in China. There is also a second agreement between ENEL and Wuhan Iron & Steel Co for the acquisition of allowances relating to five projects in energy efficiency, aimed at reducing CO_2 emissions (between 2008 and 2012) totalling 11.45 Mt. In May 2009, an MoU (the ENEL-Australia agreement) was signed, providing for ENEL's participation as a founding partner in the Global Carbon Capture and Storage Institute.

In 2009, an agreement was signed for collaboration between Italy and the USA on CCS on coal-fired powered plants. The *Clean Coal and Carbon Sequestration Annex* is part of the Obama Administration's on-going efforts to develop technologies to reduce CO_2 emissions. Under the Annex, both countries will co-operate on a variety of CCS projects, that include power generation processes, advanced coal gasification, power system simulations, and characterisation of sub-surface carbon storage potential. The joint work on CCS is part of the larger *Agreement on Energy Research and Development*, signed by the US DOE and Italian Ministry of Economic Development in October 2007.

8.6.1 Post-combustion capture

ENEL is engaged in the development of several MEA scrubber-based capture projects at its Brindisi and Porto Tolle power plant sites. The aim of these is the demonstration of CCS technologies on an industrial scale on conventional fossil fuel power plants. There are also proposals by SEI (Ratia Energie and partners) for a 1320 MW pulverised coal fired power plant that would feature post-combustion CO_2 capture, or at least, be built capture-ready.

The post-combustion capture and storage demo project – CCS1

A pilot project is being developed at ENEL's Federico II power plant near Brindisi (Unit 4). The plant will capture up to 2.5 t/h of CO_2 from 10,000 m^3/h of flue gas using an MEA-based scrubber. The plant comprises a flue gas pre-treatment section (to remove particulates and SO_3, and to reduce SO_2 level below 20 mg/m³) and a CO_2 separation unit. The latter will capture 5000 t/y CO_2. Pilot plant construction was completed in December 2008 and commissioning was due to start in December 2009. The project will operate for around four years. As part of the project, ENI is investigating underground storage in the depleted Stogit natural gas field. ENEL built the Brindisi CO_2 capture and liquefaction plant, whilst Italian oil and gas company ENI will be responsible for injecting the captured CO_2 into the Stogit gas field at Cortemaggiore. CO_2 will be transported in 230 trucks loads each year. Injection is due to start in October 2010. Over the project's lifetime, ~24 kt CO_2 will be injected and monitored.

On the basis of the pilot plant performance, a full-scale demonstration plant could be developed (Phase 4). This has the goal of retrofitting (equivalent of ~200 MWe) one of the 660 MWe USC PCC units of the Porto Tolle power station with CO_2 capture equipment, and starting underground storage by 2015 (Figure 9). Between 40% and 50% of the unit's flue gas will be treated (capture rate of 90%). CO_2 captured (up to 1 Mt/y) will be stored in a deep saline aquifer, 100 km to the southeast, below the North Adriatic Sea. By mid 2009, a detailed feasibility study was under way.

In a further development, the French Petroleum Institute (IFP) and ENEL have signed an MoU to test a first generation post-combustion capture process (developed by IFP) on ENEL's post-combustion Brindisi pilot unit. IFP is working towards reducing system costs and optimising the process. Following preliminary assessments, the two partners may also consider testing second-generation processes, currently being developed by IFP.

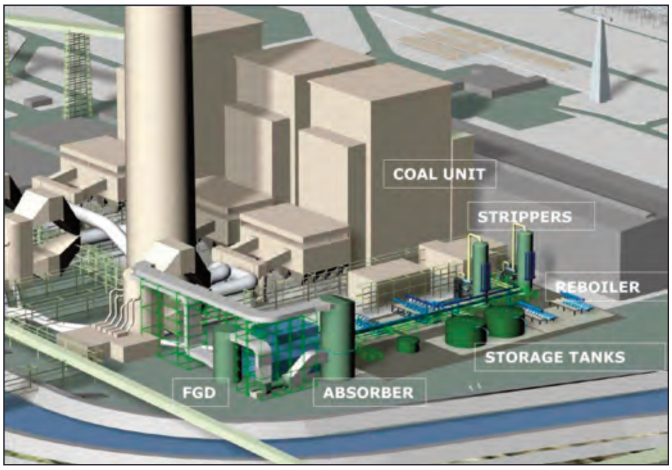


Figure 9 ENEL's proposed post-combustion carbon capture project at the Porto Tolle power plant in Italy (picture courtesy of ENEL)

8.6.2 Oxyfuel combustion

ENEL CCS2 oxyfuel project, Brindisi

ENEL is engaged in the development of a pilot-scale pressurised (PCC) oxycoal project at the Brindisi power plant site. Initially, testing was undertaken in a 3 MWth combustion test facility in ENEL's Livorno labs, where oxycoal atmospheric combustion tests were performed successfully with different recycle ratios. This was followed by testing using coal on a 5 MWth *Isotherm* pilot plant at the ITEA facility in Gioia del Colle (*Isotherm* is ITEA's patented technology that has been tested on a pilot-scale for >4000 h on its Gioia del Colle test facility). ENEL has a co-operation agreement on oxy-combustion technology with ENEA and ITEA. In 2007, the partners undertook a feasibility study for a coal-fired power plant and carried out modelling for combustor scale-up. A preliminary design for a full-scale (48 MWth) combustor demo was produced and the decision to proceed taken in April 2008. The combustor demonstration plant is expected to start commissioning at Brindisi in May 2011. This will be fed with coal slurry and operate at a pressure of 10 MPa. It will provide data for a proposed small-scale (35–70 MWe) PCC-based zero emissions power plant, using pressurised oxycoal technology (based on *Isotherm* technology) and scheduled to be operational by 2012 (Barbucci, 2007; 2009).

9 The Netherlands

The country no longer has a coal mining industry and relies entirely on imported supplies for power generation and industrial applications. In 2008, 13 Mt of hard coal was imported (Euracoal, 2009). This comprised 9 Mt of steam coal, 3 Mt of coking coal, plus 1 Mt of pulverised injection coal. Supplies came mainly from the USA, Colombia, South Africa, Australia and Indonesia.

Considerable quantities of coal also pass through the country as The Netherlands is now the main transloading point for coal imports into Europe. The ports of Rotterdam and Amsterdam (along with Antwerp in Belgium) constitute Europe's most important trading centres for imported coals. Both Dutch ports operate large stockpiling, screening and blending facilities. Coal is re-exported to countries such as Belgium, Germany, France, and the UK. Annually, Rotterdam handles more than 27 Mt of coal, and Amsterdam ~15 Mt. Both have reported annual increases in throughput in recent years. One of the main drivers has been increased imports destined for German power plants.

9.1 Power generation sector

In 2008, the Dutch power sector generated a total of 98 TWh. Coal-fired plants produced around a quarter of this (~25 TWh), with much of the balance coming from natural gas fired facilities. The country has a total of ~4GW (five plants, seven units) of coal-fired power plants in operation, varying in capacity from 400 to 630 MW. All rely on subcritical steam conditions although one (Hemweg) also operates a single SC unit. All employ comprehensive emissions control systems (Table 17). The country also has an IGCC plant at Buggenum.

9.2 Supercritical PCC plants and proposals

Hemweg 8 power plant, Amsterdam

Coming into full commercial operation in May 1994, this 630 MW supercritical PCC unit is the newest at the Hemweg site. It uses a Benson once-though boiler designed to fire a range of internationally-traded bituminous coals (or natural gas to full load) cofired with a proportion of sewage sludge. The boiler was supplied by Mitsui Babcock (although built by Stork). Steam conditions used are 26.0 MPa/540ºC/568ºC. It has a design cycle efficiency of 42% (LHV). NOx emissions are controlled by Fortum low NOx burners, and SO_2 by a wet limestone FGD from Hoogovens and GE Environmental Services. The plant is currently operated by NUON/Vattenfall.

E.ON Benelux Maasvlakte plant

E.ON has proposed an 1100 MW supercritical PCC power plant for the existing Maasvlakte power plant site in Rotterdam. The cost of the proposed plant is €1.2 billion. In early 2009, a feasibility study was under way. Like the existing Maasvlakte plant, the new unit will be able to cofire biomass. It will adopt main steam parameters of 28.5 MPa and 620ºC. Overall efficiency is expected to be ~46% (LHV). Alstom will provide the steam turbine generator package and will also carry out full plant erection, commissioning and trial runs. Seawater will be used for cooling. Commercial plant operations are scheduled to begin in 2013. The plant is being designed for subsequent retrofitting with CCS technology – this will reportedly take the form of a post-combustion capture facility. The Rotterdam Climate Initiative (an initiative to reduce CO_2 emissions in the region by 50% by 2025) is involved with the latter.

RWE Power, Eemshaven

RWE Power AG is developing a project in the Groningen province of The Netherlands. This will comprise two 800 MW USC PCC units supplied by Alstom at a cost of €500 million. Total plant costs are an estimated €2.2 billion. Plant efficiency will be ~47% (LHV). The new units are designed to cofire hard coal with up to 10% biomass. Compared to a conventional plant of the same capacity, the new facility will produce 2.5 Mt/y less CO_2. In addition, the new units are being built so that they can be retrofitted with CCS equipment at a later date. Plant completion is due in 2013.

GDF SUEZ/Electrabel, Rotterdam

In June 2009, GDF SUEZ, through its subsidiary Electrabel, began construction of an 800 MW plant. This will cost around €1.2 billion and be cofired on imported coals and biomass (up to 50%). Efficiency is expected to be ~46% (LHV). The site offers possibilities for the later addition of CCS facilities.

Table 17 Emission control systems used on Dutch power plants (CoalPower)

Plant	SO_2 control	NOx control	Particulate control
Amer	Wet limestone scrubber	OFA, SCR, low NOx burners	ESP
Borselle	Wet limestone scrubber	Low NOx burners, SCR	ESP
Gelderland	Wet limestone scrubber	Low NOx burners, SCR	ESP
Hemweg	Wet limestone scrubber	Low NOx burners, OFA, SCR	ESP
Maasvlakte	Wet limestone scrubber	Low NOx burners, OFA, SCR	ESP

9.3 Cofiring activities

In May 2002, the Dutch Coal Covenant was agreed, creating a new incentive to increase cofiring levels beyond 10 wt%. The Covenant obliged coal-fired power plants to reduce CO_2 emissions by 6 Mt/y over the period 2008-12. Around half of this reduction (3.3 Mt) is being achieved through the cofiring of biomass in existing coal-fired power plants; this equates to 475 MWe of installed capacity (Kalf and Meijer, 2007). The country now has experience of more than fifty cofiring trials of varying size. Some have successfully cofired up to 40 wt% of biomass fuels with coal. By 2007, it had become normal practice to cofire at least 10% biomass in coal-fired power plants.

Currently, cofiring (~2.2 Mt/y of biomass/wastes) is reducing overall annual coal consumption by ~12%/y. All Dutch PCC stations now regularly cofire (also the Amer 9 CFBC plant – *see below*). A variety of materials is being used, including demolition wood, sewage sludge, biomass pellets, municipal wastes, and poultry dung. These are cofired in varying proportions with different international coals or coal blends. For example, the 632 MW Gelderland power plant cofires mainly processed waste wood. The material is collected and processed into raw wood chips, cleaned, chipped, then reduced to powder. A metering system delivers this to four burner injection systems, each capable of delivering 1.1–3.5 t/h, in total supplying ~20 MWe equivalent of heat input. The system was commissioned in 1995 as the first direct biomass cocombustion demonstration in a large utility boiler in Europe. In April 2010, it was announced that Electrabel and GDF Suez Group had started up a new biomass generating system at the plant. Biomass is now replacing around a quarter of the plant's coal requirement. This will increase the Gelderland biomass capacity from 44 MW to 180 MW. The biomass feed will comprise wood pellets (compressed sawdust), some 470 kt/y being used. This will result in a reduction in CO_2 emissions of 750 kt/y. The conversion represents an investment of more than €40 million.

The Maasvlakte station also cofires mixed biomass pellets produced from sewage sludge, waste wood and paper sludge. These are blended with raw coal on the conveyor belts. Around 150 kt/y of pellets are manufactured by BioMass Nederland; this effectively replaces ~30 kt/y of coal, thus reducing overall CO_2 emissions (EBIA, nd). Capital investment requirements for cofiring biomass/wastes can be relatively modest and cofiring biomass produces the least expensive green energy in the country (Mills, 2004).

In June 2010, it was announced that Topell Energy and RWE Innogy were to build a plant for the industrial scale (60 kt/y) production of 'biocoal' pellets (combinations of coal and

Table 18 Commercial cofiring activities in The Netherlands (Mills, 2004; EBIA, nd; Kalf and Meijer, 2007)

Plant	Plant capacity, MWe	Technology	Fuel feedstocks with coal	Capacity, MWe*
Gelderland 13	632	Direct co-utilisation with separate milling, injection of pulverised wood in the pf-lines and simultaneous combustion	Scrap wood	180
Amer 8	645	Direct co-utilisation; separate dedicated milling and combustion in dedicated biomass burners	Paper pulp, bio fuel (300 kt/y)	2
Amer 9 (CFBG/PCC)	600	Direct cofiring; biomass is milled separately in dedicated mills and combusted in separate burners; CFB gasifier – wood chips	Demolition wood, bio pellets (300 kt/y)	30
Borssele 12	413	Practice 1: direct cofiring by separate milling and combustion Practice 2: direct cofiring by mixing with the raw coal before the mills	Demolition wood	12
Maasvlakte 1, 2	2 x 513	Practice 1: direct cofiring of biomass, pulverised in a separate hammer mill, injection into the PF-lines and simultaneous combustion Practice 2: liquid organics fired in separate oil burners	Wood, poultry manure	30
Claus 9, Maasbracht	2 x 600	Direct cofiring in dedicated burners	(natural gas) + palm oil	
Hemweg 8 (SC)	630	Direct co-utilisation	Sewage sludge	19
Buggenum (IGCC)	253	Direct co-gasification	Sewage sludge, chicken litter, wood (up to 30 wt% input)	43

* direct and indirect utilisation

biomass). The new €15 million plant is being built at Duiven in Gelderland and will be commissioned early in 2011. The manufacturing process will enable the continuous production of biocoal pellets from various raw materials. Their cofiring in existing coal-fired plants will not require any additional infrastructure such as separate storage and pulverisation facilities. The pellets are claimed to have a higher CV than biomass alone and have more homogeneous properties. RWE's Dutch subsidiary Essent will be the first company to use the biocoal pellets (for a period of five years) in the Amer coal-fired power plants.

A summary of commercial cofiring activities is given in Table 18. ECN is also involved in the on-going EU FP7 DEBCO project, with the goal of significantly increasing biomass cofiring levels in large-scale applications.

9.4 CFB gasification

Essent operates a CFB gasifier (Amer 9) at the coal-fired Amer co-generation plant in Geertruidenberg. The 85 MWth gasifier was supplied by Lurgi and operates at 800–950ºC at atmospheric pressure. It produces fuel gas by gasifying ~150 t/y of construction and demolition wood; this effectively replaces 70 kt/y of coal that would otherwise be burned. The fuel gas is cleaned and fed into dedicated burners on a 600 MW PCC boiler (Unit 9) at the plant (equivalent of 30 MWe capacity). An estimated 170 kt/y of CO_2 is avoided by the system.

Under EU legislation, the plant is considered a waste incineration unit, with corresponding emission limits. Plant modifications made mean that the fuel gas is now considered as clean biomass (as per the Dutch *White List*) assuming that heavy metal levels are <30 mg/MJ. Commercial operations began in 2000. However, the plant has suffered from several operational problems. Most have been resolved although cooler fouling remains an issue. By 2008, more than 3000 hours of operation had been achieved. In 2008, Essent considered extending operations at the Amer site through the addition of a further cofired coal/biomass unit (Amer 10). However, this is currently shelved due to issues associated with the future cost of carbon emissions rights. There is also some uncertainty about future policy support for biomass.

9.5 IGCC

The Willem Alexander IGCC plant, Buggenum

Developed initially by Demkolec BV, initial syngas trials were carried out in 1994-95. In 2001, the plant was bought by NUON for operation as a commercial base load station (Figure 10). Gross power output is 284 MWe (net 253 MWe); the gas turbine produces 156 MW, and the steam turbine a further 128 MW. Auxiliary plant power requirements are 31 MW. The plant generally operates at a net efficiency of 43.2% (LHV).

Around 2000 t/d of imported coal is used, usually co-gasified with biomass. The Dutch Coal Covenant requires that CO_2 emissions from the Buggenum plant are reduced by 200 kt/y (the equivalent of ~35 MWe from biomass, or ~30% by weight of biomass in the coal feed). Eventually, up to 50% biomass may be used; this would provide 60 MWe of 'green power'. At the moment, there is a focus on the use of 'clean' biomass such as sawdust. This is co-gasified with coal in a single-stage upflow Shell entrained flow, oxygen blown, dry feed gasifier. This is of the membrane walled type and operates at a temperature of 1500ºC and a pressure of 2.8%MPa. Cleaned syngas is diluted with nitrogen and steam to achieve the required specification for the gas turbine. The gasifier has a design capacity of ~4.0 million m^3/d of syngas. Siemens steam and gas turbines are used. In order to maximise thermal efficiency, the cycle uses full integration with extraction of air from the gas turbine compressor for the Air Products ASU (Mills, 2006).

In recent years, several programmes have examined other possible applications for the plant. These have included the production of biofuels by Fischer-Tropsch synthesis; feasibility studies were undertaken as part of the Dutch GAVE programme (Climate Change Neutral Gas and Liquid Energy Carriers). It was considered that the production of FT diesel was technically and economically viable when operating at part load. However, as the plant now operates in base load mode, this is unlikely to proceed.

NUON/Vattenfall are currently developing a CO_2 capture pilot programme at Buggenum in order to provide data for the Magnum project.

NUON/Vattenfall Magnum project, Eemshaven, Groningen

Originally proposed in 2005, the plant will have an installed capacity of 1300 MW (gross). However, as a consequence of factors that include rising construction costs, initial operations will be as a natural gas-fired combined cycle plant. This will be followed later by the addition of coal/biomass gasification capacity that will then provide syngas to the plant (Figure 11). Three Shell gasifiers are proposed. In 2008, estimated project costs were ~€1.5 billion. MHI will be EPC contractor and supply three 430 MW natural gas fired gas turbines for project. The company is also supplying steam turbines and

Figure 10 The Willem Alexander IGCC plant at Buggenum in The Netherlands (photograph courtesy of NUON)

Figure 11 Artists impression of NUON's Magnum IGCC plant in The Netherlands (courtesy of NUON)

generators and will commission the plant. A start date for partial IGCC operations of 2012 has been suggested. Once fully operational, the Magnum plant will produce an estimated 3.1 Mt/y CO_2; partial CO_2 capture could begin in 2013.

CGEN NV, Europoort, Rotterdam

CGEN NV has proposed the development of a 450 MW IGCC plant (fuelled on coal and biomass) that could also produce hydrogen. Foster Wheeler has reportedly undertaken a feasibility study. An estimated 2.5 Mt/y CO_2 would be produced. Captured CO_2 would be stored in a depleted oil and gas field. No other details are currently available.

Essent IGCC, Rotterdam

Essent and Shell have proposed the construction of a 1000 MW IGCC plant. This would be fuelled on coal and biomass and use Shell gasification technology. A proposed start-up date of 2016 has been suggested. Most of the CO_2 produced would be captured and a number of onshore and offshore storage options, such as depleted oil and gas fields, are being investigated.

9.6 CCS activities

In 2009, the Dutch Government announced a goal of implementing CCS on all new coal-fired power plants. This applies to plants currently under construction and any built in the future. Application would come after the completion of large-scale CCS demonstration projects. However, it is not yet clear how the Government intends to pursue this.

A pilot-scale CO_2 capture facility is currently being developed at the Buggenum IGCC plant. Construction began in 2009 and a start-up date of 2010 has been announced. Dutch Government funding has been provided towards the cost of the programme. The pilot plant reportedly features a simplified process that includes shift and adsorption sections. An extensive R&D programme will assess catalyst and solvent durability, and examine operational flexibility and performance issues. Around 2.5% of the Buggenum plant's syngas flow will be treated. The R&D programme will last for two years and is likely to cost ~€40 million. It will provide data for the larger Magnum project.

A number of Dutch organisations have been actively involved in various national and international CCS-related programmes. Major ones are noted in Table 19.

In May 2010 it was announced that the Dutch Government would provide subsidies of up to US$190.5 million during the

Table 19 Recent Dutch involvement in major CCS-related programmes (IEA GHG, nd)

Project	Partner(s)
EU Geocapacity	Geological Survey of the Netherlands (NITG-TNO), Ecofys
CRUST	Various
GESTCO	NITG-TNO, Ecofys
RECOPOL - management of GHG emissions	TUD - Delft University of Technology
NASCENT	TNO
JOULE II	TNO
Alberta ECBM	Netherlands Institute of Applied Geoscience
GEODISC	TNO
CO2STORE	NITG-TNO, Netherlands Organisation for Applied Scientific Research
CATO	(*see* Section 9.6.1)
CASTOR	TNO
CCP	Various
CO2SEALS	Production BV, Rijswijk; Shell International Exploration and Production

next decade for a CCS project involving E.ON and Electrabel. The project will capture CO_2 from E.ON's coal-fired power plant in Rotterdam and transport it 12 miles by pipeline for storage in depleted gas fields under the North Sea. The Government's subsidy is in addition to a contribution of up to US$220 million from the European Economic Recovery Plan.

9.6.1 Post combustion capture

CO_2 Capture, Transport and Storage in the Netherlands (CATO) project

The project's objective is to streamline and integrate CCT- and CCS-related activities being undertaken by Dutch organisations, with a view towards achieving a sustainable energy future in The Netherlands. As part of this, an interlinked knowledge-sharing infrastructure is being developed. Information generated during project lifetimes is being shared with other European partners via a range of collaborative activities. Co-ordination of the project is being managed by the Utrecht Centre for Energy Research and overall project costs are €25.4 million. A series of related work packages have examined CCS systems, surface and subsurface mineralisation, monitoring, safety and regulation, communication, and knowledge transfer issues. The five-year project is now drawing to a close.

A number of Dutch-based organisations have been involved in CATO. These include Shell International Exploration and Production, Nederlandse Aardolie Maatschappij, KEMA (plus six Dutch electricity generating companies via KEMA – Delta, Electrabel, E.ON, Essent, NUON Power and Reliant), NV Nederlandse Gasunie, Geochem BV, Ecofys BV, Energie Beheer Nederland, ECN, TNO-MEP, TNO-NITG, and a number of universities.

As part of the programme, in 2008, the CATO *CO_2 Catcher pilot plant* was opened. This was built and is being operated by TNO in collaboration with E.ON Benelux, which is hosting the facility on a side stream at its coal-fired power plant at Maasvlakte. The pilot plant has been designed as a multi-purpose installation for testing and developing liquids, contactors and process integration concepts. The installation has a CO_2 capture capacity of up to 250 kg/h (from a maximum of 1250 m^3/h flue gas). A programme is being undertaken to test novel gas scrubbing methods and other technologies capable of capturing CO_2 from flue gases under real conditions. As part of the programme, a new low-energy, stable absorption liquid (TNO's amino acid salt-based *CORAL*) will be tested. Other work will include testing of novel membrane contactors.

Other projects

Both the E.ON Benelux Maasvlakte and RWE Eemshaven supercritical projects are being built so that carbon capture equipment can be retrofitted. Both are likely to adopt some form of post-combustion capture system.

9.6.2 Oxyfuel combustion

SEQ Nederland BV and partners are engaged in the development of an oxyfuel (gas-fired) zero emission power plant at Drachten that will capture and inject CO_2 produced into a natural gas field for enhanced gas recovery. The plant will have a fuel input of 170 MWth (nominal 50 MWe). Overall efficiency is expected to be 48% (LHV). Up to 375 kt/y of CO_2 will be captured and stored. The plant was scheduled to begin operations by the end of 2009. Between 2007 and 2015, 52 gas fields with a initial volume of 360 billion m^3 will become available for EGR. Potentially, EGR could produce an estimated additional 36 billion m^3 of gas (SEQ, nd).

10 Poland

Poland is one of the richest countries in Europe in terms of its hard coal and lignite resources. It depends heavily on these for industrial and power generation purposes; more than 90% of Poland's electricity is generated by coal-fired power plants. The Government maintains a strong involvement in the energy sector and aims to improve security of supply, diversify energy sources, improve efficiency, and further develop and apply CCT and CCS technologies. Several options for the construction of CCT/CCS-based power plants, along with the retrofitting (to include CCS) of a number of others are being considered.

Recent years have seen the Polish economy strengthen and future energy needs are likely to include additional generating capacity of between 10 and 15 GW, In addition, much of the existing capacity is reaching the end of its operating lifetime and will also need to be replaced. Essentially, to meet this need, Poland has several options, namely continued reliance on coal (but adopting more advanced CCT-based systems), the introduction of nuclear power, or a combination of both. During 2009, state-owned Polska Grupa Energetyczna SA (PGE), Poland's largest power group by generating capacity, announced plans to build two 3 GWe nuclear power plants, one in the north and one in the east of the country. The energy security strategy approved by the Polish Government in January 2009 aims at one or two nuclear power plants to be built by PGE, the first by 2020. PGE has since signed an MoU with Electricité de France to co-operate on the plants' construction. However, even if the latter is pursued, for many years, coal will remain the main source of Poland's energy. As such, the further development and use of CCTs and CCS within the country will be critical (Buzek, 2008).

Annually, the country generates more than 200 Mt of CO_2 from sectors covered by the national allocation plan. However, overall, greenhouse gas emissions have decreased during the past two decades (33% reduction since 1988) as industrial and generation efficiency has increased and some coal-based facilities have switched to natural gas firing. The Polish Government aims to reduce Poland's carbon footprint by 20% by 2015, although there are concerns that funding and investment issues are slowing the process.

In 2008, the *Polish Clean Coal Technology Platform* was established. Poland's main energy companies are all involved. Members include Vattenfall Polska, PGE Polska Grupa Energetyczna SA, PKE Poludniowy Koncern Energetyczny SA, Elektrownia Kozienice SA, EdF Polska Sp. z o.o., Dalkia Polska, CEZ Polska, Electrabel Polska SA, and Zespól Elektrowni Ostroleka SA (Mejssner, 2008). Its first goal was to draw up a strategic plan of action for the development and deployment of CCT and CCS in industrial practice. It also aims to increase general awareness of all aspects of clean coal technologies. In co-operation with scientific, business and government agencies, the Platform intends to monitor and influence legislative processes regarding CCS in Poland and across the EU. It will also act as a contact point for EU research programmes and is collaborating with the EU ZEP programme. The Polish Platform is working towards the inclusion of Polish projects in EU programmes (Buzek, 2008).

As such a high proportion of the country's electricity is produced from coal, there has been government support for the award of one of the EU's proposed demonstration plants to be in Poland. The project selected by the Polish Government to the EU Flagship Programme for CCS was that of Belchatów Power Plant/Alstom (*see below*). This has since been granted EU funding (€180 million) within the European Economic Recovery Plan (Sliwinski, 2009). It is considered that without the adoption of CCS technology, Poland will not be able to fulfil its obligations to reduce greenhouse gases emissions under the EU's energy and climate package as well as under other international agreements (Hinc, 2010).

R&D in the fields of CCT and CCS is concentrated predominantly in three institutes, namely Glowny Instytut Gornictwa (The Central Mining Institute), Katowice; the Institute of Chemical Coal Processing, Zabrze; and Cracow Technology Academy. Polish researchers have participated in various European Framework Programmes and projects that include RECOPOL, C3-Capture, ISCC, CO2-REMOVE, MOVECBM, and HUGE (European Steel and Coal Research Programme). Activities in specific areas of CCT and CCS technologies are explored in the following sections.

10.1 Power generation sector

The sector has a total installed capacity of around 35 GWe and is the largest in Central and Eastern Europe. The vast majority of electricity generated (>90%) comes from plants fired on indigenous hard coal and lignite, with only a small contribution coming from other sources. However, lignite has a significant advantage in terms of fuel costs, and electricity generated is ~30% cheaper than that generated using hard coal. For some years, there has been an upward trend in the level of electricity generated and consumed and the Polish Government expects domestic demand to continue increasing up to 2020. During this period, power demand could increase from present levels to 170 TWh.

The public power generation sector consists of over fifty thermal power plants, of which more than 30 operate as co-generation units. The largest is the 4320 MWe Belchatów site. Most large power plants are fired on hard coal although there are six (including Belchatów) that rely on lignite; this burns ~35 Mt/y. Apart from the main generation plants, there are also around twenty major coal-fired co-generation plants. Overall, more than 15% of Poland's electricity is produced in conjunction with heat. The largest electricity producers within this category have a generating capacity of up to ~930 MWe, with maximum thermal output being nearly 3000 MWth.

Polish coal-fired power and co-generation plants vary widely in make-up and capacity, often comprising combinations of

125, 200, 360 and 500 MW units. Older plants tend to be based around smaller units, whereas newer ones generally deploy units in the range 200–500 MWe. Of the total Polish generating capacity of nearly 35 GWe, 31 GWe is in public power stations, with much of the balance comprising industrial autoproducers. Public stations account for ~93% of the total public power plant capacity, with ~28 GW being vested in 20 of the largest public plants and co-generation facilities.

Around a quarter of the total installed generating capacity (8.86 GWe) comprises lignite-fired plants. However, as production costs are lower than those of hard coal fired plants, they produce around a third of the country's supply. Polish public power plants consume >40 Mt of hard coal annually, and autoproducers a further ~4–5 Mt. Lignite is also of paramount importance and around a third of Poland's electricity is generated by a small number of large lignite-fired power stations that consume ~60 Mt/y. These plants are located close to, and fed directly from, their respective lignite mines. Almost all of the country's lignite production is used for power generation.

10.1.1 Power plant modernisation

Following Poland's accession to the EU in 2004, generators became obliged to comply fully with European emissions legislation such as LCPD (2001/80/EC) and IPPCD (96/91/EC). Thus, investment and modernisation of some power plants became necessary, a process that had actually been under way for some years. Various measures have since been instigated at major stations, such as targeted projects to increase individual plant efficiency and reduce emissions of SO_2, NOx and particulates. More recently, CO_2 emissions have also become an issue. Some facilities have been updated on a number of occasions. Boilers have been replaced with more modern units, steam turbines have been modernised and upgraded, and effective emissions control systems installed. Despite the heavy investment required, over the past decade, considerable progress has been made. By the end of 2005, 17 GW of coal-fired capacity had been modernised, enabling continued operation up to at least 2020. Important progress has been made in reducing emissions from coal-fired plant and levels at many sites have been reduced significantly through the installation of modern emissions control equipment. As a result, many of these units now generate electricity more efficiently and with much lower environmental impact than previously.

Figure 12 Turów power plant, Poland (photograph courtesy of Elektrownia Turów SA)

Apart from programmes to update existing PCC-fired capacity, repowering with CFB technology has been undertaken at a number of sites. To date, there are ~20 major CFBC units in operation. The largest is located at the Turów power plant where, since 1995, six CFBC units have been installed. Turów is now the largest individual CFB installation in the world (Figure 12). Repowering has increased site capacity by 30% and dramatically reduced emission levels.

10.2 Supercritical PCC plants and proposals

Major SC PCC projects in Poland are:

Elektrownia Patnów II (EP II)

This new lignite-fired 464 MW SC PCC unit was commissioned successfully and handed over for commercial operation in June 2008. To date, availability in excess of 90% has been achieved. The plant is contracted to deliver 464 MW to the grid, although the output at the generator at maximum continuous rating is 479 MW and the maximum power output is 488 MW. This new unit replaced two old subcritical PCC units. Alstom supplied much of the plant on a turnkey basis; this included the turbine island and the spirally wound once-through tower boiler equipped with a low-emissions firing system. The unit has an efficiency of 44% (LHV, gross), ~41% (LHV, net), making it one of the most efficient plants in Poland. Annual utilisation time is expected to be 6800 hours and electricity output 3180 GWh.

Lignite for the plant is supplied from a nearby mine and is crushed and dried in beater wheel mills before use. Heat is provided from flue gas extracted from the top of the boiler. The mixture of dried lignite, vapour and recirculated flue gas forms an inert atmosphere and is transported via short coal ducts to the burners. Two levels of overfire air are used to maintain NOx levels below 200 mg/m^3. Both SO_2 and NOx emissions are in line with EU requirements of less than 200 mg/m^3 (ZE PAK, 2008).

Belchatów II (BOT)

Construction of this 858 MWe lignite-fired facility began in 2006, under the terms of an €860 million EPC contract between Belchatów Power Plant SA and a consortium comprising Alstom Power Centrales, Alstom Power Sp. Zo.o, Alstom Power Boiler GmbH, and Rafako. Alstom has since designed and supplied major elements of the plant that include steam turbine, turbogenerator, cooling systems and electrical control systems. Rafako manufactured the SC PCC tower-type Benson once-through boiler (with a steam a capacity of 2400 t/h) and the FGD plant.

Once in commercial operation (scheduled for late 2010) the unit will become Poland's largest and most efficient lignite-fired plant. It will operate on base load for ~7500 h/y, with a total annual operational time of 8100 hours. The unit has been designed to achieve an operating life of about 200,000 hours, or around 35 years. Guaranteed efficiency is 44.2% (LHV, gross), 41.56% (LHV, net) (Mills, 2007b) and emission levels are expected to be low (NOx and SO_2 – <200 mg/m^3, and particulates <30 mg/m^3). The high plant efficiency will also result in significantly lower CO_2 emissions per unit of electricity generated compared to many existing coal-fired plants.

Piast Ruch Power Project, Wola, Silesia

This is a joint venture between RWE and Polish coal company Kompania Weglowa. At its core is a proposed 800 MW hard coal-fired plant, to be built at a cost of €1.5 billion, the largest ever private investment in the Polish power sector. It will be built at the former coal mine Piast Ruch II, owned by Kompania Weglowa, in the town of Wola in Silesia. Reportedly, the new plant will have an efficiency of up to 46% (LHV). Although not yet made public, it is likely to adopt SC PCC technology. To date, technical and economic feasibility studies have been completed. A commissioning date of 2015 has been suggested although a final investment decision based on economic viability has yet to be made.

Blachownia power plant proposal

Early in 2009, PKE/Tauron Polska Energia SA and copper miner KGHM Polska Miedz SA proposed the construction of a new 900 MW coal-fired power plant in Blachownia, in Kedzierzyn-Kozle, south Poland. This will be located at the existing Elektrownia Blachownia power plant site. The choice of generating technology has not yet been disclosed although reportedly, this may be SC PCC. PKE also plans several other coal-based power projects.

10.3 CFBC plants

10.3.1 Subcritical CFB plants

Since the 1990s, the use of CFBC for power generation and co-generation has grown rapidly. The inherent fuel flexibility and good environmental performance of the technology has encouraged the installation of systems fired on different types of coal and various opportunity fuels. Driven by the need for increased reliability, cost-effectiveness and environmental performance in recent years, there has been significant demand for new build FBC plants in Poland, and CFB has often been adopted as the technology of choice for repowering applications.

All CFB units currently operating have relied on natural circulation boilers and subcritical steam parameters. However, supercritical conditions have now been adopted at the lignite-fired Łagisza site (*see below*), the first in the world. To date, a variety of CFB systems produced by several major technology developers have been deployed in Poland, these including Foster Wheeler *Pyropower* and *Compact* designs, Kvaerner *CYMIC*, and B&W internal recirculation units (Mills, 2007b). The largest Polish facility is the Turów plant, one of the biggest individual CFB-based plants in the world. Major Polish CFBC plants are shown in Table 20.

10.3.2 Supercritical CFB plant

Foster Wheeler Energia Oy was largely responsible for the construction (for Polish utility Poludniowy Koncern Energetyczny – PKE) of the Łagisza facility, the world's first CFBC plant to adopt once-through CFB boiler technology using supercritical steam conditions. At 460 MWe, the new

Table 20 Major Polish CFBC-based power and co-generation plants (Mills, 2007b)

Owner/location	Start-up	Type	Capacity, MWe	Fuels
Turów	1998 2000 2002–04	2 hot cyclone units Hot cyclone 2 hot cyclone units + 1 *Compact*	2 x 235 235 3 x 260	Lignite Lignite Lignite
EC Katowice	2000	Steam cooled cyclone	120	Hard coal, coal slurry
Jaworzno II	1999	*Compact* unit	190	Hard coal
EC Chorzow Elcho	2003	*Compact* units	2 x 110	Hard coal
EC Zeran	1997 2001	Hot cyclone unit Steam cooled cyclone unit	315 MWth 315 MWth	Hard coal Hard coal
EC Bielsko-Biala	1997	Hot cyclone unit	177	Hard coal
Polpharma Starogard Gdanski	1993	Hot cyclone unit	2 x 60	Hard coal
EC Tychy	1999	CYMIC unit	37	Hard coal
EC Siersza	2001 2003	Hot cyclone unit Hot cyclone unit	339 MWth 339 MWth	Hard coal Hard coal

Łagisza power plant is also the world's largest individual CFB-based unit. The boiler design was based on Foster Wheeler's second generation CFB technology, with the solids separators constructed of steam-cooled panels integrated with the combustion chamber. The boiler utilises low mass flux BENSON vertical once-through technology. Operating parameters for the unit are (at the turbine inlet) a live steam temperature of 560ºC and pressure of 27.5 MPa, with a reheat temperature of 580ºC.

Erection work on the boiler island was largely completed in July 2008 and mechanical completion was achieved in August of the same year. Hot commissioning was undertaken and steam was first introduced to the turbine in February 2009, after which turbine and generator tests were started. The unit was synchronised to the grid late in February 2009 and full load operation was reached in March. On completion of commissioning, the plant was handed over to PKE. The new unit will consume 1.2 Mt/y of bituminous coal. PKE estimates that the plant will emit 25% less CO_2 per unit of electricity generated compared to the most efficient coal-fired power plants currently operating in Poland. To date, plant operating experience has reportedly been very good. Boiler operation has been stable and easily adjustable. Heat fluxes to furnace walls have been low and uniform. The plant is providing useful data for Foster Wheeler to pursue scaling up the technology to 800 MW (Jantti and others, 2009).

10.4 IGCC + CCS proposals

There is currently a major Polish coal-fuelled IGCC proposal for the Kedzierzyn Zero-Emission Power and Chemical (polygeneration) Complex. A project has also been proposed for the Belchatów power plant site, Europe's largest individual CO_2 emitter.

Kedzierzyn-Kozle Zero-Emission Power and Chemical Complex

There are proposals for a zero-emission power and chemical plant complex to be built at Kedzierzyn that will combine hard coal (from PKW's Janina mine + up to 20% biomass) gasification with CCS. The project is being developed by a consortium comprising chemicals producer Zaklady Azotowe Kedzierzyn SA (ZAK) and the electricity generator PKE. The plant's location will be in the Upper Silesian town of Kedzierzyn-Kozle, located in the Opole province of Poland. It will comprise two identical gasification trains and will be capable of producing electricity plus heat and/or heat alone, as required. Up to 309 MW of electricity and 137 MW of heat will be available. Fuel will comprise 2.07 Mt/y coal plus 0.23 Mt/y biomass. Plans call for the capture of CO_2 (3.38 Mt/y) produced – this will be stored geologically and/or used in the production of synthetic fuels, methanol, fertilisers or plastics. Up to 92% CO_2 capture is proposed, with 23% being used for chemicals synthesis, and the remainder (~2.54 Mt/y) stored in porous Jurassic and Triassic sandstones. Four potential storage areas within a range of 150 km have been identified, the largest with a capacity of up to 30 Mt CO_2.

The proposed IGCC plant will be integrated with an existing co-generation facility that uses coal-fired circulating fluidised bed technology. This will help ensure a reliable supply of process steam to ZAK's chemical processes and for ZCH Blachownia, the local district heating scheme. Like the IGCC plant, this will be capable of cofiring up to 20% biomass. Estimated project costs are ~€1.1 billion. ZAK and PKE are currently seeking funding and have applied to receive EU funds. The project has broad political backing from the Polish Government and the project partners are examining possible partnerships with companies such as Shell, GE and Siemens. The project schedule calls for the completion of feasibility studies in 2009, with plant construction taking place between 2010 and 2014. Commissioning and plant start-up will take place in 2014. The CCS component will be built between 2013 and 2015 (PKE, nd).

General Electric + BOT Belchatów

Several years ago there was a proposal for the construction of an 800–950 MW IGCC power plant that would incorporate CCS technology. However, based on recent reports, this now seems unlikely to proceed.

10.5 Underground coal gasification

Several UCG projects are being developed. At the Barbara coal mine, the Central Mining Institute (GIG) began UCG testing in April 2010. Around 15 tonnes of coal were gasified successfully. The other major project is the Rybnik SDS ('Super Daisy Shaft') CBM + UCG pilot project. Potentially, this could produce 100 million m^3 of syngas from Silesian hard coal that could be used for hydrogen production or for 30–50 MWe of electricity generation. The concept and project has been described by Couch (2007).

10.6 Cofiring activities

Since 2004, biomass cofiring has become an increasingly important source of energy production in Poland. In 2005, cofired energy production was ~877 GWh. As a result of the uptake of cofiring in almost all utility power plants, and a significant number of co-generation facilities, this had increased to ~1.3 TWh by 2006.

The IChPW undertook a major programme of cofiring trials that included tests (wood residues, straw pellets and willow chips with hard coal) in PCC boilers forming part of the Dolna Odra group of power plants, tests (lignite with sawdust) at the Patnów-Adamów-Konin group of power plants, and tests with dried sewage sludge in the Gdansk cogeneration facility. Around 20 individual plants took up direct cofiring during the period 2004-07. The most common cofiring feedstocks are wood (timber and processing wastes such as sawdust and woodchips), with a proportion of biomass generated from energy crops (an obligation on power generators since 2008) (Zuwala, 2007). The main focus of cofiring remains the use of biomass in utility-scale plant boilers although it is now cofired in a range of plants of varying size (such as the Opole power plant, Zeran co-generation plant, Dalkia Poznan ZEC SA plant, Skawina power plant, and in the Turów CFBC plant). Along with lignite, the latter has utilised sewage sludge, lignite sludge, demolition wood and RDF (IEA-FBC, 2002). Other CFB-based plants that cofire include the Swiecie plant (coal and wood chips).

10.7 CCS activities

In June 2010, Poland's new *GeoCO2 Industry Consortium* was launched. A major aim is to study the potential for storage of CO_2 in sandstone saline water-bearing formations. A storage monitoring programme is also to be undertaken. Data from the project will enable Polish CO_2 emitters to implement their individual CCS programmes, and will also help appraise the cost of future pilot and industrial scale projects. The Polish Ministry of the Environment intends to use output from the project to aid implementation of the EU Directive on the geological storage of CO_2. The consortium members include the AGH University of Science and Technology in Krakow, the Polish Geological Institute, National Research Institute, Messer Poland Ltd, and Drilling and Mining Enterprise Ltd.

10.7.1 Oxyfuel combustion

The potential for applying oxyfuel firing to the Łagisza supercritical CFBC project has been examined and modelled by Foster Wheeler. The Łagisza plant design was adopted as the reference case.

Vattenfall Heat Poland has proposed the oxycoal retrofit of the 480 MW PCC-fired Siekierki power plant in Warsaw. The project would capture 2.87 Mt/y CO_2. The project is reportedly in the planning stage; a start-up date of post-2015 has been suggested.

10.7.2 Post-combustion capture

PGE's Belchatów power plant currently consumes 32–35 Mt/y of lignite, in 2008, producing nearly 31 Mt of CO_2. This exceeded its EU-set ceiling by 4 Mt. In the years up to 2012, these levels are expected to remain the same, hence, in 2012, the company will be short by some 14–20 Mt of CO_2 permits. CO_2 output will increase further when the new lignite-fired 858 MW supercritical PCC block comes on line. This will be equipped with a pilot-scale Alstom/Dow amine scrubber to capture 100 kt/y of CO_2 from the plant's flue gases (about a third of the unit's output). This is forecast to be operational by 2011 and will be Poland's first CCS installation. In January 2010, PGE announced that it will also develop a larger CCS project at the site, aimed at capturing and storing 2.1 Mt/y of CO_2 from the Belchatów plant. This is scheduled to begin commercial operations by the end of 2015.

10.7.3 CO_2 storage

Potentially, Poland has a number of possible locations suitable for underground storage. In particular, the country has thick (several kilometres) of Permo-Mesozoic sedimentary rock complexes, combined with salinar tectonics (salt pillars, pillows and banks). Similar conditions also exist in parts of other countries that lie within the Permo-Mesozoic basin of Central and NW Europe.

Storage possibilities comprise enhanced gas recovery at operational sites in Borzecin and Kamien Pomorski (where CO_2 storage already takes place), depleted oil and gas reservoirs in the Western and South-Eastern regions (where EOR and/or EGR may be an option), several closed hard coal mines (where ECBM recovery may be a possibility), and saline aquifers in the central region. Between them, these have an estimated storage capacity of tens of billion tonnes. However, overall, the potential for EOR, EGR and ECBM in Poland is viewed as being relatively small compared to the potential offered by saline aquifers (Pyka, 2010). These is also the possibility for offshore storage below the Baltic Sea although its relative shallowness may present a problem.

Poland, together with northern Germany, has potentially the largest European on-shore deep saline aquifer reservoir suitable for CO_2 storage in Mesozoic sediments. In 2008, a national programme for defining the best storage sites was launched (Siemaszko, 2009). The programme is being led by the Ministry of Environment with support from the Polish Geological Institute. In 2009, a research programme was also initiated by the Ministry of Higher Education intended to support innovative energy technologies, such as advanced power generation and oxyfuel combustion technologies integrated with CCS.

Polish gas group PGNiG is reportedly co-operating with domestic and foreign partners on projects that would include capture and underground storage of CO_2 from power plants. There is considerable capacity available in former gas fields. As noted, PGNiG currently operates two active CO_2 sequestration sites at Borzecin and Kamien Pomorski.

11 Romania

The country has a long mining tradition and possesses significant energy resources that include natural gas, oil and coal. A significant proportion of its primary energy demand is met from indigenous energy resources. Much of the country's electricity comes from a combination of fossil fuels, nuclear power and hydro. Romania acceded to the EU in 2007 and, as a new Member State, an on-going goal is to produce energy efficiently, in line with EU requirements. The Romanian energy strategy (up to 2020) includes proposals that will have an impact on the future use of gas, oil, coal and nuclear energy. However, production of both gas and oil is expected to decline over the next decade.

In recent years, annual production in Romania has amounted to 2.5–3 Mt of hard coal plus 35 Mt of lignite. The current hard coal production level is expected to be maintained for some time although by 2020, will have risen to ~4 Mt/y. A further 4 Mt/y of hard coal is currently imported (~1 Mt from Russia). Hard coal is mined in one region (the Jiu Valley) with reserves estimated at 801 Mtce. Much is fed directly to local power plants. However, output is insufficient to meet needs and the balance is provided by imports. National lignite reserves are estimated at 1.36 Gt, deposits being located mainly in the southern part of the country (the Oltenia basin). Around 90% of the country's lignite production comes from seven major opencast sites, with most being supplied directly to nearby power and co-generation plants. Lignite production is forecast to increase slightly from ~33 Mt/y to 35 Mt/y by 2020.

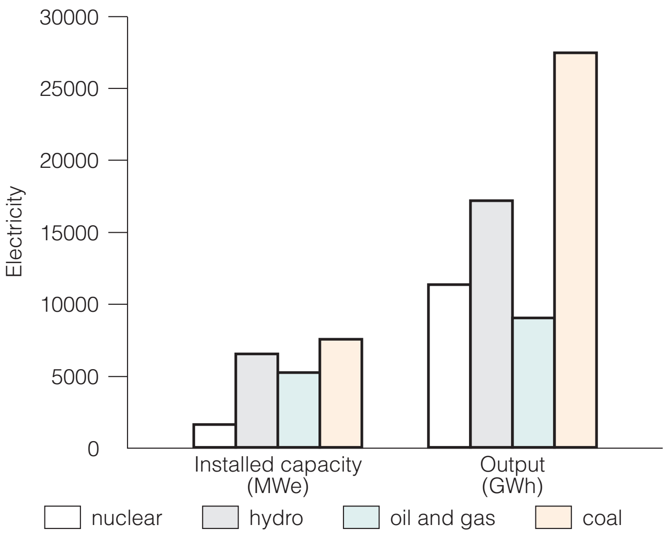


Figure 13 Romanian electricity generation (2008) (Sandulescu, 2009)

11.1 Power generation sector

In 2008, Romania's installed generating capacity amounted to 20.38 GW, and total generation to 64,772 GWh (Figure 13).

In the period up to 2020, electricity demand and production is forecast to rise significantly. Increased output is expected to come from a combination of renewables, nuclear, and thermal stations. However, with the latter, only coal-fired capacity is expected to increase and gas- and oil-fired output is expected to remain at current levels (Figure 14). In 2008, hard coal and lignite-fired plants generated ~40% of the country's electricity, with most of the balance coming from oil, natural gas and nuclear. Output from nuclear stations is expected to increase significantly when two new 700 MW reactors at the existing Cernavoda plant come on line by 2015. This will increase nuclear power output from the current level of ~10 TWh/y to 21.6 TWh/y by 2020 (Burdett, 2007).

Announced in 2007, Romania's new energy strategy is focused on the country's aim of becoming a major electricity exporter by 2020. By this time, Romania aims to be exporting some 15 TWh/y. During this period, an estimated €35 billion investment will be required in the country's energy infrastructure; some €17.2 billion will be used to increase output from new power generating capacity, plus to modernise and upgrade existing plants. It appears that most proposed new hard coal fired plant will depend on imported supplies (*see* Table 21).

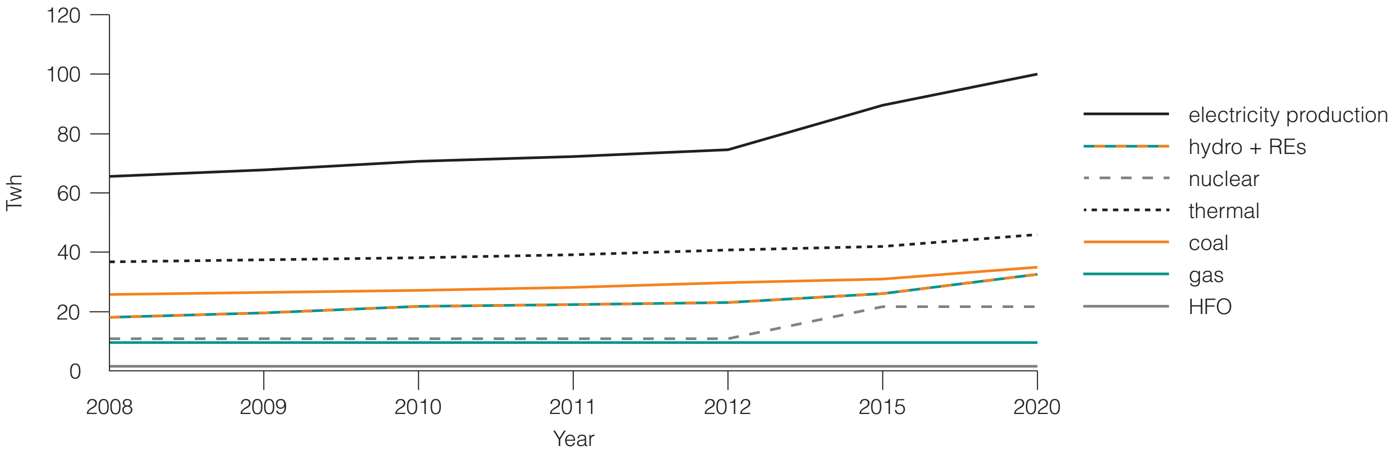


Figure 14 Romanian power generation up to 2020 (TWh) (estimate. Burdett, 2007)

Table 21 Romanian coal-fired power generation proposals

Developer(s)	Capacity, MWe	Comments
Energy Holding S.R.L.	400–800	
TM Power (Slatina Alro/Vimetco), InterAgro)	~1000	Sited at Turnu Magurele. Suggested start-up 2012 Feasibility study being undertaken by two Tractebel Engineering units Imported hard coal fired
Electrabel/Termoelectrica SA	400	Contracted to build a new unit at Termoelectrica's Borzesti power plant site Imported hard coal fired
Termoelectrica, E.ON Kraftwerke, ENEL	800	At Termoelectrica's Braila power plant site E.ON and ENEL will contribute investment capital New plant will probably use SC PCC technology It will be fully compliant with EU emission standards Estimated efficiency of ~46% Plant will be built carbon-capture-ready
ENEL, Global International 2000, Romelectro	800	Greenfield site at Galati – location being sought Project at early phase although feasibility study has been completed Estimated cost €1 billion Plant will probably adopt SC PCC technology
CEZ/Termoelectrica SA	400	Contracted to build a unit at Termoelectrica's Galati power plant site

11.1.1 Power plant modernisation

Many of the country's thermal power plants are now nearing the end of their design lifetimes, and an estimated 40% will require rehabilitation or replacement in the near future (de Coninck and others, 2005). More than 5 GW of thermal generating capacity is considered to be outdated and requires addressing; over 80% of the equipment at thermal power plants is more than 20 years old. It will be uneconomic to rehabilitate or upgrade some units, hence up to 3.5 GW of capacity could be shut down by 2015. Concurrently, 2.83 GW of thermal capacity may be rehabilitated. An estimated 1.95 GW of new thermal capacity is expected to be built during the same period (OECD/IEA, 2005).

The Romanian Government has approved a major overhaul of its thermal energy sector (Global Power Review, 2008). As part of this, a number of rehabilitation programmes are under way at existing coal-fired stations. Units at major stations such as Turceni, Rovinari, Isalnita and Mintia have undergone, or are in the process of undergoing, various performance and environmental upgrades.

On joining the EU in 2007, Romania became obliged to bring its power plant emissions into compliance with EU environmental standards by 2011. Power plants therefore have a tight deadline for achieving this reduction, and will not be allowed to continue operation if they fail to comply. Thus, environmental clean-up has become a priority in the Romanian power sector and, although so far limited, the latter includes measures to reduce emissions of SO_2 and NOx. A significant need for investment in FGD has been identified and installations are planned for a number of lignite-fired power/co-generation plants that include those at Craiova, Doicesti, Isalnita, Poroseni, Rovinari and Turceni.

In 2008, Austrian Energy & Environment (AE&E) was awarded a turnkey contract for the supply of FGD equipment for the first project, at the Turceni plant. The total value of the project was >€220 million. The *Turceni Thermal Power Plant Pollution Abatement Project* has elected to make use of a yen-denominated ODA loan from the Japan Bank for International Co-operation to finance the project. Under the contract with S C Complexul Energetic Turceni SA, AE&E is acting as the general contractor with responsibility for the engineering and construction, assembly and commissioning of the plant's four flue gas scrubbers. The first three units are scheduled for handover by the end of 2010, with completion of the fourth in 2013. Yokogawa (Austria) and its Austrian partners (Siemens Elin and Elin EBG Motoren) are supplying electrical equipment and instrumentation for the FGD systems (Processing Talk, 2008).

Emissions of NOx from the country's coal-fired power plants have also been flagged up as a major issue. For instance, at 20 kt/y, the Turceni plant has been identified as one of the top twenty NOx-producing point sources in the EU-27 (Hontelez and others, 2008). However, efforts are being made to reduce national emissions levels. To date, this has been limited to the installation of low NOx burners on a number of power and co-generation plants such as the hard coal-fired Suceava co-generation unit. These were installed as part of the plant's conversion (by Fortum Engineering) from lignite firing (CoalPower). The hard coal fired Iasi CET II co-generation plant has been similarly equipped and units at major stations such as Braila and Galati have also been fitted with low NOx burners; more installations are planned.

Alongside rehabilitation programmes, there have been several proposals for new coal-fired generating capacity and there are now a number at different stages in their development (Table 21).

11.2 Supercritical PCC plants and proposals

In recent years, studies have been undertaken exploring the potential for the introduction of the technology to Romania. For instance, the application of SC PCC technology for a hypothetical 2 x 600 MW plant at Mintia was examined. This was to replace existing low efficiency lignite-fired units, leading to increased efficiency and reduced CO_2 emissions. The use of SC PCC technology was also compared with alternative CCTs within a Romanian context (de Coninck and others, 2005). Currently, there are no supercritical PCC plants operating in Romania. However, should they proceed, several of the plants noted in Table 21 are likely to adopt SC PCC technology.

11.3 CFBC plants

At present, there are no CFBC plants operating in Romania. However, there are a number (>50) of small capacity (2–10 t/h steam; 2–12 MWth) bubbling fluidised bed boilers in operation, mainly in industrial power plants (Dragos and others, 2003). These were designed and developed in Romania over a twenty-year period by OVM-ICCPET, who has also carried out cofiring trials using lignite with petcoke and biomass in a 100 kW pilot plant. A design for a CFBC has also been produced.

Although, historically, work has been undertaken examining the potential of Romanian lignite in CFBC systems, its use for power generation was considered uneconomic. However, more recently, the issue has been re-evaluated and the technology is now being considered for the cofiring of coal with low cost biomass or waste-derived fuels. For instance, a feasibility study has been undertaken for the replacement of two outdated PCC units and a bubbling FBC-based plant at the Motru co-generation/district heating plant; these units would be replaced with a CFBC unit cofired on lignite and various locally available fuels such as agricultural wastes (straw and corn), wood waste (sawdust), and domestic waste. A 150 kW CFBC pilot plant has successfully cofired mixtures of lignite and sawdust and a design for a 50 MWth CFB boiler has been produced (Girjoaba1and others, 2006). Other studies have examined the potential for cofiring lignite with high CV carbon waste from the manufacture of carbon electrodes used for metals production. Currently, more than 1.2 Mt of this waste has been landfilled. Its potential as a CFB fuel has been examined (Dragos and others, 2005).

11.4 Cofiring activities

As noted, several studies are in hand, examining cofiring possibilities in CFB-based systems. Hungary is also a partner in the EU NETBIOCOF cofiring initiative, being represented by Universitatea Politehnica din Timisoara (UPT).

11.5 CCS activities

Coal-based CCS-related activities in Romania are limited although the country is represented in the EU GeoCapacity project by the Romanian National Institute of Marine Geology and Geo-ecology (GeoEcoMar) of Bucharest.

The new 800 MW coal-fired power plant being built by E.ON and ENEL at Termoelectrica's Braila power plant site will reportedly be built carbon capture-ready.

Although not coal-based, the Romanian oil and gas company Petrom Future Energy is developing several projects. The first is examining the feasibility of CO_2 separation during natural gas production and its subsequent re-injection for EOR applications in the Turnu oilfields. The project is focusing on a reservoir study and a pre-feasibility study of surface facilities. A second project is assessing the feasibility of an oxyfuel-based pilot-scale power plant, also to be located in the Turnu field. The assessment covers the basic engineering of the oxyfuel combustion process, the economic and financial profile, the risk assessment, and associated regulatory issues (Petrom, 2008).

12 Spain

Spain depends on imports of oil, gas and coal to meet a significant proportion of its energy needs. The latter is the country's only significant indigenous energy resource, although output has declined in recent years. As a consequence of this decline, coupled with increasing electricity demand, the percentage of electricity generated by coal-fired plants has fallen, even though overall, the amount has increased. However, in the future, output could rise again as there are several new power plant + CCS projects under consideration.

Spanish hard coal reserves are estimated to be 1156 Mt, and lignite, 354 Mt (Euracoal, 2009). In 2007, Spain produced 3.5 Mt of hard coal, much of which was burnt in local power stations. It also produced 4.4 Mt of anthracite (OECD/IEA, 2009). Hard coal is produced in several parts of Spain (Asturias, Castilla-León, Aragón, León-Palencia, Ciudad Real, and Cordoba) mainly from deep mines. There are also major opencast operations in Aragón and Ciudad Real, and between Asturias and León. A large amount of hard coal (16.5 Mt in 2008) was also imported for power generation; the main suppliers are Colombia, South Africa, Australia and Indonesia.

The country's main lignite fields are in Galicia, Ginzo de Limia, Arenas del Rey, and Padul. The largest individual deposit is located at the opencast As Pontes mine, owned by Endesa. In 2007, Spain produced a total of 3.1 Mt of subbituminous coal and 6.2 Mt of lignite (OECD/IEA, 2009). Most was used in power plants located close to the mines. However, there has been a significant decline in lignite production during the past few years as accessible deposits have become depleted.

12.1 Power generation sector

Spain's total installed power plant capacity at the end of 2008 is shown in Figure 15. The main electricity providers were hydro, hard coal + lignite, natural gas, nuclear and wind. Spain's coal-fired capacity amounts to 11.9 GW (OECD/IEA, 2009) fired on a combination of indigenous and imported hard coal, and until recently, lignite.

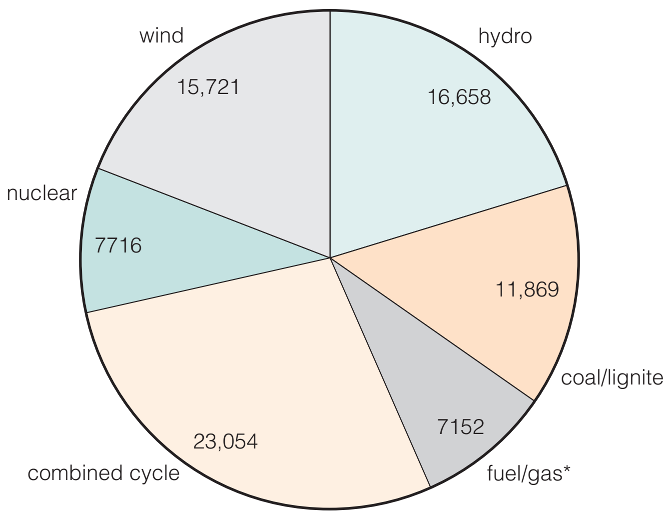
In recent years, total electricity generated has been around 300–305 TWh/y. Typically, the bulk of this has come from coal (81 TWh), gas (80 TWh) and nuclear (57 TWh) (Global Power Review, 2008). Primarily through cost considerations, coal-fired stations typically operate for ~6000 hours a year, far longer than natural gas or oil-fired units. In 2008, the biggest generators were Endesa, Iberdrola and Union Fenosa. These three supply most of Spain's electricity; Iberdrola has a 40% market share, Endesa has 39%, and Union Fenosa 15%.

There are more than 20 major coal-fired Spanish power plants, most of which are based on variants of conventional PCC technology using subcritical steam conditions. Some are fired on combinations of domestically-produced and imported bituminous coal, anthracite and lignite. The biggest individual coal consumer is Endesa's 1400 MWe As Pontes power plant, that uses nearly ~9 Mt/y. The next largest are the Compostilla, Meirama and Teruel plants that each use between 3.5 and 4.5 Mt/y (CoalPower).

12.1.1 Power plant modernisation

For some years, a series of power plant updates and modernisation programmes have been undertaken by major Spanish generators; several remain on-going. For instance, Endesa has a €54 million on-going programme focused on its biggest stations. This includes the modernisation of steam turbines at the As Pontes, Compostilla, Teruel, Litoral and Los Barrios plants. The upgrades (due for completion in 2010) will extend turbine working life by ~25 years. Not all stations have been upgraded in the same manner, reflecting local circumstances. For instance, The As Pontes station (4 x 350 MWe) was originally designed to fire local subbituminous coal, but has since been converted to operate solely on imported low sulphur hard coal. As part of this, various control system upgrades have been installed. The Los Barrios plant was similarly re-equipped. The modernisation of the Endesa plants is expected to increase efficiency by around three percentage points, reduce coal consumption by 290 kt/y, and reduce annual CO_2 emissions by 550 kt.

Between 2007 and 2011, Union Fenosa is investing €260 million to make efficiency and environmental improvements to a number of its stations. For instance, its La Robla station is being equipped with a sophisticated spatial combustion monitoring system in the boiler that will allow monitoring of oxygen, NOx and CO profiles above the burners. The aim is to minimise the levels of unburnt carbon in the ash.



* includes Puertollano IGCC plant

Figure 15 Make-up of Spanish installed generating capacity in 2008 (MW) (OECD/IEA, 2009)

In recent years, environmental control measures have been applied to all major Spanish coal-fired power plants. To reduce SO_2 emissions, FGD plants have been installed on most of the bigger stations (including units at Abano, Alcudia, Compostilla, Guardo, La Robla II, Lada, Litoral de Almeria, Los Barrios, Puente Nuevao, Narcea III, Soto de Ribera, and Teruel). In some cases, installation programmes remain on-going. The majority of plants now use limestone-gypsum FGD technology, although the Alcudia power plant uses a spray dryer scrubber, and the plants at Granadilla (Tenerife) and Barranco de Tirajana (Gran Canaria) use seawater-based desulphurisation systems. In 2009, Iberdrola SA opened a €60 million FGD unit at the Lada power plant where SO_2 emissions are expected to fall by 91%. The Le Perada CFBC-based plant uses limestone addition for SO_2 control. Improvements are also being made to the ESPs at Narcea II and La Robla I.

Union Fenosa is converting its lignite-fired Meirama plant to fire imported low sulphur bituminous coal. This is expected to reduce slag production by 50%, reduce CO_2 emissions by 24%, and reduce SO_2 and NOx emissions by 74% and 50% respectively. All of the bigger stations now deploy some form of NOx control. This takes the form of either low NOx burners or overfire air systems. Some stations (such as Abano, Alcudia and La Robla) use both. Union Fenosa is installing new low NOx burners at La Robla II, Narcea III and Meirama.

12.2 Supercritical PCC plants and proposals

The use of supercritical conditions is currently limited to Unit 4 of the Lada power plant. This uses steam conditions of 26 MPa/540ºC/540ºC. Although there appear to be no immediate prospects, Union Fenosa has reportedly selected a number of sites suitable for the construction of new SC PCC plants in the future. In 2007, it was reported that Endesa had options on generation assets that included 1600 MW in new SC PCC plants.

12.3 CFBC

There are several small Spanish facilities based on bubbling fluidised bed technology, firing municipal waste and/or biomass. There is also a single coal-fired CFBC unit operating in Spain, the 50 MWe Le Perada plant operated by Hulleras del Norte, located at Mieres. Commercial operations began in 1994. The unit (construction of which was partially funded under the EU Thermie programme) is fired on combinations of run-of-mine coal, waste anthracite (culm), and wood waste. This results in a heterogeneous fuel with a very high ash content (65%) and a low CV. The CFBC unit uses Foster Wheeler technology. Babcock & Wilcox Espanola acted as the main contractor, responsible for its design and construction. For an annual operating period of 6500 hours, total fuel requirements are typically 242 kt culm, 143 kt run-of-mine coal, and 20 kt of wood waste (although the latter varies).

Historically, several Spanish organisations such as CIEMAT have examined the use of CFBC within a Spanish context. CIEMAT has undertaken R&D, modelling and pilot-scale studies using both lignite and bituminous coal, also cofired with biomass.

CFBC technology will now feature in the on-going Spanish CIUDEN project. Part of this will develop a 30 MWth CFBC oxyfuel combustion pilot project at El Bierzo in Spain. A 500 MWe oxyfuel CFBC-based plant (OXYCFB300 project) could also be later built by Endesa; potentially, this could be operational by 2015.

12.3.1 Supercritical CFBC plants

Endesa and Foster Wheeler have undertaken a study for an 800 MWe CFB-based power plant using supercritical steam conditions. A conceptual boiler design has been developed (Hack and others, 2008).

12.4 Pressurised fluidised bed combustion (PFBC)

The Escatron PFBC plant is one of only a handful of such units in the world. It was built as a repowering exercise by a consortium comprising ABB Carbon and Babcock & Wilcox Espanola (B&WE), replacing an old coal-fired boiler. Initial operations started in 1990. The plant is based around a single P200 module and generates 80 MWe – 63 MWe from a steam turbine and 17 MWe from a gas turbine. Fuel is local high sulphur (5–8%), high ash (25–36%) 'black lignite'. Annual consumption is around 250 kt. Plant particulate emissions are controlled using a system of nine cyclones; one of these has been replaced with a high pressure, high temperature ceramic filter supplied by B&WE. However, reports in 2010 suggest that the plant had now been closed (OECD/IEA,2009).

12.5 IGCC

Puertollano is the location of Spain's 335 MWe coal/petcoke-fuelled IGCC plant. The plant was built by ELCOGAS, a consortium of eight European utilities and three technology suppliers, set up in 1992 to undertake the planning, construction, management and operation of the project. The Puertollano plant uses a Krupps-Koppers PRENFLO single stage, oxygen-blown entrained flow gasifier with dry pulverised coal feed. Fuel is transported pneumatically to the gasifier using nitrogen as carrier gas. The coal/petcoke is fed to the gasifier with oxygen (85%), steam and nitrogen as moderator through four horizontally arranged burners located in the lower part of the gasifier. The reaction chamber has a membrane wall with an integral cooling system that produces pressurised steam. Gasification takes place at a pressure of 2.5 MPa, in the temperature range 1200–1600ºC (Fernando, 2009). The plant started commercial operation in 1996 with natural gas, but has operated with syngas since 1998.

The plant's basic fuel is local high ash (~40+%) subbituminous coal blended in equal proportion with high sulphur (5.5%) petcoke from the Puertollano REPSOL refinery. At full operational capacity, the plant burns 700 kt/y of mixed fuel. However, there have been several trials where the normal fuel blend has been successfully co-gasified with Meat and Bone Meal (MBM – 1% and 4.5%, in 2001) and olive oil waste (Orujillo – 1–4%, in 2007-08).

12.6 Cofiring

During the past decade, limited trials of biomass cofiring have been carried out in conventional PCC power plants. Some investigative work remains on-going. In 2007, Endesa had 350 MW of projects under development for biomass cofiring at its coal-fired power plants (Global Power Review, 2008).

Between 1999 and 2002, Spain's first cofiring project (managed by the Natural Resources Division of CIRCE) was undertaken at the 160 MWe black lignite-fired Escucha power station. The project included full-scale cofiring trials where up to ~5% (~8 MWe) of the station's electricity was produced using forestry residues, harvested close to the plant. This was handled separately from the coal and injected into the boiler independently through a central duct in the coal burners. This helped minimise investment costs. Reportedly, no operational problems were encountered.

Elsewhere, as noted, the HUNOSA CFBC plant located Le Perada cofires coal, mining waste and waste wood, and the Puertollano IGCC plant has co-gasified MBM and olive oil waste.

12.7 CCS activities

The Spanish *Climate Change and Clean Energy Strategy Horizon 2007-2012-2020* includes CCS as an option to combat climate change and considers it to be an important technological option. The Government is supporting R&D and innovation for CO_2 capture and storage, in collaboration with several national research centres and companies active in the energy sector. These include CIEMAT, a public research agency involved in the fields of energy and environment, and the National Institute for Coal (INCAR), a research institute forming part of the Spanish Council for Scientific Research (CSIC). There are also a number of utilities, private companies and universities active in CCS-related work (Aristizabal, 2009). A summary of Spanish involvement in major CCS-related programmes is given in Table 22.

A major focus for CCS activities is the *Spanish CO2 Technology Platform* (PTECO2), created in 2006 to mirror the ETP ZEP. Supported by the Spanish Government, its 160+ members now include industrial partners, R&D providers and universities. The platform's main objective is the creation of an environment favourable to RD&D and increased technical expertise in the area of CCS. To date, two major initiatives have been completed, namely a Vision Document, and a Strategic Overview and R&D Agenda; these are helping to identify industries and technology centres for the development of CO_2 capture and storage in Spain (Spanish CO2 Technology Platform, 2009). The platform's main goals are:

- to advise on the technological national strategy on CO_2 capture and geological storage;
- to support the R&D initiatives for the energetic efficiency in big industrial facilities;
- to advise on the legal framework;
- to study specific problems related to the reduction and capture and storage of CO_2 ;
- to support R&D alternatives in the short, medium and long term for CO_2 capture, transport, and storage;
- to establish alliances that strengthen technological progress needed to fulfil the EU aims for 2020.

The Spanish Association of CO2 (AECO2) is a non-profit entity formed in 2007 that undertakes complementary and support work for PTECO2.

12.7.1 Post-combustion capture

Several Spanish organisations are engaged in development and deployment activities in the area of post-combustion capture technologies for coal-based systems. Currently, the largest proposal is for the installation of an amine scrubber-based system at Union Fenosa's anthracite/bituminous coal-fired La Robla power plant in León.

The SOSTENER project is being undertaken by the LEIA Technology Centre (leader) and the University of Pais Vasco. This is developing and testing new chemical solvents suitable for post-combustion CO_2 capture from industrial emissions. This four-year project was funded partially by the Basque Government and was due for completion in 2009.

The Spanish utility Iberdrola owns the UK's Scottish Power and is engaged in a pilot-scale post-combustion test programme at the latter's Longannet station. The pilot plant is using Aker Clean Carbon amine scrubbing technology. It started up in September 2008 and is engaged in a programme of solvent and operational testing.

12.7.2 Oxyfuel combustion

In 2006 CIUDEN (Fundación Ciudad de la Energía) was created by the Spanish Government, involving three ministries (environment, industry and economics). CIUDEN is a research and development foundation set up with the objective of developing and demonstrating efficient, cost-effective and reliable CO_2 capture and storage. A €84 million CO_2 capture test facility is under construction at El Bierzo and will become operational in 2010. This will include both oxyfuel pulverised coal (20 MWth) and circulating fluidised bed (30 MWth) combustors. A range of fuel types including different coals, petcoke and possibly biomass has been proposed. The main objective is the development of a demonstration plant by 2015. The CIUDEN project will provide essential support in the scaling up of the technology and will feed data into a major oxyfuel demonstration project proposed for Endesa's Compostilla power plant site.

Table 22 Spanish involvement in major CCS-related programmes (PTECO2, nd)

Project type	Project	Spanish partners	Comments
CO_2 capture and storage			
R&D	CENIT CO2	ENDESA, Union Fenosa consortium	Four-year project (2006-09)
R&D	Dynamis	ENDESA	
Pilot	PSE CO2	CIEMAT-led consortium	Includes development of 14 MWth pre-combustion CO_2 capture and H2 production pilot at Elcogas Puertollano IGCC Completion late 2009
Pilot	Ciuden	Ciudad de la Energia Foundation	Development of 20 MWth PCC and 30 MWth CFBC oxyfuel pilots at El Bierzo
Commercial demo	OXYCFB300	ENDESA	At ENDESA power plant To develop 500 MWe oxy-combustion-based CFBC Operational by 2015
Commercial demo	La Robla	Union Fenosa-led	To develop ~500 MWe power plant with post-combustion CO_2 capture
CO_2 storage			
R&D	GeoCapacity	IGME, ENDESA	European geological CO_2 storage capacity
Pilot	Castor	Repsol YPF	Storage of CO_2 from Tarragona refinery in depleted Casablanca oil field
Commercial demo	ENDESA CO_2 storage demo	ENDESA	Characterisation of four saline aquifers
CO_2 capture			
R&D	CENIT II – SOST CO2	Consortium led by Carburos Metalicos and Iberdrola	Examining new sustainable uses for CO_2
R&D	NanoGloWa	ENDESA	Development of nano-structured membranes for CO_2 capture from flue gases
R&D	CACHET	CSIC, ENDESA	Development of technologies to reduce CO_2 from NGCC power plants by 90%
R&D	SOSTENER	LEIA Technology Centre, University of Pais Vasco	Development of new CO_2 capture sorbents
R&D	MICROALGAS	Led by Aurentia	CO_2 capture by micro seaweeds + biofuel production
R&D	MECOLIX	Universities of Cantabria and Cadiz, ICMAN-CSIC	Effects of CO_2 leakage on marine environment
Pilot	La Pereda	ENDESA, HUNOSA, CSIC	Development of carbonate looping post-combustion technology (2008-11)

OXYCFB300 demonstration project

Endesa and CIUDEN have created a joint venture to develop a CCS project at the Compostilla II power plant. CIUDEN has committed to a 30% stake in the OXYCFB300 project, estimated at more than €200 million. Foster Wheeler (FW) is involved in the project as the main technology developer; the plant will be based around a Foster Wheeler oxyfuel 500 MW *Flexi-Burn* CFB unit. Praxair will provide the main auxiliary components, the air separation unit, and the CO_2 processing unit. Potentially, the plant could be operational by 2015.

As part of the project's development, a FW-Praxair-Endesa joint feasibility study has been carried out for a Spanish greenfield power plant of ~500 MWe (Eriksson and others, 2009). It is estimated that within the first 20 years of operation, this could capture and geologically store some 18 Mt of CO_2. As part of the project, Endesa is examining and characterising four saline aquifers that have the potential for CO_2 storage. The objective is to identify at least two CO_2 storage sites before 2015.

In December 2009, the OXYCFB300 project was selected as one of the EU's CCS demonstration plants. The project will be partly financed with €180 million from the European Energy Programme for Recovery with an extra €280–450 million in the form of EU Emission Allowances. The EC contribution of €180 million for Phase I will be spilt between the partners in the ratio: Endesa 45%, CIUDEN 51%, and Foster Wheeler 3%. The project will proceed in two stages. During the first stage (2009-12) CIUDEN will develop and validate the oxyfuel fluidised bed concept. It will also study the geological storage of CO_2 via an experimental plant in Hontomín (Burgos) and, in order to resolve associated technical issues, will construct a test unit for CO_2 transport. Endesa, as project co-ordinator, will carry out technical feasibility studies, analyse risks, and undertake the basic engineering for a 300 MWe demonstration project. Endesa will also define and characterise suitable locations for CO_2 generated by the OXYCFB300 demonstration plant and undertake basic engineering for the necessary pipeline infrastructure. During Phase II of the project (2013-15), the partners will focus on the construction and operation of the 300 MWe Plant and storage of up to 1 Mt/y of CO_2 (Endesa, 2010).

12.7.3 IGCC + CCS

A 14 MWth pilot facility is being developed and integrated with the Puertollano 335 MW IGCC plant. The project forms part of a national strategic research programme (PSE-CO2) aimed at developing and demonstrating the technical and commercial feasibility of large-scale CCS. The €18.5 million budget is being provided partly from the state and regional governments, and partly by the owners of ELCOGAS (Endesa, EdF, Iberdrola, Hidrocantábrico, ENEL, EDP, Siemens, BWE, and Krupp Koppers).

The CO_2 capture plant will rely entirely on commercially available, proven technology to treat a portion of the syngas from the IGCC plant. This will be passed through a water-gas-shift reactor which will reform the gas into a mixture consisting of ~50% hydrogen and 39% CO_2, which combined with a pressure of 16 MPa, will provide conditions suitable for CO_2 capture. Linde Gas has been contracted to deliver a turnkey CO_2 absorption plant; this was due for completion in 2009. It will capture 35 kt/y of CO_2, whilst producing 700 t/y of hydrogen that will be fired in the IGCC plant. The project is focused on bench-, laboratory- and industrial-scale validation of pre-combustion capture technologies. Other technologies such as solid adsorbents and membranes may be evaluated later. Expertise developed as part of the programme will contribute towards the development of the Chinese GreenGen IGCC project (Utgård, 2008).

13 United Kingdom

The UK's coal resources are estimated at around 2 Gt, with proven reserves amounting to 220 Mt (Euracoal, 2009). In 2008, the country produced 17.6 Mt coal; 8.1 Mt of this came from deep mines and 9.5 Mt from opencast operations. A further 43.9 Mt of hard coal was imported. Thus, total UK coal supply amounted to 57.9 Mt. The biggest overseas coal suppliers are currently Colombia, South Africa, Australia, Indonesia and Russia. The biggest coal-consuming sector is power generation (47.8 Mt), followed by coke manufacture (5.88 Mt) and blast furnaces (1.2 Mt) (DECC, 2009).

13.1 Power generation sector

At the end of 2008, total installed generating capacity of major producers amounted to 76.45 GW, with an overall total of 83.54 GW (DECC, 2009) (Figure 16). Most of the UK's electricity is generated by a combination of coal, gas and nuclear plants; major stations are noted in Table 23. In 2008, UK generators produced 385,560 GWh and a further 12,294 GWh were imported, giving a total supply of 400,671 GWh.

13.1.1 Power plant modernisation

Many of the larger coal-fired stations have been modernised and upgraded in recent years. One of the biggest projects currently under way is the turbine upgrade/replacement of low pressure and high pressure turbines on all six units at Drax. This £100 million project started in 2008 and will take Siemens Power Generation around four years to complete. It is estimated that this will boost efficiency (to around 40%, LHV), helping reduce annual CO_2 emissions by a million tonnes. Average heat rate improvement is expected to be 4–5%, with high pressure cylinder efficiency improving from 87% to 93%. Coal consumption should be reduced by 0.5 Mt/y. Turbine upgrade programmes have also been undertaken at other stations (for instance, at Eggborough). This involved replacement of the HP inner module (new inner casing, inlet nozzle belt, new rotor with eight stages of advanced rotating blades, and a new set of fixed blade diaphragms).

In 2008, RWE npower undertook a £65 million programme of power station improvements that included the installation of new steam turbines at its Aberthaw and Didcot B stations; these moves are expected to save 420 kt/y of CO_2. Upgraded control systems have also been installed in a number of stations such as International Power's Rugeley B station (Figure 17). State-of-the-art turbine supervisory and vibration monitoring installation upgrades have been undertaken at the Uskmouth power plant, replacing outdated systems that had previously caused operational problems.

As elsewhere, in order to comply with EU emissions legislation, all of the UK's major coal-fired power stations now employ some form of flue gas clean-up system. Particulates are captured predominantly using ESPs, and SO_2 through the use of several variants of FGD (mostly limestone-gypsum units, plus several seawater-based plants). The installation of FGD has allowed stations to meet the Large Combustion Plant Directive and to continue generating post-2015. Drax was the first UK power station to be fully

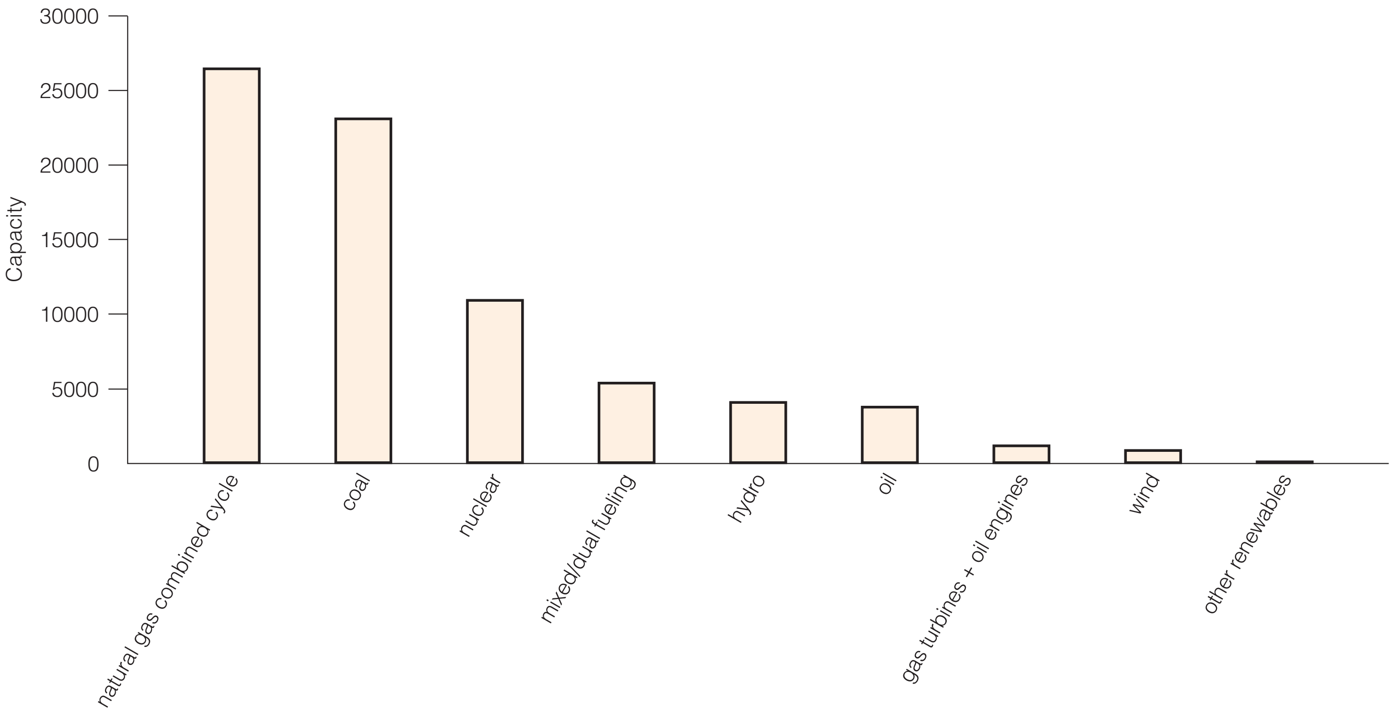


Figure 16 Generating capacity of major UK power generators (DECC, 2009)

Table 23 Major UK coal-fired power stations (May 2009) (DECC, 2009)

Operator	Plant	Main fuel(s)	Capacity, MWe
AES	Kilroot	Coal, oil	600
Drax Power	Drax	Coal	3870
EdF Energy	Cottam	Coal	2008
	West Burton	Coal	2012
E.ON UK	Kingsnorth	Coal, oil	1940
	Ironbridge	Coal	970
	Ratcliffe	Coal	2000
RWE npower	Aberthaw B	Coal	1586
	Didcot B	Coal, gas	1958
Scottish & Southern Energy	Ferrybridge C	Coal, biomass	1960
	Fiddlers Ferry	Coal, biomass	1980
Scottish Power	Cockenzie	Coal	1152
	Longannet	Coal	2304
Uskmouth Power	Uskmouth	Coal, biomass	363
International Power	Rugleley B	Coal, biomass	1000

Figure 17 Updated plant control system installed in International Power's 2 GW Rugeley B station (photograph courtesy of Russell Mills Photography)

retrofitted (by Doosan Babcock) with FGD plant. Annually, the plant now produces between 1.5 and 1.75 Mt of gypsum, all sold commercially. The most recently completed project was at the Aberthaw station, where a £235 million FGD plant was completed in 2009. NOx from UK power plants is controlled using several variants of low NOx burner, usually with OFA or BOFA systems.

13.2 Supercritical PCC plants and proposals

The UK currently has no SC PCC plants in operation although several are proposed. All are proposed to be carbon capture ready (Table 24). There have also been several other proposals, although in November 2009 RWE npower announced that it would no longer pursue proposed SC projects at Tilbury and Blyth, as under current market conditions they felt unable to make an economic case for new coal-fired power stations in the UK. The company is considering the implications of the Government's policy review on the conditions to be applied to new coal-fired stations. A joint venture comprising Peel Energy CCS, RWE npower and DONG Energy for a new SC station at Hunterston will also not now proceed. The company stated that it will not submit a bid to progress to the next stage of the UK's current CCS competition. However, in June 2010, Ayshire Power (owned by Peel Energy) submitted a proposal for a new 1600 MW SC PCC plant to be built near Hunterston.

13.3 CFBC

The UK formerly had several major coal-fired CFB boilers in use, although only one is currently operating (but now cofired). One of the last coal-only plants to operate was a 28 MWth CFB unit based on Battelle technology at an ICI site in Dumfries. This closed in 1998.

There are currently only three sites still using CFBC technology. One is the co-generation plant at Slough Estates, near London. This incorporates two CFBC units that were originally designed to operate on coal and natural gas. However, there has been a gradual replacement of coal with various biomass and waste-derived fuels and in 2000, the plant ceased cofiring coal. In Scotland, the Caledonian Paper Mill, operated by UPM-Kymmene, relies on a CFB boiler for

Table 24 UK supercritical PCC power plant proposals

Developer	Location	Capacity, MWe	Schedule	Fuel	Comments
E.ON	Kingsnorth	1600	Notional commissioning date of 2012, but project deferred 2–3 years in October 2009	Coal	Dry cooling, FGD and SCR proposed Funding for FEED CCS studies (June 2010)
E.ON	High Marnham	1600	Start-up 2012 suggested	Coal	Considering construction of 1600 MW CCGT plant on site (Nov 2009)
SSE	Ferrybridge	800	Start-up post-2014	Coal	Consortium includes Doosan Babcock, Siemens, UK Coal
Iberdola/ Scottish Power	Longannet	2304	Start-up 2012	Coal	Funding for FEED CCS studies (June 2010) Pilot carbon capture plant operating on site
Iberdrola/ Scottish Power	Cockenzie	1152	Start-up 2012	Coal	Feasibility study under way
Ayrshire Power (Peel Energy)	Hunterston	1600	na	Coal ('multifuel')	Planning application made in June 2010. CCS proposed.

steam production. This has a maximum capacity of 58 MWth and is fired on combinations of coal (80–85%), wood bark (5–10%) and wastewater treatment sludge (5–10%).

In Middlesborough, a biomass-fuelled BFB boiler is operating at a site belonging to SembCorp. The unit was supplied by Foster Wheeler and started up in 2007.

In early 2010, an order was placed by RWE npower Renewables with Metso Power and Aker Solutions for a 50 MWe biomass-fired CFB co-generation unit plus a flue gas treatment plant for a Scottish paper mill. Aker will supply all major plant items excluding the fluidised bed boiler and flue gas system which will be provided by Metso Power. The new unit will replace old coal-fired capacity and should be operational by 2013.

13.4 IGCC + CCS proposals

Powerfuel project, Hatfield Colliery

The UK coal producer Powerfuel, which is 30% owned by the Russian mining company Kuzbassrazrezugol (KRU), owns and operates the Hatfield colliery via its subsidiary, Powerfuel Mining Ltd. The previously closed mine was re-opened in 2007 and has access to ~100 Mt of coal. In 2003 the UK Government gave consent for the construction and operation of a 430 MW IGCC plant at the site, although Powerfuel now plans to build a 900 MW (gross) minemouth IGCC power project. The funding structure to support the project is currently being developed by another Powerfuel subsidiary, Powerfuel Power Ltd.

The project will be developed in two phases. Phase I will involve the development of a 900 MW syngas-ready CCGT power island which will operate on natural gas alone. During Phase II, the plant will be converted to IGCC operation through the addition of a coal gasification island, together with an associated carbon capture facility (capture target of ~90%). CO_2 captured will be piped to the North Sea and used for EOR purposes. Main technology suppliers are expected to include Shell, Air Products and GE. The EPC tender process for Phase I of the project is under way and a full FEED study is being undertaken. Phase I consent for the plant was granted in February 2009. A completion date of 2013 has been suggested for Phase II. In December 2009, it was announced that the project was to be awarded EU funding of €180 million (£164 million) as a selected CCS demonstration project. These funds will be matched by the UK Government.

Killingholme, Yorkshire

In 2006, E.ON announced proposals for a 450 MW IGCC plant to be built on a site next to the existing Killingholme power station. This was to be designed as retrofittable for CCS (90% capture). A total capture of 2.5 Mt/y was suggested, this being piped to the North Sea for EOR applications. A pre-FEED study was undertaken and a start-up date of 2012-13 suggested. However, the project is currently on hold.

Coastal Energy, Teesside

Coastal Energy Ltd, a joint venture between Centrica and Progressive Energy, planned to build an 850 MW IGCC plant with CO_2 capture (~85%) on a brownfield site in Teesside. The technology selected comprised oxygen-blown, entrained flow quench gasification, fuelled on up to 2 Mt/y coal and petcoke (50:50) plus possibly up to 10% biomass. Up to 5 Mt/y CO_2 capture was anticipated, to be piped to the North Sea via a network of pipes also carrying CO_2 from other power plants and industrial processes in Teesside and the

North East; this was being developed by COOTS Ltd, which was also a joint venture between the two companies. However, in May 2009, Centrica withdrew from project, selling its 50% stake to Progressive Energy. A start-up date of 2012-13 had been suggested although the project is currently on hold.

Valleys Energy Ltd, Onllwyn, South Wales

Valleys Energy Ltd (a partnership that includes Progressive Energy) has developed a proposal to build a 450 MW IGCC plant at Onllwyn, near Drym, in the South Wales coalfield. The plant would use oxygen-blown, entrained flow gasification, fuelled on around 1.05 Mt/y of coal. A 305 MW GE 9FB gas turbine and a 210 MW steam turbine has been proposed. Around 85% CO_2 capture is planned (~2.4 Mt/y) using a physical solvent-based process. This would be piped offshore for storage in a sandstone reservoir. Current status of the project is unclear although it was reportedly still live in mid 2009.

13.5 Cofiring

The UK Renewables Obligation (RO) was introduced in 2002, providing financial incentives for power generators to take up renewable sources (including cofiring). It also imposed a legal obligation on all licensed suppliers to meet a defined percentage of retail sales from renewable sources (effective from 2002 to 2027). The obligation was 5.5% in 2005-06, increasing to 15.4% in 2015-16. Biomass cofiring remains eligible until 2016.

The introduction of the RO produced a relatively large increase in biomass cofiring that involved all of the UK's major generators operating coal-fired plant. A series of trials and commercial operations, using both direct and indirect cofiring techniques has since been pursued. To date, UK utilities have fired significant quantities of biomass and continue to do so, with most major PCC stations actively firing or trialling cofiring (Table 25). However, the level of cofiring activity at individual stations continues to vary considerably. In 2008, RWE npower, one of the UK's bigger cofirers, used 135.6 kt of biomass at its stations, producing 178.2 GWh of electricity and avoiding ~156 kt of CO_2.

Major UK power stations are (or have been) typically cofiring biomass up to 6% heat input, predominantly by pre-blending dry biomass in the coal yard. Technical limitations to the cofiring ratio have been related mainly to the capacity of the handling and blending systems and the performance of the coal mills; this depends on the type of biomass and mill. Generally, operations have confirmed that biomass cofiring has had a positive effect in reducing levels of CO_2, NOx and SO_2 emissions from coal-fired plants. Most of the ash produced has remained saleable.

The biggest individual project is at Drax, where a £10 million EPC contract is being undertaken by Doosan Babcock for the supply of direct injection biomass cofiring systems to all of its six coal-fired generating units. On completion, the cofiring facility will be the largest of its type in the world. To date, £80 million has been invested in a processing unit for biomass (wood, straw and other plant-based fuels). However, in May 2010, Drax announced that it had suspended its cofiring plans and that the new unit will operate at only a fraction of its capacity as it is cheaper to continue burning coal. Drax is one of a number of companies delaying investments in new biomass power stations because of uncertainty over the Government's policy on long-term subsidies.

As noted above, the CFB boiler at UPM-Kymmene's paper mill also cofires coal, wood bark and wastewater treatment sludge.

13.6 CCS activities

13.6.1 Post-combustion

UK post-combustion capture competition

In November 2007, the UK Government launched a competition to support a demonstration of the full chain of CCS technologies on a commercial-scale coal-fired power plant. Post-combustion carbon capture was selected as the most likely to have the biggest impact on global CO_2 emissions and because of its potential for retrofitting to existing plants once the technology has been demonstrated at a commercial-scale. The project selected will demonstrate the technology on a UK coal-fired power station, with CO_2 produced stored offshore. The Government will consider a phased approach to the project as long as the full CCS chain is demonstrated by 2014, and the project captures ~90% of the CO_2 emitted by the equivalent of 300–400 MW generating capacity as soon as possible thereafter. The Government's advisory Climate Change Committee, in its first report issued in December 2008, stated that coal-fired plants should only be built on the expectation that they will be fitted with CCS equipment by the early 2020s. The Government sees significant export potential for UK CCS technology developers.

In mid 2008, it was announced that four bidders (from nine contenders) had pre-qualified in the CCS competition. These were BP Alternative Energy International Ltd, E.ON UK Plc with a project for its planned new Kingsnorth coal-fired plant, Peel Power, and Scottish Power with a project at Longannet power station. Currently, two projects remain live, namely those at Kingsnorth and Longannet. In March 2010, funding was awarded to both to support design and development/ FEED studies. In June 2010, it was announced that Ayrshire Power (which is owned by Peel Power) had applied for full planning permission for the construction of a new £3 billion coal-fired power plant at Hunterston, to be located between the existing Clydeport coal handling facility and the Hunterston nuclear power plant. Reportedly, the proposed 1600 MW plant will adopt supercritical steam conditions and be equipped with some form of carbon capture equipment.

The UK's April 2009 budget pledged to reduce UK CO_2 emissions by 34% (on 1990 levels) by 2020 and, as part of this, announced further support for the development and application of carbon capture measures. A new funding mechanism will be developed for CCS that is expected to

Table 25 Cofiring operation in major UK coal-fired power plants (Colechin and Canning, 2004; Livingston, 2008)

Station	Capacity, MW	Generator	Examples of cofiring fuels	Cumulative GWh (2007)
Aberthaw	1455	RWE Npower	Various – tallow/palm oil, PKE, olive pellets, sawdust, wood chips, miscanthus, rape grass, willow	302
Cockenzie	1200	Scottish Power	Wood	103
Cottam	2000	EdF	Various – SRC willow	262
Didcot A	2100	RWE Npower	Wood, animal feeds, sawdust, crop husks and pulp, grass, PKE, olive pellets	259
Drax	4000	Drax Power	Various – wood, sunflower pellets, peanut shells, straw pellets	1004
Eggborough	1960	British Energy	Various – solid and liquid biomass	414
Ferrybridge	2035	SSE	Various – wood, olive cake, PKE	1833
Fiddlers Ferry	1995	SSE	Various – olive pellets, palm kernel expellers, citrus pulp pellets, wood	1126
Ironbridge	970	E.ON UK	Various – wood, palm kernel expellers	173
Kingsnorth	2034	E.ON UK	Various – cereal residues	510
Longannet	2400	Scottish Power	Waste-derived fuel, sewage sludge	479
Lynemouth	420	Alcan	Sawdust, wood pellets, olive residues	–
Ratcliffe	2010	E.ON UK	Various	38
Rugeley	1000	International Power	Various – olive pellets	337
Tilbury	1085	RWE Npower	Wood, PKE	74
Uskmouth	363	Welsh Power Group Ltd	Various agri-products	–
West Burton	1980	EdF	Various – olive cake, SRC willow	149
Total				**7063**

result in two, three or four demonstration plants (both post-combustion and pre-combustion). These will include those already engaged in the existing CCS competition. As with the latter, it is expected that the Government will agree to support any new projects at the 300–400 MW capacity level. Companies engaged with existing CCS proposals are being offered £90 million to help with preparatory work.

In future, any company seeking planning approval for new coal-fired power plants will have to demonstrate CCS on at least 300 MW of any new coal-fired power station's capacity and commit to retrofitting CCS across the whole plant once the technology is available. In a White Paper published in July 2009, the UK Government set out its plan for the country's transition to a low-carbon economy, including how 2020 emissions reductions targets will be achieved through application of departmental carbon budgets. A levy on electricity suppliers to fund CCS demonstration projects will be in place from 2011. In December 2009, it was announced that the Government would finance up to four large-scale CCS projects (to be operational by 2020) via a levy on electricity bills.

Other post-combustion projects and proposals

There are a number of other projects and proposals at different stages in their development. Currently, there are three pilot facilities operational. At the Dicot power plant site, RWE npower has developed a Combustion Test Facility (CTF) which is amine scrubber-based. This is rated at 0.1 MWe and captures ~1 t/d of CO_2. The process is fully operational and tests have demonstrated >90% CO_2 removal from plant flue gas. RWE is also developing a capture pilot-scale project at its Aberthaw power plant in South Wales. Originally intended to be 1 MW capacity, it is now being enlarged to a 3 MW scale. Operations are expected to begin in 2010. A second phase may increase capacity to 25 MW. The third pilot unit, located at Scottish Power's Longannet power plant, started initial operations in September 2008. This was the UK's first example of CO_2 capture on a working coal-fired power plant. The test unit was developed by Aker Clean Carbon and replicates, on a small scale, the features of a full-scale capture plant. It comprises three main parts: a flue gas pre-treatment unit where most of the impurities are removed, an amine scrubber in which the CO_2 is removed from the flue gas, and a reclaimer to recover degradation products. It is

Table 26 UK post-combustion capture projects and proposals

Developer	Location	Capacity, MW	Capture technology	Destination of CO_2	Comments
RWE npower + consortium	Aberthaw	1500	Scrubber	Off-shore storage	1 MW capture plant operational by 2010 Planning permission being sought to increase to 3 MW (Nov 2009)
RWE npower	Tilbury	1400	Scrubber	na	Demonstration of scaled up Aberthaw technology – 100 MW But proposed SC project cancelled in November 2009
RWE npower	Didcot A	2000	Scrubber	na	New test facility completed in 2008
E.ON	Kingsnorth	1600	Amine scrubber	Up to 2.5 Mt/y captured and piped to North Sea gas fields Could commence in 2014	UK Government CCS Competition entry Proposal for scrubber to be fitted to one of two new 800 MW SC PCC units although E.ON has offered to equip entire station with CCS if the Government covers £1 billion building costs (March 2009) MHI/Foster Wheeler undertaking pre-FEED
RWE, DONG Energy/Peel Energy (Peel Energy CCS)	Hunterston	1600	Amine scrubber	EOR in North Sea	First 800 MW unit planned for operation by 2014. But proposed SC project cancelled in November 2009
SSE, Doosan Babcock and others	Ferrybridge	–	Scrubber	100 t/d capture	5 MW pilot project proposed in November 2009 Cost £12 million Construction in 2010. Trials 2011-12
SSE	Ferrybridge	450	Scrubber	1.7 Mt/y captured and stored in saline formation	Doosan Babcock-Siemens undertaking FEED
Scottish Power + Aker	Longannet	–	Aker amine scrubber pilot	na	Started up September 2008 Solvent testing programme
Scottish Power, Aker, Shell, National Grid	Longannet	2400	Aker amine scrubber	2 Mt/y captured and piped to North Sea for EOR	Proposed SC PCC plant refit Will adapt two of Unit 4's burners for Aker CCS technology 330 MW capacity project Could start up by 2014

capable of treating 1000 m^3/d of flue gas. An amine test programme is under way with the aim of verifying process improvements under actual plant conditions. The data will allow Scottish Power to better understand the science of carbon capture technology, prior to construction of a full-scale demonstration project. A summary of UK projects and proposals is given in Table 26.

In June 2010, it was announced that sandstone formations beneath the Moray Firth in Scotland were to be examined for their potential for CO_2 storage. This forms part of a study funded by the Scottish Government and industry; the Scottish Centre for Carbon Storage (SCCS) will carry out the study.

Geological mapping and modelling of the formation will appraise the thickness, extent and fluid flow properties of the rock. CO_2 injection and monitoring will also be addressed.

13.6.2 Oxyfuel combustion

The main focus of oxyfuel combustion is the *Oxy-coal UK Project* where several consortia are engaged in a three-phase programme aimed at developing and demonstrating a competitive oxyfuel firing technology suitable for full-scale plant application post-2010. Phase One (2007-08) examined fundamentals and underpinning technologies, Phase Two (2007-09) will lead to a demonstration of an oxyfuel combustion system, and Phase Three (2009-10) will develop appropriate reference designs.

The consortium involved in **Phase One** comprised Doosan Babcock Energy (lead), Air Products, E.ON UK, RWE npower, BP Alternative Energy International, the University of Nottingham and Imperial College. Scottish and Southern Energy (SEE), Scottish Power, EdF Energy, Drax Power and DONG Energy A/S were sponsor participants. This phase of the project investigated a range of issues that included coal ignition, devolatilisation, char burnout, nitrogen partitioning, development of kinetics parameters for CFD modelling and CFD simulation, and undertook a series of oxyfuel firing test programmes.

The consortium for **Phase Two** (which is concentrating on the development of an oxyfuel combustion system) comprises Doosan Babcock Energy (lead), Imperial College, and the University of Nottingham. Air Products, Scottish and Southern Energy, Scottish Power, E.ON UK, EdF Energy, Drax Power and DONG Energy A/S are sponsor participants, with SSE being the prime sponsor. The project has three main tasks:

- develop a purpose-designed oxyfuel test facility (based on modifications to Doosan Babcock's 90 MW MBTF);
- develop design and manufacture burner (design and manufacture of first generation 40 MWth oxyfuel burner);
- demonstrate an oxyfuel combustion system. Further system testing may follow.

RWE npower is also engaged in oxyfuel testing. This is being carried out alongside post-combustion capture studies at its 0.5 MWth Combustion Test Facility (CTF) at Didcot. The CTF has been modified to replicate oxyfuel combustion and will be used to test a range of process parameters. RWE's programme is intended to help increase understanding of safety, operation and fuel options for the process.

E.ON is also operating a 1 MW oxyfuel test unit at its Ratcliffe power station, simulating the combustion process under real operating conditions. Trials have provided data on the impact of oxyfuel technology on the entire generation process. This will be used to aid process scale-up. E.ON is involved with the oxy-coal UK project and was also a partner in the German research project ADECOS (Advanced Development of the Coal-fired Oxyfuel Process with CO_2 Separation; 2004-08) within the COORETEC programme. This addressed the development of the technology for mid-term application in power plants, and its techno-economic assessment.

14 Non-power generation coal use

The power sector is by far the biggest coal user in most of Europe. Although this is dominant in many Member States coal is also used in some for a number of other important industrial and commercial applications.

14.1 Iron and steel manufacture

Iron and steel production is important in a number of countries; all of those considered in the present report produce iron and steel. There are several European companies (such as Grupo Riva of Italy and ThyssenKrupp of Germany) that are ranked amongst the top 30 global producers. The sector uses coal in a number of ways. Coking coal is used for coke oven operations and non-coking coals for pulverised coal injection (PCI) into blast furnaces. The former is the largest category, used for producing coke by most of the countries considered. With eight major coking plants, Poland is the biggest producer. Several countries (particularly France, Germany and The Netherlands) also employ PCI. Coke oven coke production, PCI use and crude steel production are shown in Figure 18. PCI provides several advantages to the iron making process. It has been examined fully by Carpenter (2006).

There are several initiatives under way aimed at improving the effectiveness and/or reducing the environmental impact of iron and steel production. For instance, the Ultra Low CO2 Steelmaking (ULCOS II) Project aims to set up a pilot facility in Germany during 2010-14, plus a demonstration plant in France in 2011-15. This €44 million, part-EC-funded, multi-partner R&D initiative is investigating new steel production processes that could reduce CO_2 emissions by at least 50%, compared to current production methods. ULCOS comprises a number of sub-projects that include a radical re-examination of the dominant iron-producing (blast furnace-based) process. Replacement of hot air with pure oxygen and recycling of the top gas into the furnace is the most promising line of research. A key step will be the capture and storage of CO_2 from the furnace top gas. The *New Blast Furnace* will remain a coke-based process which will produce liquid iron suitable for conversion to steel in the current way.

There are also initiatives in the area of coke production. In Germany, the CSQ (Coke Stabilization Quenching) process, a further development of the conventional wet quenching process, has been developed and adopted at a number of coke-making plants. The CSQ process features the simultaneous application of top and bottom quenching. The high quenching rate is an essential process element. It enables a rapid reduction of the coke temperature, a shorter reaction time, less formation of water gas and H_2S, and produces high mechanical strength and stabilisation of the quenched coke, uniform grain distribution and thus a better coke quality. This helps reduce energy demand in the blast furnace. Plants such as those at the Krupp Mannesmann steelworks and the Schwelgern coke plants in Germany now operate the system, although wider application would be beneficial throughout the remainder of the European sector and beyond.

14.2 Patent fuels/BKB plants

Patent fuel is a composition fuel manufactured from coal fines by shaping with the addition of a binding agent such as pitch. *Brown Coal Briquettes* (BKB) are composition fuels manufactured from brown coal. This is crushed, dried and moulded under high pressure into evenly-shaped briquettes without the addition of binders.

There is some application of brown coals/lignites in this manner in Bulgaria, the Czech Republic and Greece. However, the largest application is in Germany where nearly 12 Mt of brown coal/lignite is used annually for the production of such fuels. This accounts for most of the OECD Europe annual total of ~13 Mt (OECD/IEA, 2009). Smaller amounts of steam coals are also briquetted in Hungary and Germany. In several countries, brown coal/lignite briquettes are used in a number of industrial sectors that include power generation, iron and steel manufacture, cement production, and for residential and commercial heating. For instance, in 2007, the German iron and steel sector used 11 kt of BKBs.

Germany is the biggest European briquette producer, followed by Bulgaria. About 9% of the latter's coal production is used for making briquettes; in 2007, briquette production exceeded 1 Mt, used mainly for commercial and residential heating. In recent years, coal from the Maritsa East Mines (Brikel EAD) has been the major supply for briquetting. These mines produce ~3 Mt/y of brown coal, used to produce most of the country's briquette output. The Brikel plant has a briquette production capacity of 1.3 Mt/y; around 250 kt/y are supplied to the Maritsa East power plant (Brikel, nd: Methanetomarkets, 2009) with much of the balance used for heating. A typical Bulgarian binderless fuel briquette contains ~11% moisture, up to 22% ash, and up to 3.8% sulphur.

Brown coal/lignite briquettes are also produced in the Czech Republic (247 kt in 2007), Hungary (10 kt) and Greece (97 kt) (UN data, nd). In the Czech Republic, Sokolovská uhelná, a.s, is a major manufacturer of brown coal/lignite briquettes. This forms part of its portfolio of activities that include coal mining, heat production, power generation and chemical production. In Greece, lignite extracted at the Ptolemais-Amyndeon Lignite Centre is fed mainly to power plants although some is also supplied to a local briquette factory.

14.3 Non-metallic minerals

The largest contributor in this category is cement manufacture, although not all production relies entirely on coal; other fuels such as natural gas may be used, and coal may also be cofired in cement kilns with various waste-derived fuels. For instance, alongside coal, Poland uses

~4 Mt/y of combustible wastes and biomass in cement production processes. However, each country considered uses some hard or brown coal for cement production. The biggest users are Poland, the UK and Italy. Total OECD Europe consumption in 2008 amounted to 7.23 Mt (hard + brown coal). The scale of cement production varies widely between countries, the biggest producers being Italy, Spain, France and Germany (Figure 19). The largest operating companies in the world with cement interests in the EU include Heidelberg Cement (Germany), Italcementi (Italy) and Lafarge (France).

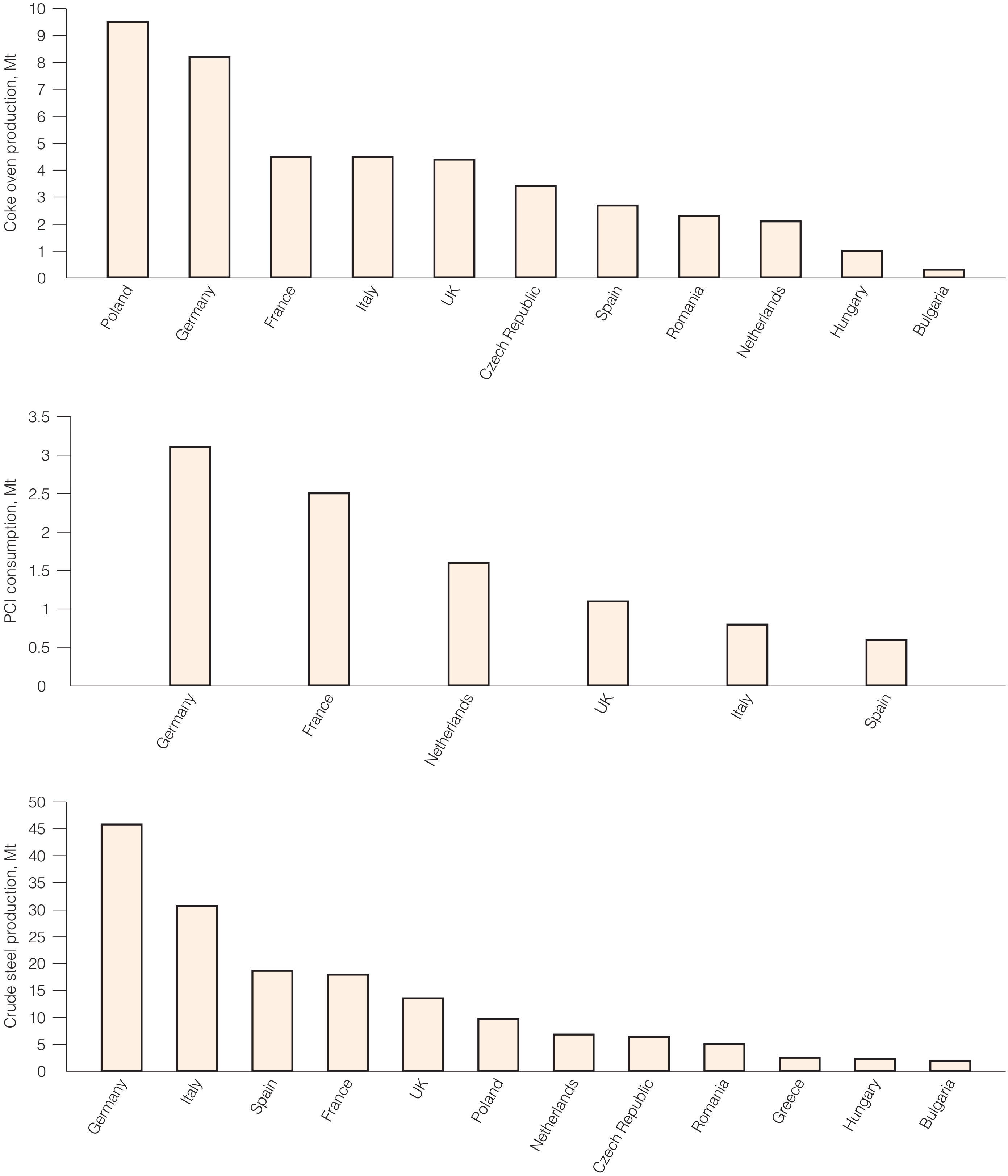


Figure 18 Coke oven coke production, PCI consumed and crude steel output (IEA, 2009) (OECD/IEA, 2008; WSA, 2009; Jones, 2009)

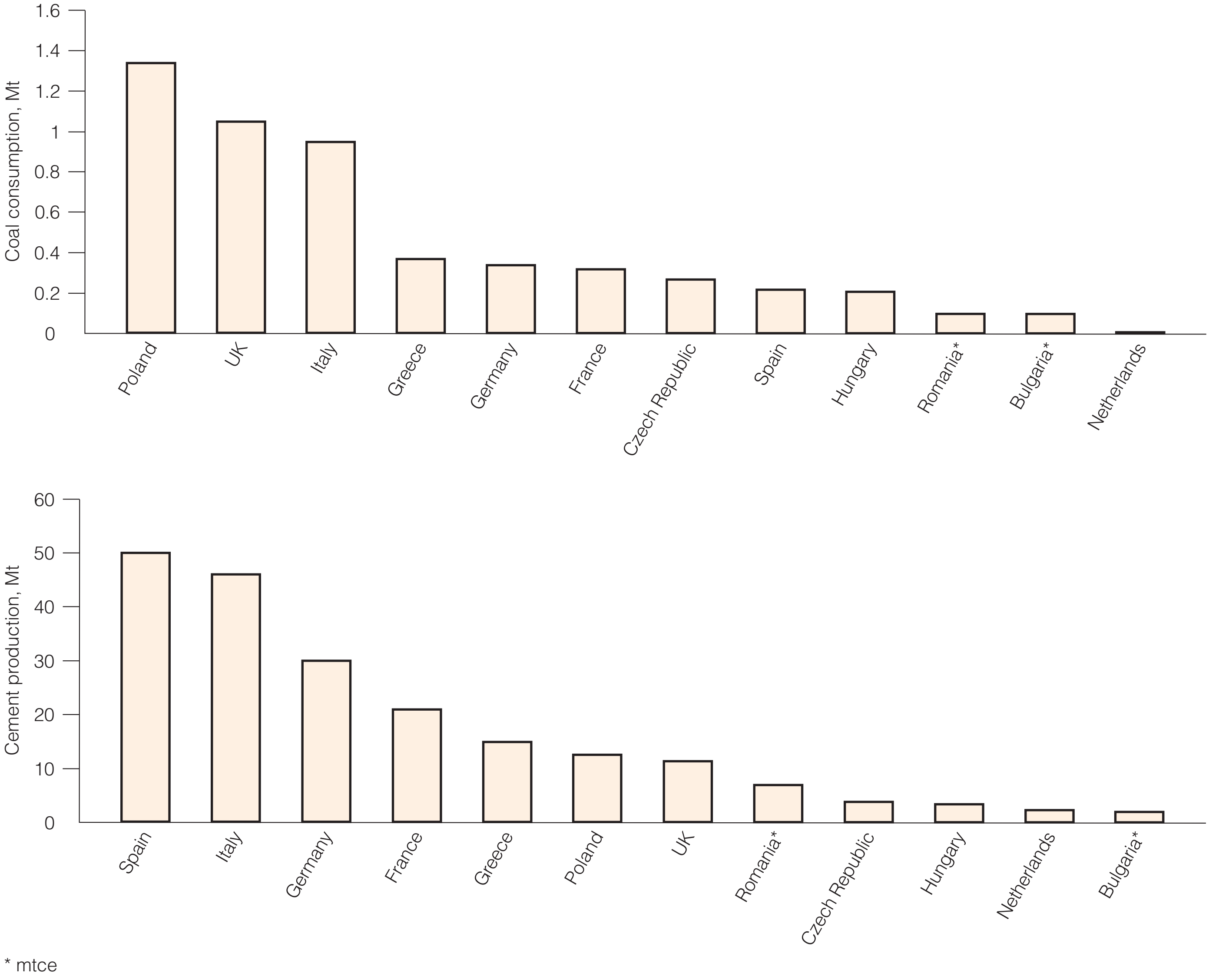


Figure 19 Coal consumption and cement production in EU Member States (2008) (USGS, 2008; OECD/IEA, 2009)

14.4 Other uses

Hard and brown coals are used for the production of **chemicals** although in most countries, tonnages are relatively small. The biggest users are the Czech Republic and Poland. In the former, DEZA, a. s. Valašské Mezirící produces aromatic hydrocarbons (such as benzene, toluene, phenol, cresols, xylenols, anthracene and naphtalene) from coal tar and benzol obtained during coke production.

There are several large Polish chemical companies that rely at least partially on coal for their feedstocks. The Ciech Chemical Group is the largest chemical producer in Poland and Central Europe. Core products include soda ash, phosphate, mixed fertilisers, resins, and other organic chemicals, used in various industrial sectors, construction and agricultural. The Group uses around 1 Mt/y of bituminous coal, as well as some coke and anthracite.

Polish nitrate fertiliser producer ZA Pulawy (with the Bogdanka coal mine) has recently completed a feasibility study for a coal gasification project; this was undertaken by Bechtel. It aims to diversify gas supplies through the use of domestic coal. The new installation will more than double the company's coal consumption from the current 800 kt/y to ~2 Mt/y. It will supply around half of the company's gas requirement of ~900 million m^3/y. The plant will cost between US$1.2 and 1.8 billion and is scheduled to start up in 2013. The company is already supplied with coal from the Bogdanka mine.

Zaklady Azotowe Kedzierzyn SA (ZAK SA) is one of Poland's largest manufacturers of chemical products, producing nitrogen fertilisers, plasticisers, oxo alcohols and basic chemicals. The company (with PKE) is currently developing the Kedzierzyn-Kozle Zero-Emission Power and Chemical Complex, a zero-emission power and chemical plant complex to be built at Kedzierzyn (*see* Section 10.4). In 2009, it was announced that I Grupa Chemiczna (1st Chemical Group) would be formed by the privatisation and amalgamation of chemical companies Ciech S.A (the largest in Poland), Zaklady Azotowe Tarnów SA and Zaklady Azotowe Kedzierzyn SA.

In the European **pulp and paper production** sector, the main sources of energy are natural gas and biomass and overall, coal provides only a small percentage of energy requirements. However, a small amount of brown coal is used in the Czech Republic and some steam coal is used in Poland, France, Spain, Germany and the UK. The biggest coal consumers are Poland, Spain and Germany – annually, each uses around half a million tonnes. Germany is the largest European paper producer, ranked fourth globally after the USA, China and Japan.

Both hard and brown coal is also used to provide energy for a range of **general industrial uses** in most of the countries considered. At ~2 Mt/y, Poland is the largest individual user of those considered.

In the area of **residential, commercial and public services**, both hard and brown coals are used in some countries. Brown coals are used in the Czech Republic (some as briquettes), Poland, Hungary and the Netherlands. Steam coal is used in all of the countries considered (apart from Greece). Poland is the biggest user in this category. Around half a million tonnes is used annually in the UK, Germany and France, with smaller amounts elsewhere. Total OECD Europe (hard + brown) coal use (Table 27) amounts to around 22 Mt (OECD/IEA, 2009).

Table 27 Coal used for residential, commercial and public services in selected EU countries (OECD/IEA, 2009)

	Amount used, Mt/y
Czech Republic	2.03 BC
Poland	10.12 S + 0.25 BC
Italy	0.01 S
Hungary	0.09 S + 0.42 BC
Netherlands	0.03 S + 0.02 BC
France	0.48 S
Spain	0.31 S
Germany	0.49 S
UK	0.56 S
Bulgaria	0.4 (Mtce)

S = steam coal; BC = brown coal/lignite

15 Summary

Coal remains of great importance to the EU, helping to meet a significant proportion of its energy needs. This is particularly so for electricity generation (around a third of the EU-27's electricity is generated by coal-fired plants), although some major industries also continue to rely heavily on coal. About 80% of Europe's fossil fuel reserves comprise hard coal and/or lignite. Coal is readily available in most Member States, many of which possess indigenous resources of one or both types. In 2008, between them, Member States produced around 146 Mt of hard coal (43% of total EU hard coal consumption) and 434 Mt of lignite (99% of total EU lignite consumption). A further 211 Mt of hard coal was imported. Thus, total EU coal consumption amounted to 783 Mt. In some countries, coal accounts for more than 50% of total power generation. In a few, it is considerably more.

Despite moves to increase the use of alternatives sources of energy, in many EU countries, there are often a combination of strong commercial and strategic incentives to continue using coal or lignite as a component of the national energy mix. Although reasons vary between individual nations, they generally encompass issues of security of supply, minimisation of import dependency, the relative stability of coal prices, and the maintenance of national coal and power industries.

During the present decade, a number of additional countries have become Member States of the European Union. Several have brought with them significant coal and lignite resources, adding considerably to the EU's total (in particular, Bulgaria, the Czech Republic, Hungary and Poland). Each has a coal industry based on domestic coal reserves, and in each case, coal forms a major component of the respective energy mix. Despite some reductions in production and consumption in recent years, for each, as with many long-established Member States, coal will remain important for the foreseeable future, particularly for power generation.

This continuing use of coal, potentially, brings raises a number of environmental issues such as emissions to air. However, in recent years, the growing application of increasingly stringent legislation has obliged many power generators throughout Europe to adopt a raft of measures to reduce emissions of pollutants such as SO_2, NOx and particulates. Many major power plants have been comprehensively re-equipped with systems to address these issues, a process that remains on-going. More recently, growing concerns over global warming has prompted a range of initiatives focused on reducing CO_2 produced from coal-fired power plants and industrial processes. Thus, in all coal-consuming countries of the EU, there are now various on-going activities centred on the development and application of clean coal technologies and carbon capture and storage. The level of activity varies significantly between them, although all are engaged in some manner. It is now accepted that the future of coal in Europe will depend heavily on the growing use of high-efficiency power plants coupled with the widespread deployment of CCS. Many of these on-going activities form component parts of EU Framework Programmes and other Europe-wide initiatives involving academia, R&D providers, plus utilities and other major industrial partners.

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