Technology Roadmap

High-Efficiency, Low-Emissions Coal-Fired Power Generation

International Energy Agency

INTERNATIONAL ENERGY AGENCY

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Foreword

Current trends in energy supply and use are patently unsustainable – economically, environmentally and socially. Without decisive action, energy-related emissions of carbon dioxide (CO_2) will more than double by 2050 and increased fossil energy demand will heighten concerns over the security of supplies. We can and must change our current path, but this will take an energy revolution and low-carbon energy technologies will have a crucial role to play. Energy efficiency, many types of renewable energy, carbon capture and storage (CCS), nuclear power and new transport technologies will all require widespread deployment if we are to reach our goals to reduce greenhouse gas (GHG) emissions. Every major country and sector of the economy must be involved. The task is urgent if we are to make sure that investment decisions taken now do not saddle us with sub-optimal technologies in the long term.

Awareness is growing on the need to turn political statements and analytical work into concrete action. To spark this movement, at the request of the G8, the International Energy Agency (IEA) is leading the development of a series of roadmaps for some of the most important technologies. By identifying the steps needed to accelerate the implementation of radical technology changes, these roadmaps will enable governments, industry and financial partners to make the right choices. This will in turn help societies make the right decisions.

Coal is an important source of energy for the world, particularly for power generation. In fact, demand for coal has grown rapidly over the last decade, outstripping demand for gas, oil, nuclear and renewable energy sources. Anticipated growth in energy demand is likely to extend the growth trend for coal. This presents a major threat to a low-carbon future. In the context of a sustainable energy future, we must find ways to use coal more efficiently and to reduce its environmental footprint. This roadmap focuses on the development and deployment of high-efficiency, low-emissions (HELE) coal technologies for power generation.

To limit the average rise in global temperature to between 2°C and 3°C, it will be necessary to halve (from current levels) CO_2 emissions by 2050. Coal has a major contribution to make; emissions from coal-fired power generation will need to be reduced by around 90% over this period. The need for energy and the economics of producing and supplying it to the end-user are central considerations in power plant construction and operation. Economic and regulatory conditions must be made consistent with the ambition to achieve higher efficiencies and lower emissions. Recognising the importance of HELE coal technologies in realising these aims, the IEA, with valuable support from our colleagues at the IEA Clean Coal Centre, have developed a technology roadmap for the application of HELE coal technologies in power generation.

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Table of contents

List of figures

List of tables

List of boxes

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Key findings

- In 2011, roughly 50% of new coal-fired power plants used HELE technologies, predominantly supercritical (SC) and ultra-supercritical (USC) pulverised coal combustion units. Though the share of HELE technology has almost doubled in the last 10 years, far too many non-HELE, subcritical units are still being constructed. About three-quarters of operating units use non-HELE technology; more than half of current capacity is over 25 years old and comprises units of less than 300 MW.
- USC pulverised coal combustion is currently the most efficient HELE technology: some units reach efficiency of 45% (LHV, net), reducing global average emissions to 740 grams of carbon dioxide per kilowatt hour (gCO_2/kWh). Efforts to develop advanced USC technology could lower emissions to 670 gCO_2/kWh (a 30% improvement). Deployment of advanced USC is expected to begin within the next 10 to 15 years.
- To raise its efficiency, integrated gasification combined cycle (IGCC) needs to operate with gas turbines that allow higher turbine inlet temperatures. IGCC with 1 500°C-class gas turbines (currently under development) should be able to raise efficiency well above 45%, bringing CO_2 emissions down towards 670 gCO_2/kWh – and less for IGCC units with more advanced gas turbines.
- To achieve CO_2 intensity factors that are consistent with halving CO_2 emissions by 2050, deployment of CCS is essential. CCS offers the potential to reduce CO_2 emissions to less than 100 g/kWh. Programmes to demonstrate large-scale, integrated CCS on coal-fired power units are under way in many countries. Some deployment of CCS is anticipated in the 2020s, with broader deployment projected from 2030-35 onwards.
- HELE technologies need to be further developed as:
  - inefficient power generation from low-cost, poor quality coal is currently being used by many countries;
  - though trials have demonstrated the potential to reduce emissions by co-firing biomass, the practice is not widespread; and
  - operating coal-fired power plants consume copious quantities of water, a cause of major concern in arid regions and regions where water resources issues are gaining prominence.
- Non-greenhouse gas pollutants can cause severe health issues and often harm local infrastructure and, consequently, the local economy. Though technologies are available for reducing such emissions, not all countries yet deploy them effectively.

Key actions in the next ten years

- Increase – by about 4 percentage points – the average efficiency of operating coal-fired power generation plants. This implies substantially reducing generation from older, inefficient plants, improving the performance of operational plants, and installing new, highly efficient, state-of-the-art plants.
- Deploy, at minimum, supercritical technology on all new combustion installations producing over 300 MW_e and avoid installation of smaller sized units (on which it is impractical to apply supercritical conditions) where possible.
- Provide funding and support mechanisms for research, development, demonstration and deployment (RDD&D) to enable the timely deployment of next-generation technologies, in particular to:
  - demonstrate advanced combustion and gasification technologies;
  - demonstrate the integration of CO_2 capture with state-of-the-art combustion and gasification technologies;
  - improve the efficiency of generation from indigenous, low-cost, low-quality coal; and
  - reduce the water consumption of HELE technologies, while maintaining their performance.
- Develop and deploy – possibly through mandatory policies – efficient and cost-effective flue-gas treatment to limit non-GHG emissions. Initiate or improve pollutant monitoring, promoting joint responsibility on the part of the users and the appropriate authority to verify full compliance with legislation and to ensure the technology applied is meeting its potential.

Introduction

Rationale for the roadmap

Over the past decade, fossil fuels, and particularly coal, have satisfied the major share of the incremental growth in primary energy demand. As coal is a widely dispersed and relatively low-cost energy resource, it is used extensively around the world: at present, almost two-thirds of coal demand in the energy sector is for electricity generation. But the growing reliance on coal to meet rising demand for energy presents a major threat to a low-carbon future. On average, the efficiency of existing coal-fired capacity is quite low, at about 33%. This means that large amounts of coal must be combusted to produce each unit of electricity. As consumption rises, so do the levels of both greenhouse and non-GHG.

Collectively, the large number of coal-fired power generation units around the world hold potential to make a substantial contribution to a low-carbon future. As large point sources of CO_2 emissions, concerted efforts to improve their efficiency can significantly reduce coal consumption and lower emissions. But achieving these goals will require strong policies to encourage the development and deployment of state-of-the-art technologies. This roadmap describes how HELE coal technologies[2] could contribute to reducing the growing emissions of CO_2 from coal-fired power generation between now and 2050. In particular, it examines the potential for combustion of coal under supercritical and ultra-supercritical conditions, and through the use of integrated gasification combined cycle.

2. The terminology used is consistent with that used by the Major Economies Forum on Energy and Climate in its "Technology Action Plan: High-Efficiency, Low-Emissions Coal" (MEF, 2009).

Roadmap objectives, scope and structure

Apart from improved demand-side energy efficiency, which reduces the amount of electricity needed, there are three principle ways to reduce emissions of CO_2 from coal-fired power plants:

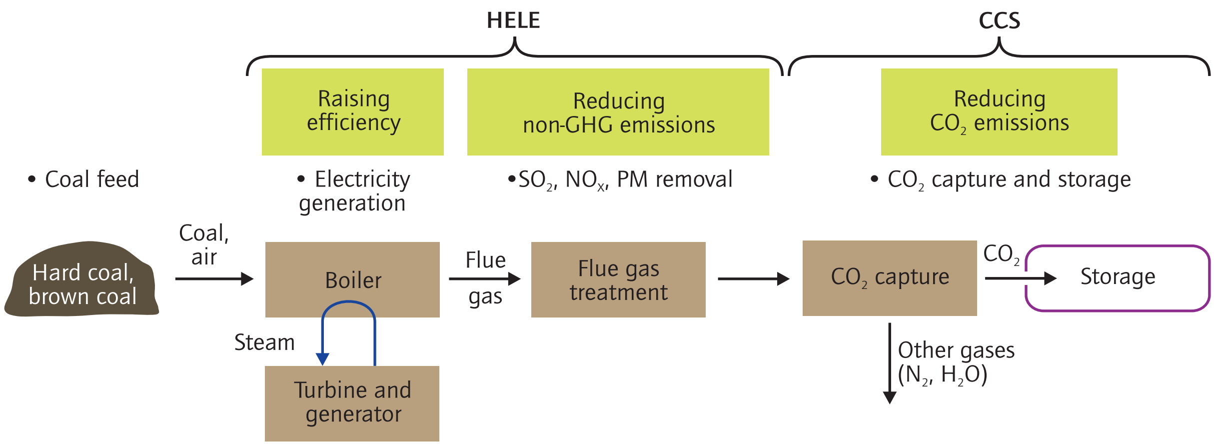
- Deploy and further develop HELE coal technologies, *i.e.* use more efficient technology and continue to develop higher-efficiency conversion processes.
- Deploy CCS; recent demonstration projects show that CCS is technically viable and, in fact, essential to achieving long-term CO_2 reduction targets.[3]
- Switch to lower-carbon fuels or to non-fossil technologies as a means of reducing generation from coal.

This roadmap focuses predominantly on the first of these options, the use and development of HELE technologies. In actual fact, an important interplay exists among these three measures: the extent to which coal-fired plants can be made more efficient and less polluting will determine the ultimate need for – and cost of – CCS and fuel switching.

The relationship between HELE technologies and CCS is particularly important. While HELE technologies show substantial potential to reduce emissions, only the addition of CCS can deliver the cuts needed to achieve climate change mitigation goals. Consequently, CCS is discussed throughout the roadmap. Though CCS is technically viable, it

3. Roadmaps for CCS in both the power and industry sectors have been and will continue to be published by the IEA.

Figure 1: Example of pathways for cleaner coal-fired power generation



creates cost and energy consumption challenges for coal-fired plants. Thus, balancing the two technologies in fully integrated plants is extremely important.

Switching to lower-carbon fuels or to non-fossil technologies is discussed in several previous roadmaps and is not covered further in this roadmap.

The primary technology pathways to fulfilling the role of coal in a lower-carbon future include raising efficiency and reducing both non-GHG and CO_2 emissions (Figure 1). For health reasons and to prevent damage to infrastructure, reducing non-GHG emissions is particularly important at the local or regional level, and can be achieved to a large extent through deployment of HELE technologies.

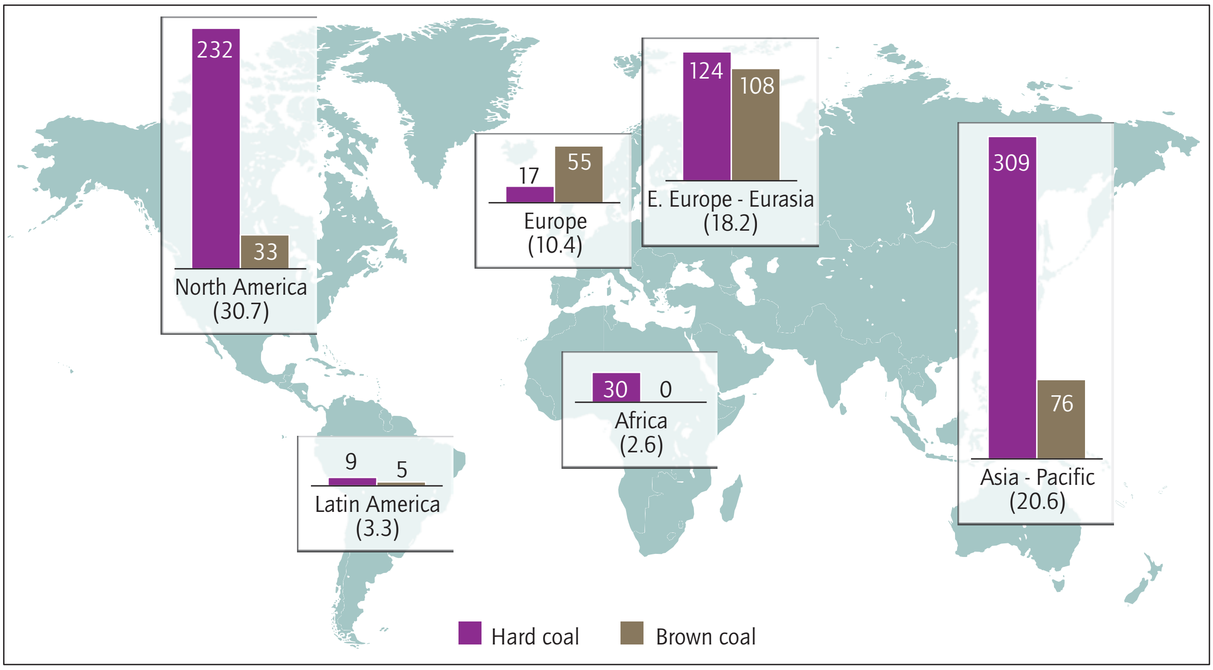
This roadmap is organised in four main parts: after the introduction, a vision is laid out for using HELE technologies to increase efficiency and reduce CO_2 emissions. After describing the current status of the more important HELE technologies, the roadmap concludes with the actions and milestones necessary to achieve this vision.

Coal-fired power generation today

Coal's place in the energy mix

Coal is by far the most abundant fossil fuel, with proven global reserves of nearly 1 trillion tonnes (Figure 2), enough for 150 years of generation at current consumption rates (BGR, 2010). In terms of energy content, reserves of coal are much greater than those of natural gas and oil. Recoverable reserves of coal can be found in more than 75 countries and production has been relatively inexpensive (WEC, 2010), so it is not surprising that coal has been an important component of the global energy mix for many decades.

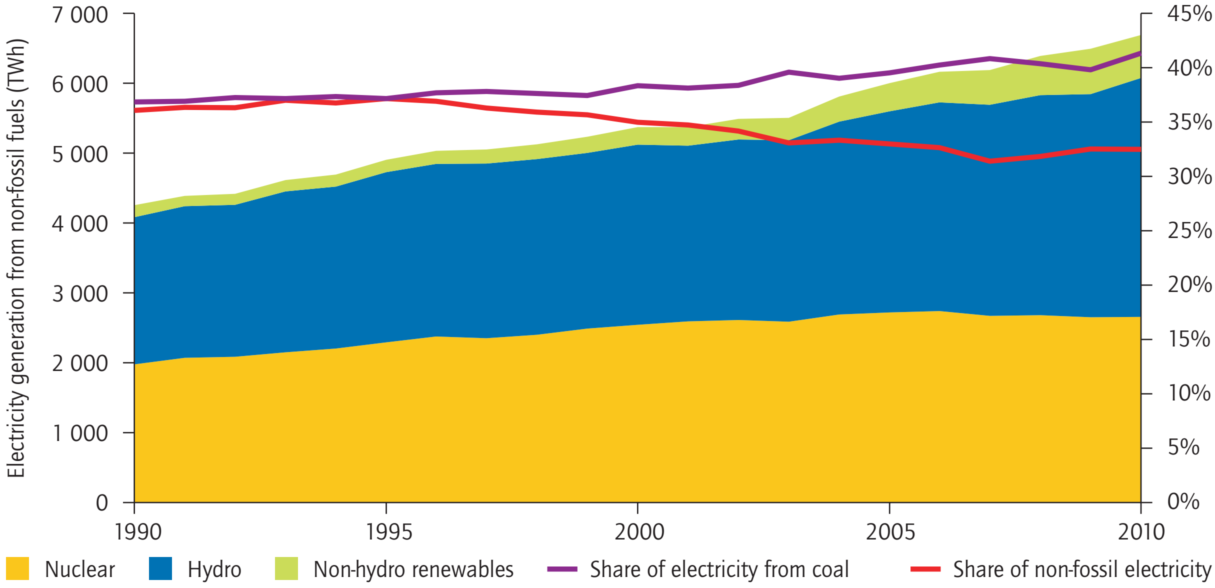
Figure 2: Coal reserves by region and type (end-2009)



Notes: Numbers in parentheses represent the ratio of total coal resources-to-reserves for each region. Coal reserves in gigatonnes (Gt).

Coal has satisfied the major part of the growth in electricity over the past decade. Even though non-fossil power generation has risen considerably over the past two decades, it has failed to keep pace with the growth in generation from fossil fuels (Figure 3). Between 1990 and 2010, generation from nuclear power rose by 492 TWh, from hydro renewables by 1 334 TWh and from non-hydro renewable energy technologies by 454 TWh. By contrast, generation from coal grew by 4 271 TWh, far exceeding the increase in electricity generation from all non-fossil energy sources combined. Consequently, CO_2 emissions continue to increase.

Figure 3: Electricity generation from non-fossil fuels



Source: Unless otherwise indicated, all tables and figures in this chapter derive from IEA data and analysis.

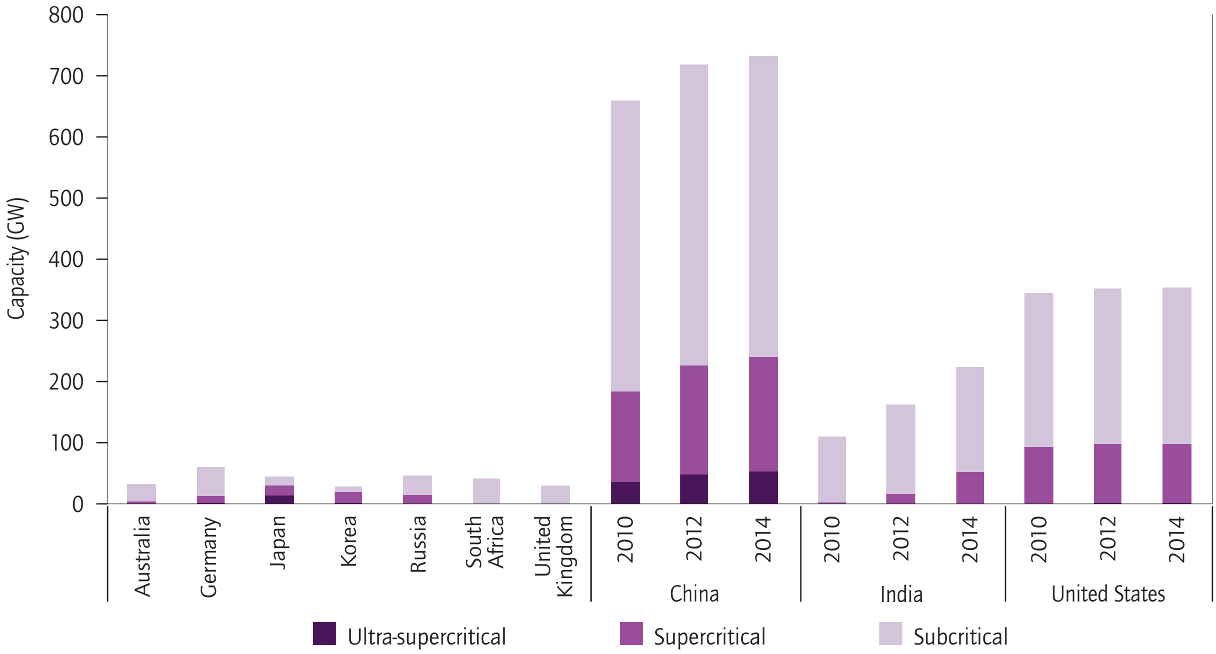
Potential to improve efficiency

The average efficiency[4] of coal-fired power generation units in the major coal-using countries varies enormously, from under 30% to 45% (LHV, net). These differences arise from diverse factors, including the age of operating plants, the steam conditions, local climatic conditions, coal quality, operating and maintenance skills, and receptiveness to the uptake of advanced technologies.

4. Unless otherwise noted, efficiency notations in this chapter are based on the lower heating value of the fuel and net output (LHV, net). Lower heating values, unlike higher heating values (HHV), do not account for the latent heat of water in the products of combustion. European and IEA statistics are most often reported on an LHV basis. For coal-fired power generation, efficiencies based on HHV are generally around 2% to 3% lower than those based on LHV. Net output refers to the total electrical output from the plant (gross) less the plant's internal power consumption (typically 5% to 7% of gross power).

At present, a large number of low-efficiency plants remain in operation: more than half of all operating plant capacity is older than 25 years and of relatively small size (less than 300 MWe). Almost three-quarters of operating plants use subcritical technology. While deployment of SC and USC technologies is increasing, their share of total capacity remains extremely low (Figure 4).

Figure 4: Capacity of supercritical and ultra-supercritical plant in major countries



Note: Refers to capacity in 2010 unless specified otherwise. Definitions of subcritical, supercritical (SC) and ultra-supercritical (USC) technology are described in Box 3.

Source: Platts, 2011.

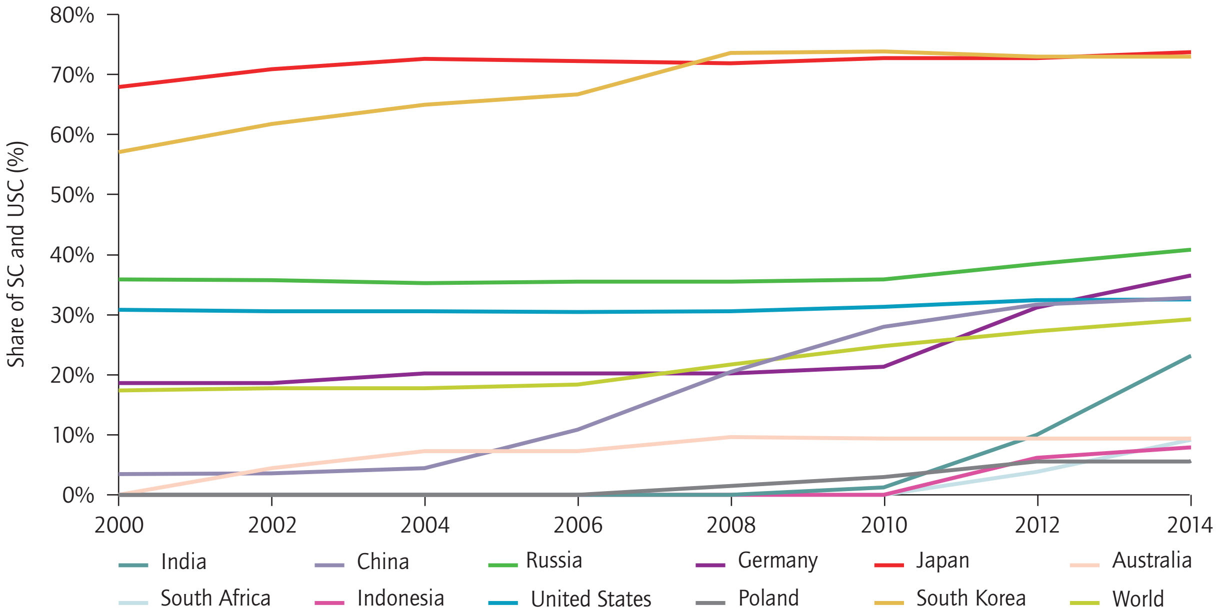
A handful of countries have made it a priority to improve the efficiency of their coal fleets (Figure 5). For example, Japan and Korea, where SC technology was adopted before 2000, have high-performance coal fleets, with average efficiencies in excess of 40% (LHV, net). Since the mid-2000s, China has experienced high growth in coal-fired generation, with the share of SC and USC increasing rapidly. More recently (since 2010), India has seen rapid growth in coal-fired generation, and a growth in the share of SC units.

The number of HELE plants in the world remains low, however, and must be increased in order to improve the efficiency and environmental performance of global power generation. More opportunities should be taken to adopt SC technology or better for new plants, which would significantly increase the global average efficiency of coal-fired power generation. Research and development (R&D) by industry, with the support of enabling policy, is absolutely essential to ensure that more advanced and efficient technologies enter the market place.

Potential to reduce emissions

Recent growth in coal use is directly related to increased emissions from the power sector. In 2009, coal-fired power generation alone contributed 30% of total CO_2 emissions. As shown in the IEA *Energy Technology Perspectives 2012* (IEA, 2012b), HELE technologies can make a major contribution to reducing the growing emissions from coal-fired power generation (Box 1). Achieving the 2°C Scenario (2DS), which entails halving energy-related CO_2 emissions by 2050, will require contributions from all sectors and application of a portfolio of technologies. But coal-fired power plants represent the greatest potential to reduce substantially the large volumes of emissions arising from a single point source.

Figure 5: The share of supercritical and ultra-supercritical capacity in major countries



Note: For India, achieving 25% SC and USC by 2014 is an ambition, with perhaps up to 10% likely to be achieved in practice.

Source: Analysis based on data from Platts, 2011.

Box 1: Emissions from coal

The major challenges to the continued use of coal arise from its environmental impact. Although reducing emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_X) and particulate matter (PM) from coal-fired power generation is important, particularly at the local or regional level, the spotlight globally in recent years has been fixed to a large extent on reducing CO_2 emissions.

Many elements are bound up within the complex structure of coal, and are released when it is converted into power or heat. To improve local air quality, highly effective technologies have been developed to reduce the release of pollutants such as SO_2, NO_X, particulates and trace elements, such as mercury. Many of these technologies are mature, with a competitive market. The levels of emissions of these pollutants are more often a function of existing legislation and compliance with regulation rather than the capabilities of modern pollution control technology. In many cases, the application and effective operation of modern technology could reduce emissions significantly further than presently achieved in practice.

Given that its carbon content varies from 60% in lignites to more than 97% in anthracite, coal is also a major source of CO_2. More than 43% of anthropogenic CO_2 emissions result from coal (2009) and these emissions are rising. Coal produces almost three-quarters of the 40% of energy-related CO_2 emissions that comes from the generation of electricity. Reducing CO_2 emissions from coal-fired electricity generation would have a significant impact on global emissions and, therefore, on climate change.

Vision for deploying HELE technologies

The aim of deploying HELE technologies is twofold: to increase conversion efficiencies and reduce CO_2 emissions. Both supercritical and ultra-supercritical technologies are available now, with even higher efficiencies possible when advanced ultra-supercritical becomes available. Poorer quality or low-grade coals (such as lignite[5]) are candidates for more efficient generation, notably by employing pre-combustion drying. Expanded use of IGCC also promises higher efficiency and reduced CO_2 emissions.

5. Lignite, a sub-category of brown coal, is the lowest rank of coal and is used almost exclusively as fuel for electric power generation.

The IEA *Energy Technology Perspectives 2012* (IEA 2012b) charts a least-cost pathway for combining technology and policy to achieve the goal of limiting global temperature rise to 2°C (IEA, 2011). For comparison, it also charts a scenario in which no specific effort is made to alter current trends in energy demand or associated emissions, which result in a temperature rise of 6°C (Box 2).

Box 2: *ETP 2012* scenarios

The 2DS describes how technologies across all energy sectors may be transformed by 2050 to give an 80% chance of limiting average global temperature increase to 2°C. It sets the target of cutting energy-related CO_2 emissions by more than half by 2050 (compared with 2009) and ensuring that they continue to fall thereafter. The 2DS acknowledges that transforming the energy sector is vital but not the sole solution: the goal can only be achieved if CO_2 and GHG emissions in non-energy sectors are also reduced. The 2DS is broadly consistent with the World Energy Outlook 450 Scenario through 2035.

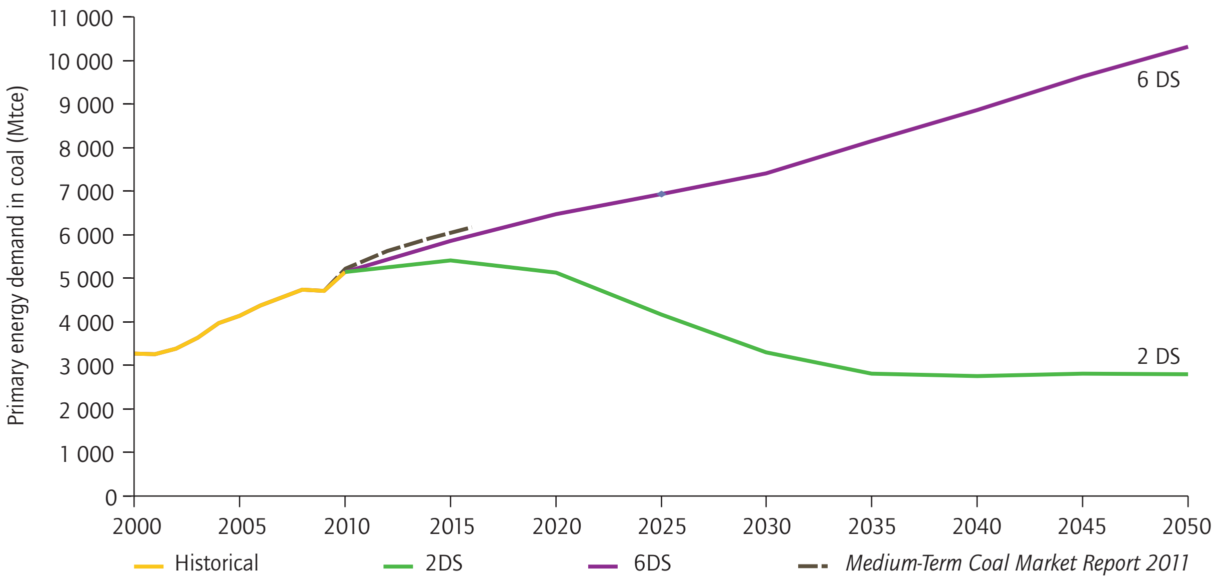
The model used for this analysis is a bottom-up TIMES model that uses cost optimisation to identify least-cost mixes of technologies and fuels to meet energy demand, given constraints such as the availability of natural resources. The ETP global 28-region model permits the analysis of fuel and technology choices throughout the energy system, including about 1 000 individual technologies. The model, which has been used in many analyses of the global energy sector, is supplemented by detailed demand-side models for all major end-uses in the industry, buildings and transport sectors.

ETP 2012 also considers 6°C and 4°C scenarios. The 6°C Scenario (6DS) is largely an extension of current trends. By 2050, energy use almost doubles (compared with 2009) and total GHG emissions rise even more. In the absence of efforts to stabilise atmospheric concentrations of GHGs, average global temperature is projected to rise by at least 6°C in the long term. The 6DS is broadly consistent with the World Energy Outlook Current Policy Scenario through 2035.

The 4°C Scenario (4DS) takes into account recent pledges by countries to limit emissions and step up efforts to improve energy efficiency. It serves as the primary benchmark in *ETP 2012* when comparisons are made between scenarios. Projecting a long-term temperature rise of 4°C, the 4DS is broadly consistent with the World Energy Outlook New Policies Scenario through 2035 (IEA, 2011). In many respects, this is already an ambitious scenario that requires significant changes in policy and technologies. Moreover, capping the temperature increase at 4°C requires significant additional cuts in emissions in the period after 2050.

It is worth noting here that the 2DS projection for the rate of increase in coal demand is not consistent with the projected near-term trajectory for coal consumption (IEA, 2011d), where demand is continuing to rise and, in fact, is outstripping projections even in the 6DS. A sustained high growth in coal beyond 2016 looks increasingly possible under business-as-usual scenarios. Unless urgent steps are taken, there is little doubt that the substantial gap that exists between the 2DS and actual coal demand will continue to increase.

Figure 6: Different futures in primary energy demand for coal



How technology influences efficiency, emissions and costs

At the time of installation, the choice of technology has a substantial – and long-term – influence on the life-time efficiency and emissions of a given power plant. While few generators would completely disregard the need to improve both factors, in reality economic factors play an important role in their investment decisions. Thus, it is important to understand the interplay of these factors, comparing in particular the characteristics of standard and HELE technologies currently in operation or under development (Box 3).[6]

6. Costs for plants are often difficult to establish because they are not usually publicly available. Estimates can be made based on equipment costs provided by vendors or accessed from equipment cost databases.

Box 3: Coal-fired power generation technologies

Non-HELE power generation

Subcritical technology. For conventional pulverised coal combustion (PC) technology – the type most commonly used in coal-fired plants – powdered coal is injected into the boiler and burned to raise steam for subsequent expansion in a steam-turbine generator.[7] Water flowing through tubing within the body of the combustor is heated to produce steam at a pressure below the critical pressure of water (22.1 MPa). Subcritical units are designed to achieve thermal efficiencies typically up to 38% (LHV, net)[8] and would not be considered as meeting the performance required to be described as a HELE technology. The overnight cost[9] of a subcritical unit is estimated to be from USD 600/kW to USD 1 980/kW, approximately 10% to 20% lower than for a supercritical unit (IEA, 2007, 2012b).

HELE power generation

Supercritical technology. Steam is generated at a pressure above the critical point of water, so no water-steam separation is required (except during start-up and shut-down). Supercritical plants typically reach efficiencies of 42% to 43%. The higher capital costs of supercritical technology are due largely to the alloys used and the welding techniques required for operation at higher steam pressures and temperatures. The higher costs may be partially or wholly offset by fuel savings (depending on the price of fuel). The overnight cost of a supercritical unit is estimated to be from USD 700/kW to USD 2 310/kW (IEA, 2011b).

Ultra-supercritical technology. This is similar to supercritical generation, but operates at even higher temperatures and pressures. Thermal efficiencies may reach 45%. At present, there is no agreed definition: some manufacturers refer to plants operating at a steam temperature in excess of 600°C as USC (this varies according to manufacturer and region). Current state-of-the-art USC plants operate at up to 620°C, with steam pressures from 25 MPa to 29 MPa. The overnight cost of ultra-supercritical units may be up to 10% higher than that of supercritical units, ranging from USD 800/kW to USD 2 530/kW (IEA, 2007; IEA, 2011b), again due to the incremental improvements required in construction materials and techniques.

Advanced ultra-supercritical (A-USC) technology. Using the same basic principles as USC, development of A-USC aims to achieve efficiencies in excess of 50%, which will require materials capable of withstanding steam conditions of 700°C to 760°C and pressures of 30 MPa to 35 MPa. The materials under development are non-ferrous alloys based on nickel (termed super-alloys), which cost much more than the steel materials used in SC and USC plants. Developing super-alloys and reducing their cost are the main challenges to commercialisation of A-USC technology.

Integrated gasification combined cycle. Coal is partially oxidised in air or oxygen at high pressure to produce a fuel gas. Electricity is then produced via a combined cycle. In the first phase, the fuel gas is burnt in a combustion chamber before expanding the hot pressurised gases through a gas turbine. The hot exhaust gases are then used to raise steam in a heat recovery steam generator before expanding it through a steam turbine. IGCC incorporating gas turbines with 1 500°C turbine inlet temperatures are currently under development, which may achieve thermal efficiencies approaching 50%. IGCC plants require appreciably less water than PC combustion technologies. The overnight cost of current IGCC units ranges from USD 1 100/kW to USD 2 860/kW (IEA, 2011b). In OECD countries, the overnight cost is estimated at about USD 2 600/kW, but this number can vary by around 40% (IEA, 2011a).

7. These descriptions relate to HELE technologies, except where stated to the contrary. For combustion technologies, pulverised coal combustion technology is used as the example to describe the advances in steam conditions that are deployed to raise plant efficiency. Circulating fluidised bed combustion technology could equally well have been used.

8. Efficiency values quoted in this report are generally based on typical European conditions and could vary depending on a number of factors, including local climatic conditions, coal quality and plant elevation.

9. The overnight cost is the cost of a power plant minus any interest incurred during construction, *i.e.* as if the plant were completed overnight.

Table 1: CO_2 intensity factors and fuel consumption values

	CO_2 intensity factor (Efficiency [LHV, net])	Coal consumption[1]
A-USC (700°C[2]) IGCC (1 500°C[3])	670-740 g CO_2/kWh (45-50%)	290-320 g/kWh
Ultra-supercritical	740-800 g CO_2/kWh (up to 45%)	320-340 g/kWh
Supercritical	800-880 g CO_2/kWh (up to 42%)	340-380 g/kWh
Subcritical	≥880 g CO_2/kWh (up to 38%)	≥380 g/kWh

[1] For coal with heating value 25 MJ/kg; [2] Steam temperature; [3] Turbine inlet temperature.

Note: The CO_2 intensity factor is the amount of carbon dioxide emitted per unit of electricity generated from a plant. For example, a CO_2 intensity factor of 800g CO_2/kWh means that the coal-fired unit emits 800g of CO_2 for each kWh of electricity generated.

Source: VBG, 2011.

A range of HELE technologies will need to be deployed, including those available now. Development of those in the RD&D pipeline needs to be accelerated. They will need to be developed, deployed and actively encouraged, using a mixture of policy, regulatory and market-based incentives, supported by large-scale, targeted R&D and demonstration programmes.

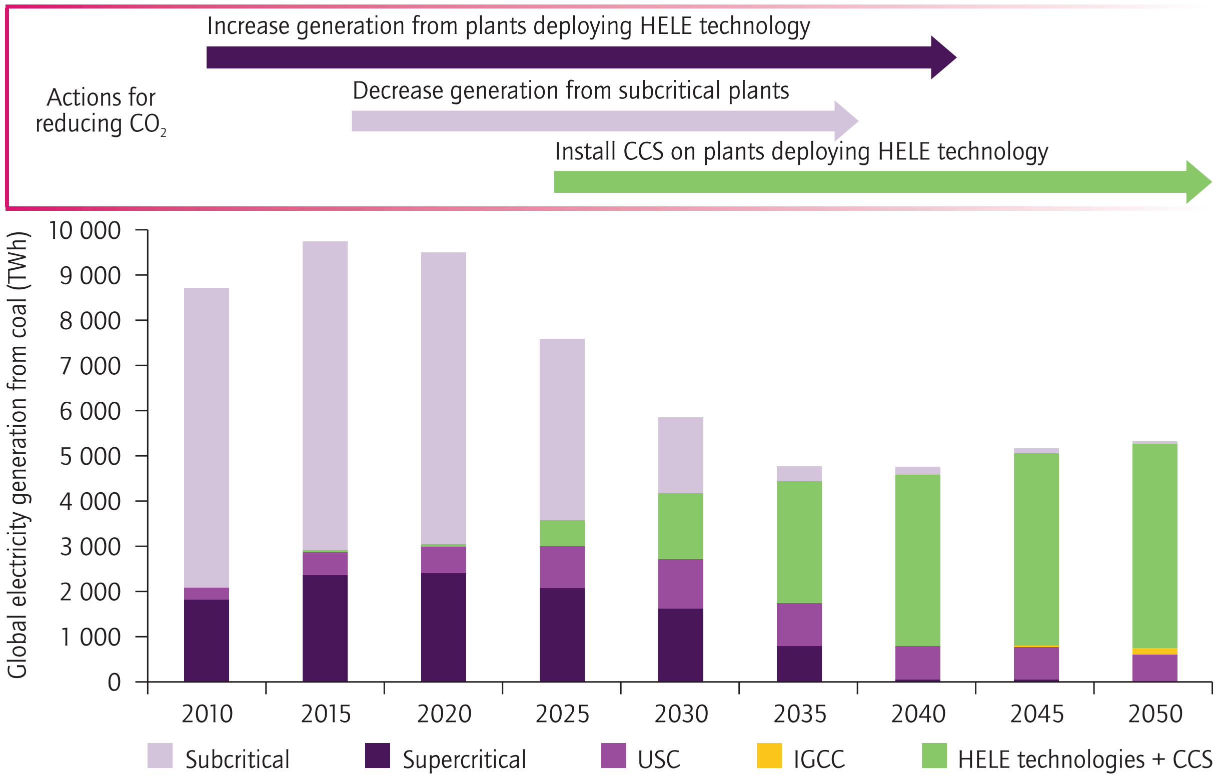
Most new power plants projected for construction between 2010 and 2015 are located in the emerging economies of China, India and Southeast Asia. Investment decisions and key technology choices for these plants will already have been made – the technology will have been "locked in", with a major bearing on efficiency and emission levels for decades to come.

Efficiency

In the short term, meeting electricity demand would require raising dramatically the average efficiency of the global coal fleet – primarily by cutting back on generation from low-efficiency plants and increasing generation from plants based on HELE technologies. Existing plants would need to be upgraded to operate at higher efficiencies and new, high-efficiency plants constructed – with an initial target minimum efficiency of 40% (LHV, net). In the 2DS, 5 292 TWh of electricity is generated from coal in 2050, around 3 400 TWh less than generated in 2010.[10]

10. Note that actual reduction will be very sensitive to the costs assigned for generation from coal and, hence, the cost of HELE technologies and of CCS. The lower the costs, the more coal might be used for power generation while remaining consistent with the aims of the 2DS.

Figure 7: Electricity generation from different coal-fired power technologies in the 2DS



Note: Carbon capture is integrated with HELE coal-fired units to minimise coal consumption and CO_2 abatement cost.

Emissions

Under the 2DS, the coal-fired power generation sector is projected to contribute around 29% of potential CO_2 emissions worldwide in 2020, and just 6% in 2050. To meet this scenario, CO_2 emissions from coal-fired power generation will have to peak by 2020.

On their own, HELE technologies have the potential to reduce CO_2 emissions from coal-fired generation to around 670 g/kWh, compared with the global average value for coal plants of around 1 000 g/kWh – effectively delivering one-quarter of total CO_2 abatement. Thus, although CCS will need to handle the vast majority of CO_2 emissions, the HELE contribution is important because it reduces the volume of CO_2 to be captured and hence the capacity of capture plant required and the quantity of CO_2 to be transported and stored.

To decrease the average CO_2 intensity factor in the global coal fleet, it is vital to reduce generation from subcritical coal units. The 2DS projects generation from subcritical coal units ceases by 2050. Increased generation from high-efficiency coal plants with and without CCS accounts for the difference. If the gap in coal electricity demand in 2050 is filled by generation using HELE technology with and without CCS, it would significantly contribute to reducing CO_2 emissions from the coal fleet.

Meeting efficiency and emissions goals of the 2DS

To meet the 2DS, electricity demand in 2050 would require more than 700 GW of coal-fired plant, requiring an additional 250 GW capacity with CCS to be installed. If the additional 250 GW capacity included CCS based on oxy-fuel technology, the global overnight investment costs are estimated at USD 750 to USD 1 000 billion, whereas if they comprised USC (with no CCS), the estimated cost is USD 575 billion (IEA, 2012b).[11] For consistency with this scenario, the majority of subcritical plants would need to be decommissioned before the end of their design lifetimes.

Assuming that a coal-fired plant has an average lifespan of 50 years, the capacity projected in the 2DS to be operating in 2050 has, in practice, already been met (Figure 8) – with subcritical units providing almost half of total capacity, which presents an unattractive proposition for CCS retrofit (IEA, 2012a). With no policies to encourage their early retirement, newly constructed power stations could operate with low efficiency and emit substantial volumes of CO_2 up to 2050, presenting a major barrier to meeting the 2DS target.

As forced early retirement of sub-critical plants would lead to substantial loss of revenue for generators, low-carbon policies establishing such measures would need to consider the full implications (Box 4). In addition, after 2020, the more efficient SC and USC plants would need to be fitted with CCS.

11. This estimate is the cost assumed for the United States.

Box 4: Decommissioning or reducing generation from subcritical plants

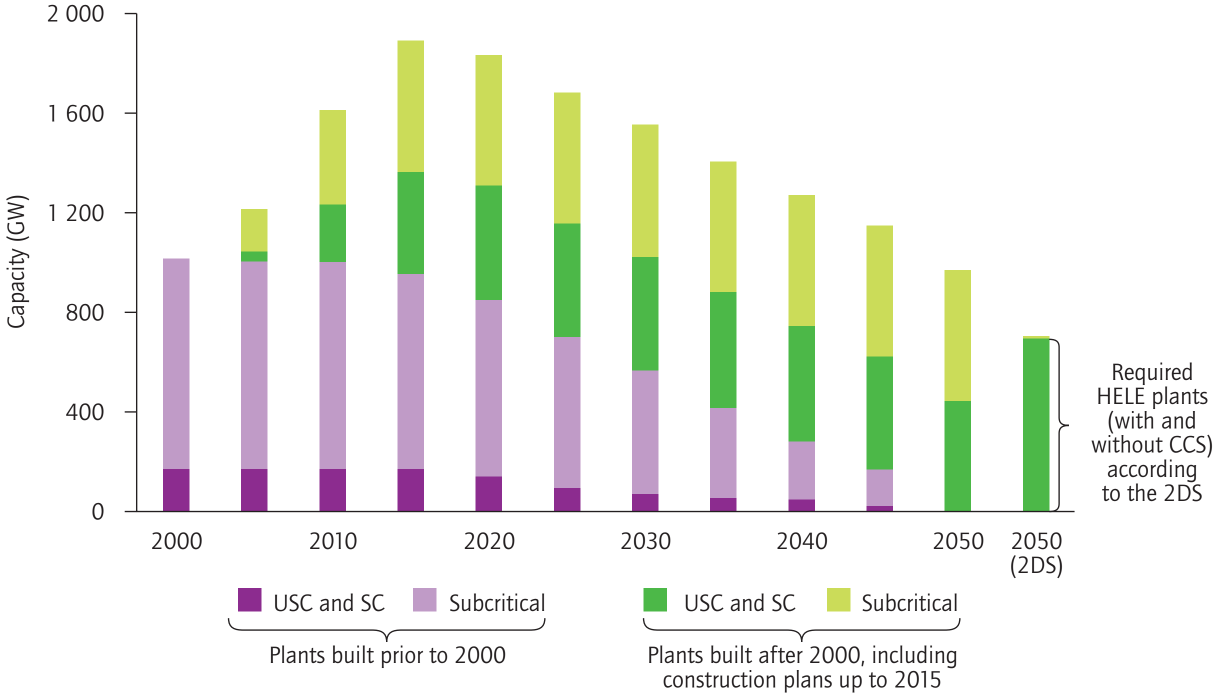
To meet 2050 2DS goals, *ETP 2012* analysis suggests there needs to be zero generation from less efficient, subcritical units. This is a long way from the current reality.

In 2010, more than 1 600 GWe of coal-fired power generation plant was in operation globally. Over 75% of it was subcritical, much of it older than 25 years and comprising units of 300 MWe or less. Though new subcritical units can have an efficiency of 38% (LHV, net), existing operating units cover a range of values: depending on their location, age, operating conditions and feedstock; some operate with efficiencies in the range of 20% to 25%.

Many subcritical plants are already "paid for" and, in most cases, provide a continuous source of revenue for the plant owners. Furthermore, subcritical plants continue to be constructed, particularly in the developing economies. To close down revenue-making units and replace them with lower-carbon technology would be expensive and would undoubtedly increase the cost of electricity generated. To meet the challenging 2050 goals, power generation targets will need to be policy driven, with incentives to satisfy the private sector. Furthermore, if countries are unwilling to take unilateral policy actions that could ultimately reduce their competitiveness, international solutions must be sought. The topic is complex and will require governments, at a high level, to seek solutions with industry to satisfy this policy goal.

At present, few mechanisms exist to promote closing these plants or reducing generation from them prior to the end of their commercial lifetime. The exceptions are China and India, where many GWe of coal capacity have been closed under policies to decommission units of less than 200 MWe. These are vitally important measures, but they reach only the tip of the iceberg.

Figure 8: Projected capacity of coal-fired power generation to 2050



Note: Plant lifetime is assumed to be 50 years. Capacity is estimated from electricity generation data in the 2DS, assuming a capacity factor of 80%.[12]

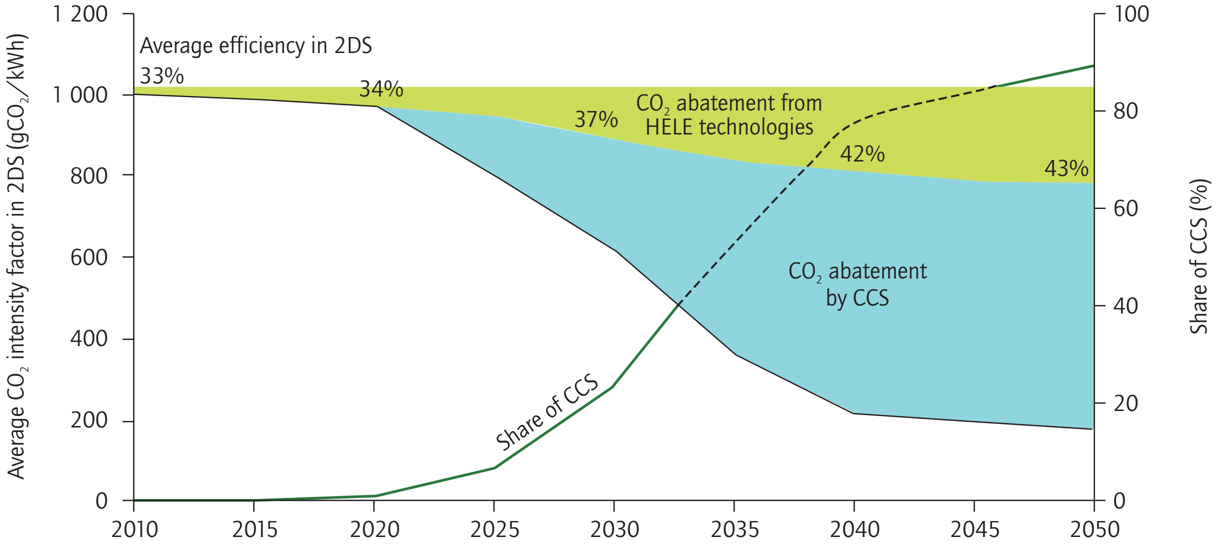
Source: Analysis based on data from Platts, 2011.

Table 2: Actions for CO_2 reduction in coal-fired power plants

Technology development	1. Develop and deploy plants with efficiencies above 45% (LHV, net). 2. Accelerate development and demonstration of large-scale, integrated CCS to reduce costs and energy penalties.
Policy	3. Encourage reduced generation from less efficient subcritical units and/or replace them with more efficient technology. 4. Promote deployment of most efficient technology for new installation and repowering. 5. Promote broad deployment of large-scale CCS plants.

12. The capacity factor of a power plant is the ratio of its actual output over a period of time compared to its potential output, if it had operated at full capacity over that same period. 80% may be high for a future when renewable energy technologies are projected to penetrate substantially for power generation. If coal-fired power generation is to operate flexibly, to complement variable output from renewable generation and satisfy the demands of the electricity grid, it may well be required to operate with a significantly lower capacity factor.

Figure 9: Achieving a lower average CO_2 intensity factor in the 2DS



Carbon capture and storage

The 2DS projects that, by 2050, 90% of electricity would come from HELE plants fitted with CCS. This wide-scale deployment of CCS leads to a sharp decline in the CO_2 intensity after 2020, reaching less than 200 g/kWh in 2050 (Figure 9).

CCS must be developed and demonstrated rapidly if it is to be deployed after 2020 at a scale sufficient to achieve these 2DS objectives. Given the magnitude of ongoing investments in new coal-fired power plants, it is almost certain that CCS will need to be retrofitted on better-performing plants as well as being integrated into new plants built after 2020. Though it would prevent the need for early and costly retirement, retrofitting an existing plant with CCS is complex and requires consideration of many site-specific issues. The energy penalty[13] is high for currently available CCS technologies: they typically reduce plant efficiency by 7 to 10 percentage points. Thus, the economic and technical barriers to deployment of CCS for coal are clear.

CCS, the only technology capable of achieving the necessary deep cuts, can reduce CO_2 emissions by 80% to 90%, bringing CO_2 intensity of coal-fired units down to less than 100 g/kWh.

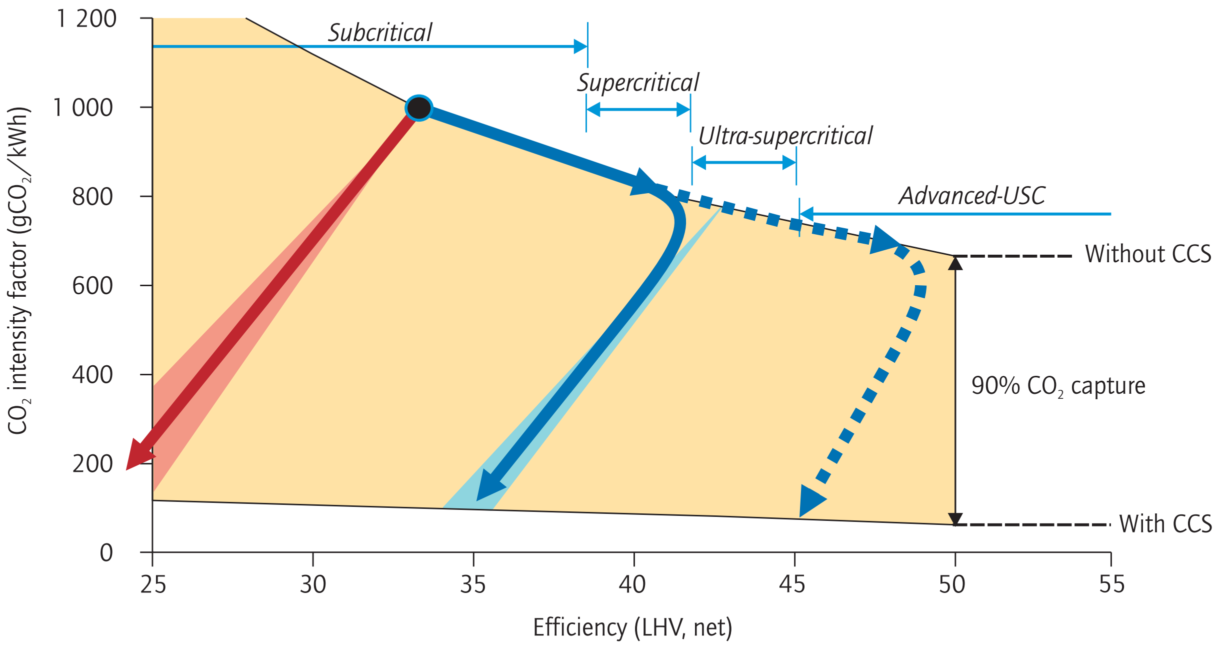
An important relationship between plant efficiency and the need for CCS must be noted. Compared to a subcritical plant with an efficiency of 35%, a USC plant of the same size with an efficiency of 45% requires about 25% less CO_2 capture. Consequently, for the same net electrical output, higher-efficiency plants require CCS units with smaller capacity; hence, high efficiency plants have lower operating costs for CCS. Deploying HELE technologies to increase plant efficiency is important to reduce the eventual cost of CO_2 abatement (Figure 10).

A recent IEA report proposed that retrofitting CCS technologies becomes unattractive for coal-fired power generation plants with efficiencies less than 35% (LHV, net) (IEA, 2012). In fact, deployment of CCS in coal-fired power generation is more favourable for plants operating under SC or USC steam conditions, *i.e.* for efficiencies higher than 40% (LHV, net).

The future of CCS will depend on developing technologies that reduce its energy penalty and cost, particularly by testing and gaining operational experience on large-scale demonstration plants. Strong policies and regulations can accelerate technology demonstration of large-scale, integrated CCS.

13. Energy penalty refers to the auxiliary power (electricity, steam or heat) utilised by the plant above that required in operation of CCS.

Figure 10: Reducing CO_2 emissions from pulverised coal-fired power generation



Note: The quantity of CO_2 that has to be captured per unit of electricity generated decreases markedly as the efficiency of the PC plant increases.

Source: Adapted from VGB, 2011.

HELE technologies to raise efficiency and reduce emissions

Ultra-supercritical pulverised coal combustion

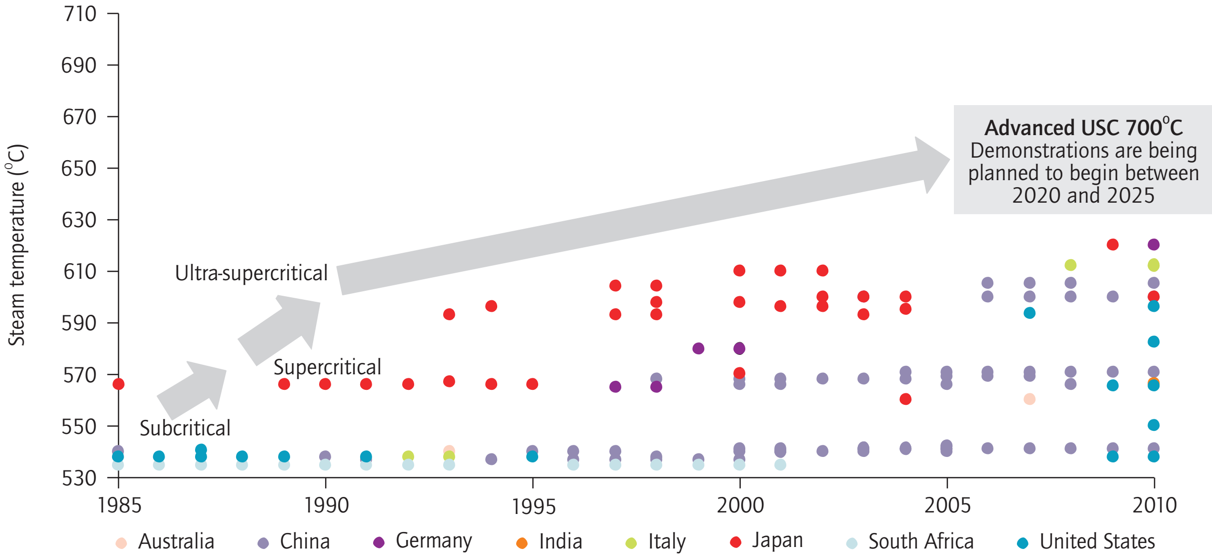
Many factors determine the efficiency of PC plants. The most effective means of achieving high efficiency is to use steam temperatures and pressures above the supercritical point of water, *i.e.* at pressures above 22.1 MPa. USC units, often defined as units with pressures above 22.1 MPa and temperatures above 600°C, are already in commercial operation. State-of-the-art USC units operate with steam parameters between 25 MPa and 29 MPa, and temperatures up to 620°C (Figure 11). With bituminous coal, plants incorporating USC technology can achieve efficiencies of up to 45% (LHV, net) in temperate locations. Lignite plants can achieve efficiencies close to 44% (Vattenfall, 2011a). As steam conditions are increased, both fuel consumption per kilowatt hour (kWh) and specific CO_2 emissions decrease.

To reduce CO_2 emissions further, CO_2 capture must be applied. The options are to apply post-combustion capture or oxy-fuel combustion; in neither case, however, have the technologies been demonstrated at commercial scale. At present, they are expensive and the operating costs are high. The overnight cost of a supercritical unit is up to 10% higher than the cost of a supercritical unit. However, the additional cost may be offset from saving fuels, depending on the cost of the fuel.

USC plants are already in commercial operation in Japan, Korea, some countries in Europe, and more recently, in China (Figure 11). As of 2011, China had 116 GW of 600 MWe USC units and 39 GW of 1 000 MWe USC units in operation, out of a total coal-fired fleet of 734 GW (Zhan, 2012).

To raise the efficiency of USC, A-USC must be developed, which is described next.

Figure 11: Applying state-of-the-art steam conditions in PC combustion units



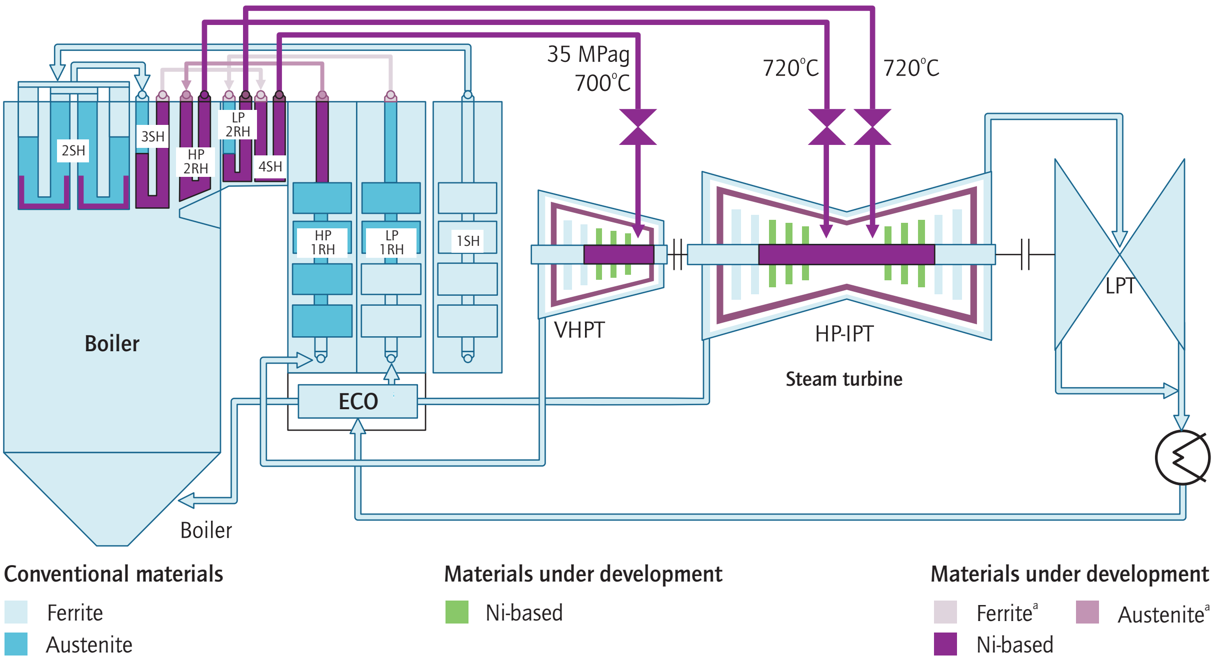
Note: Only units over 600 megawatt-electrical (MWe) output are included.

Source: Analysis based on data from Platts, 2011.

Advanced ultra-supercritical pulverised coal combustion

Advanced ultra-supercritical pulverised coal combustion (Advanced USC or A-USC) is simply a further development of USC. But the aim of further raising the pressure and temperature of the steam conditions to those required for A-USC systems requires the use of super-alloys (non-ferrous materials based on nickel) for plant components (Figure 12). Super-alloys are already established in gas turbine systems, but component sizes in a coal plant are larger, the combustion situation is different, and pressure stresses are higher. Consequently, new formulations and fabrication methods are necessary.

Figure 12: High-temperature materials for a double-reheat advanced USC design



a: compostition of ferrite and austenite are adjusted for particular applications.

Note: The thermodynamic efficiency of a steam cycle increases with the increasing temperature and pressure of the superheated steam that enters the turbine. It is possible to further increase the mean temperature of heat addition, by taking back partially expanded and reduced temperature steam from the turbine to the boiler, reheating it, and re-introducing it to the turbine. This can be done either once or twice, which is known as single and double reheat, respectively. Addition of the second reheat stage can improve thermal efficiency by one percentage point.

Source: Fukuda, 2010.

Advanced USC is under development in China, Europe, India, Japan and the United States, with demonstration projects planned after 2020. By using A-USC steam conditions of 700°C to 760°C at pressures of 30 MPa to 35 MPa, manufacturers and utilities are working to achieve efficiencies approaching 50% (LHV) and higher. A-USC is expected to deliver a 15% cut in CO_2 emissions compared with SC technology, bringing emissions down to 670 g CO_2/kWh.

For CO_2 capture, post-combustion or oxy-fuel combustion would be applied in the same manner as for USC. As shown in Figure 10, raising the efficiency of a unit reduces the capacity of the capture process required; hence, high efficiency plants have lower specific operating costs for CCS. A-USC with CO_2 capture system can reduce the eventual cost of CO_2 abatement.

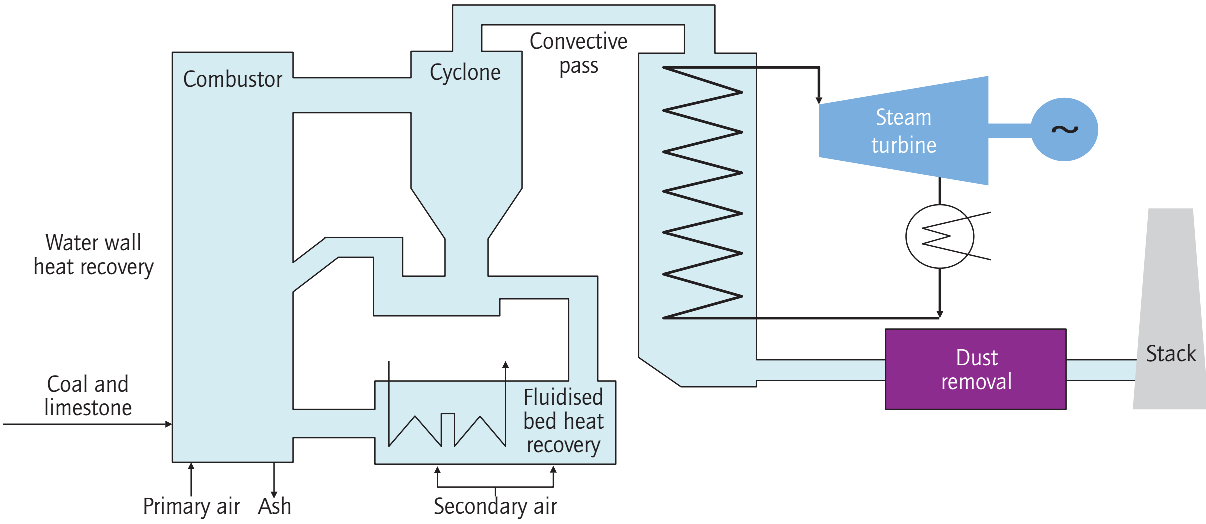
Cost is a major challenge to commercialisation potential of A-USC. The far higher temperatures and pressures to which components in an A-USC system are exposed, as well as altered chemical environment, require the use of super-alloys, which are markedly more expensive than steel. Fabricating and welding the materials is much more complicated. Commercial deployment of A-USC is unlikely to begin until the mid-2020s.

Circulating fluidised bed combustion

In circulating fluidised bed combustion (CFBC) systems, the fuel is crushed rather than pulverised, and combustion takes place at lower temperatures than in PC systems. An upward current of combustion air supports a highly mobile bed of ash and fuel. Most of the solids are continuously blown out of the bed before being re-circulated into the combustor. Heat is extracted for steam production from various parts of the system (Figure 13). The capacity factor of CFBC power plants is comparable with PC plants.

Emissions of NO_x in CFBC systems are intrinsically low because the combustion temperature is relatively low. Limestone is fed into the combustion

Figure 13: Circulating fluidised bed combustion



system to control SO_2 emissions, typically achieving 95% abatement. As for PC combustion, post-combustion or oxy-fuel combustion would be required to capture CO_2.

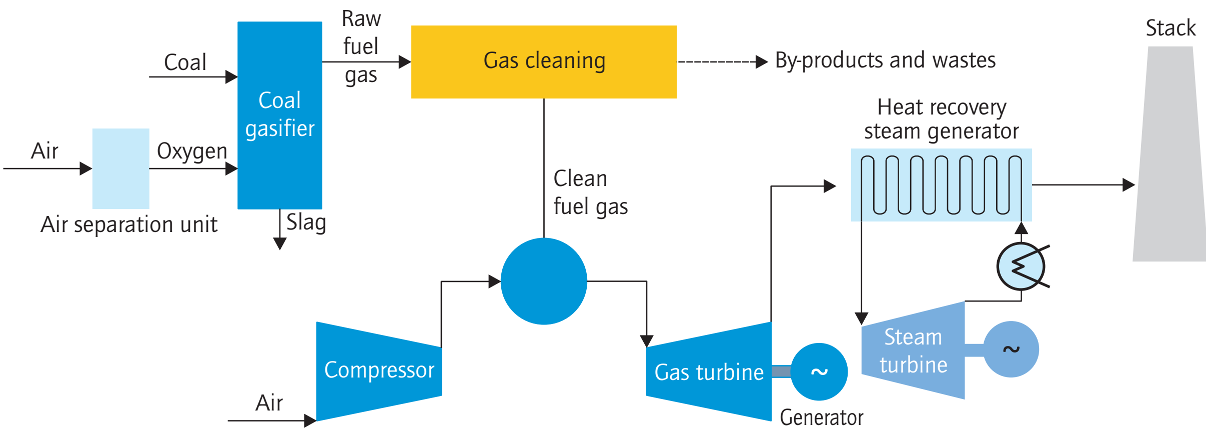
Although the cost of CFBC may be somewhat higher than for PC, due to the limitation on unit capacity, CFBC will remain an important technology, with large units burning coal, biomass and wastes, as well as other opportunity fuels.

CFBC is a mature technology; supercritical CFBC plants are now in operation or under construction in China, Poland and Russia (Jantti *et al.*, 2009; Li *et al.*, 2009; Minchener, 2010; Jantti and Rasanan, 2011). The technology is particularly suited to fuels with low heat content. To raise the efficiency of CFBC further, more advanced steam conditions must be used, following the same principles as applied to PC combustion.

Integrated gasification combined cycle

Integrated gasification combined cycle uses gasification, with low (sub-stoichiometric) levels of oxygen or air, to convert coal into a gaseous fuel (Figure 14). IGCC incorporating the latest 1 500°C-class gas turbines can achieve efficiencies higher than 45% (LHV, net; *i.e.* comparable with those of A-USC systems for pulverised coal) with bituminous coals.

Figure 14: Integrated gasification combined cycle



IGCC has inherently low emissions, partly because the fuel is cleaned before it is fired in a combined cycle gas turbine (Figure 14). By 2050, the introduction of 1 700°C-class gas turbines could bring CO_2 emissions from IGCC below 670g/kWh.

CCS trials have been undertaken with IGCC, but large-scale integrated demonstration is still required. IGCC might become more cost-competitive with PC when CCS becomes commercially available with both systems

Compared to PC plants, IGCC plants have higher capital and operating costs for power generation: higher redundancies are applied to mitigate risks, there are a larger number of sub-systems and a need to contend with aggressive conditions in the gasifier. The fact that the size of the gas turbine constrains the unit size has also limited market deployment of IGCC. Until IGCC reaches maturity, it is unlikely to compete economically with PC plants.

Commercial prototype demonstration plants are operating in the United States, Europe and Japan, and more plants are under construction in China, Japan, Korea and the United States. Overall, IGCC has much less operating experience than PC plants because few reference plants are in commercial operation (IEA, 2011c). Cost-competitiveness will depend on sufficient numbers of plants being deployed.

Important RD&D objectives for IGCC include reducing costs, improving plant reliability and raising efficiency. The use of lower-grade coals in IGCC tends to reduce efficiency and raise capital costs; R&D to mitigate this penalty currently focuses on using drying systems for lignite and solid feed pumps. A second challenge is that IGCC plants require a large amount of oxygen – and conventional large-scale oxygen production uses a considerable amount of energy. Air requires a larger gasifier and produces a fuel gas with lower heat content; around 4 megajoules per normal cubic metre (MJ/Nm^3) compared with 12 MJ/Nm^3 to 16 MJ/Nm^3 for an oxygen-blown gasifier and 38 MJ/Nm^3 for natural gas. R&D to find a more economical and efficient process to produce oxygen currently focuses on ion transport membrane (ITM) technology as one possibility, although development has only reached the pilot scale, with commercial-scale plants still some way off (NETL, 2009). A more efficient version of IGCC, the integrated gasification fuel cell, is being developed (Box 5).

Important niche technologies

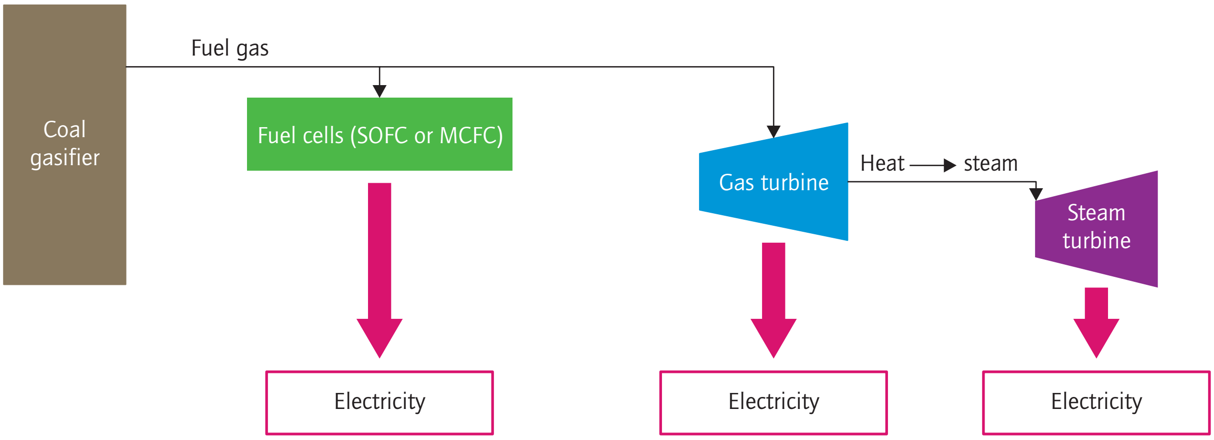
Some coals exist in deep deposits or in narrow seams that can not be mined economically using conventional methods. Other coals have properties, *e.g.* high moisture content, that reduce the efficiency by which they may be converted into electricity. Biomass, largely treated as a carbon-neutral fuel, is expected to contribute significantly to future power generation; however, as its composition and handling properties are much different from coal, the means to use it effectively need to be developed. Possible solutions to these diverse issues are described.

Box 5: IGCC developments

The fuel gas from coal gasification (syngas), which consists mostly of hydrogen and carbon monoxide, can be used for power generation but also to produce hydrogen, transport fuels, synthetic natural gas (SNG) and chemicals. Consequently, IGCC in some locations may provide the basis of polygeneration plants with the flexibility to switch product output according to market demand. This flexibility could potentially offset the higher capital requirements of such systems. In theory, CCS could integrate well with polygeneration (Carpenter, 2008).

A further advance is to integrate fuel cells into integrated gasification systems. Integrated gasification fuel cell (IGFC) technology differs from IGCC in that part of the syngas exiting the gasifier is diverted into a high temperature fuel cell, such as a solid oxide or molten carbonate fuel cell (Figure 15) (NEDO, 2006). IGFC has the potential to raise the conversion efficiency significantly above that possible using just IGCC.

Figure 15: Integrated gasification fuel cell

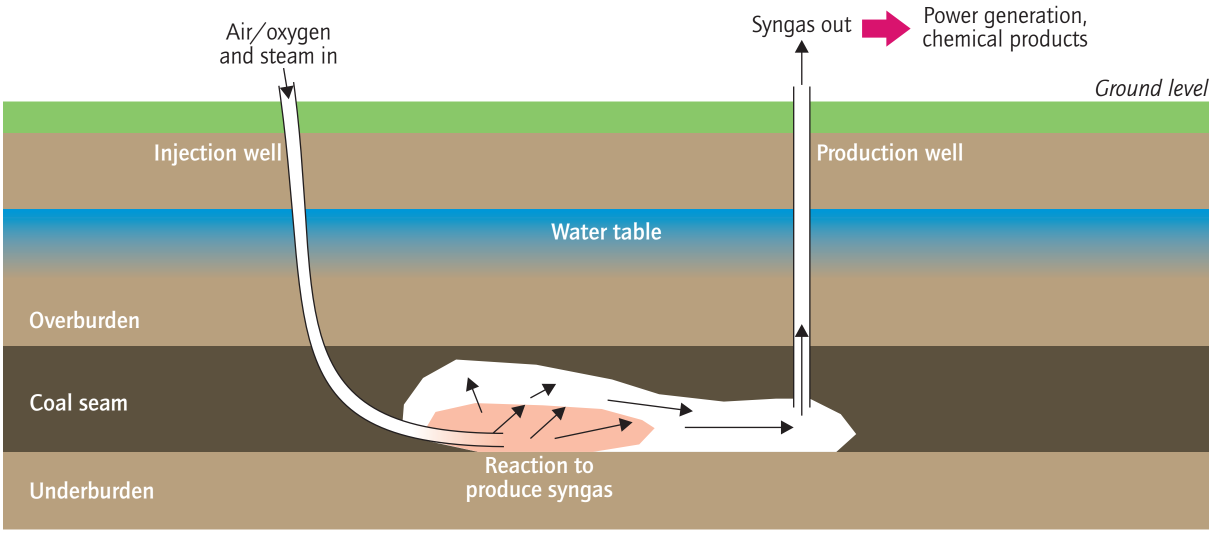


Underground coal gasification

Underground coal gasification (UCG) offers the potential to use the energy stored in coal in an efficient, economic and environmentally-sensitive manner. It shows strong potential particularly for use in deposits that are inaccessible or uneconomic to access using conventional mining methods. If UCG were successfully developed as a commercial proposition and widely deployed, then the world's exploitable coal reserves would be revised substantially upwards.

UCG involves burning (reacting) coal in situ/in-seam, using a mixture of air or oxygen, possibly with some steam, to produce a syngas (Figure 16). The steam may come from water that leaks into the underground cavity, from water already in the coal seam or from steam deliberately injected. Some coal combustion takes place, generating enough heat to support the process reactions. Elevated temperatures in a low-oxygen atmosphere (*i.e.* under sub-stoichiometric conditions) stimulate gasification, as the coal is partially oxidised. The principal gases formed are hydrogen and carbon monoxide (Couch, 2009). UCG using state-of-the-art gas turbines could approach the efficiencies achieved by IGCC.

Figure 16: Underground coal gasification



UCG might offer a relatively simple and low-cost way of storing CO_2; given favourable geological conditions, CO_2 from reacted syngas could be stored underground in the cavities created by the UCG process.

Many resource-rich countries, including Australia, China, India, South Africa and the United States, have been developing UCG in recent years (Lauder, 2011). Its future role will depend strongly on the outcomes of recent or current trials and pilot operations. Several challenges remain to commercial application and broader deployment, including the need for increased characterisation of the geology around potential coal seams and legislation on the extraction of these underground resources.

Power generation from low-grade coals

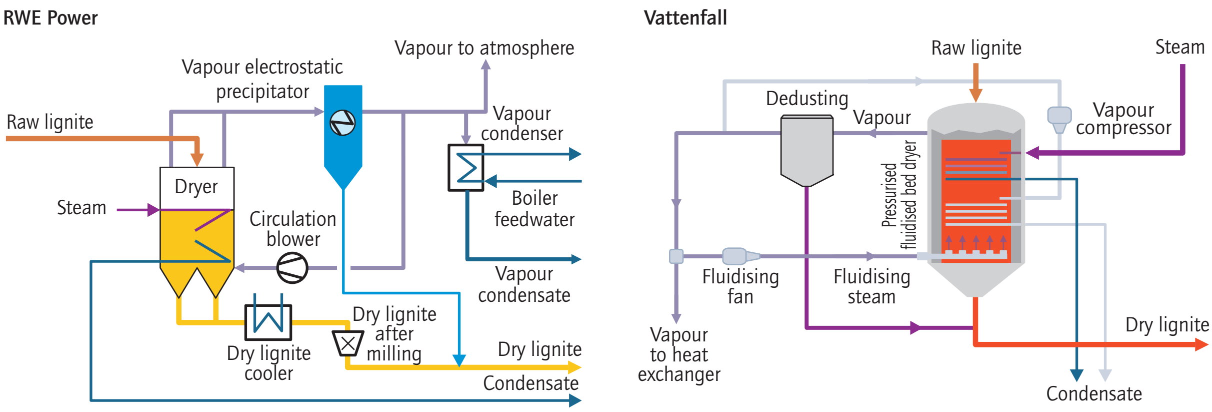
Low-grade coals (such as hard coal and lignite) present particular challenges for both efficiency and emissions, partly because of their high content of either moisture or ash. Drying and cleaning processes can help to address these challenges.

Lignite often has high moisture content. Because this moisture absorbs energy as it boils, it often means a loss of efficiency when lignite is used to fuel conventional power plants (such energy is not recovered except in condensing boilers). Lignite drying can increase the efficiency of conventional plants and substantially reduce CO_2 emissions, particularly by recovering as much energy as possible from the low-grade heat.

RWE has installed a full-scale prototype drier to dry 25% of the fuel feeding its 1 000 MWe USC lignite unit at the Niederaussem plant in Germany. Energy for drying comes from in-bed tubing in which low-pressure steam is condensed, with waste heat recovered from the condensate. The altered heat balances in the boiler necessitate changes to the furnace size, heat-transfer surface area and flue gas recirculation. Boiler cost savings will be largely offset by the cost of the drier. Vattenfall has also applied the same principles to dry the lignite. In both processes, the steam cycle is optimised for maximum efficiency (Figure 17). Such technology may be applied to combustion or gasification-based plants (Hashimoto, 2011). Drying systems are also being developed in Australia, Japan, OECD Europe and the United States (Harris, 2012; Bowers, 2012; Kinoshita, 2010).

Both hard coal and lignite may have a high ash content, which can detract from the operational performance of the power generation unit. In both combustion and gasification plants, significant energy may be required to raise the temperature of the ash (in some cases above its melting point), energy which is often lost. The ash content can significantly affect the efficiency of the overall process. To maximise efficiency, as much ash as possible should be removed during the coal beneficiation operation before coal is fed into the power generation unit, which should be designed to burn or gasify coal in the most effective manner. This may affect, for example, the design of the heat recovery systems and of the water/steam circuit, as well as the sizing of the ash collection vessels.

Figure 17: Advanced lignite pre-drying in pulverised coal combustion



Note: RWE Power's WTA process shows one of several process variants being developed and tested.

Source: RWE, 2010; and Vattenfall, 2011b.

Another technology for utilising lignite, still at an early stage of development, is termed Micronised Refined Coal – Direct Injection Coal Engine (MRC-DICE). The process utilises physical coal cleaning, which liberates minerals via a micronising and flotation process. The fine coal powder (micronised refined coal), which is finer than pulverised coal, is then mixed with water to create a slurry that is intended to be combusted in diesel engines, returning an efficiency similar to that obtained from diesel fuel (Wibberley, 2012).

Biomass co-firing

Another means of increasing the efficiency of coal-fired plants while also reducing emissions is to adopt a practice of co-firing coal and biomass.[14] As coal-fired plants generally operate with much higher steam parameters than biomass-fired power plants, the co-fired biomass is converted at a higher efficiency. Because biomass incorporates CO_2 during its growing period, it is regarded as a carbon-neutral fuel that provides an opportunity for direct reduction of emissions.

The technology has been trialled or adopted commercially in gasification and particularly in combustion systems around the world, and has attracted government support in several countries, including the United Kingdom and Denmark.

Despite the advantages, several factors constrain the use of biomass for power generation. The composition of biomass is very different from that of coal. Biomass can contain much higher moisture levels, up to 50%, which adversely affects combustion by absorbing heat during evaporation. Also, the heating values of biomass are lower than those for coal and biomass is much less dense than coal, so greater volumes need to be collected, handled, transported and stored.

For many biomass crops, supplies are readily available during harvesting but scarce during cultivation and growth. In many countries, biomass supply is widely dispersed and there is no established infrastructure for harvesting and transporting it to power plants. Logistical costs can mean that small biomass units are favoured, but these tend to be less efficient than large units that benefit from economies of scale.

14. Biomass refers to renewable energy from living (or recently living) plants and animals; *e.g.* wood chippings, crops and manure.

Wood products are a more consistent product for co-firing, and supply is less affected by the issue of seasonality. Substantial effort is being directed at developing torrefaction[15] to make biomass a more uniform product that more closely resembles the characteristics of coal. Pelletisation is already being used on a large scale: for example, RWE has opened a 750 000 t/y wood pellet facility in Georgia, United States (Fernando, 2012).

On a large scale, co-firing at 10% to 15% has been found to cause few problems for coal-fired power plants and, in some cases, much higher shares of biomass are planned or already in use – often driven by subsidies to encourage the deployment of renewable energy technologies. It should be noted, however, that co-firing 10% to 15% of the energy content in a large-scale thermal power plant (say, of 1 000 MWe capacity) would correspond to a biomass supply chain of around 250 to 350 MWth, which may present logistical and economic challenges.

Looming challenges in coal-fired power generation

When considering the deployment of HELE technologies, external factors should also be considered. Two factors of importance are addressed below: the deployment of coal-fired power generation plant in arid regions and the case where the load demand on a plant may be variable or intermittent.

Water consumption

At present, large quantities of water are required for coal production, coal beneficiation, power generation from coal and for reducing both non-GHG and CO_2 emissions (US DOE, 2006). Recent growth in coal-fired generation has driven up water consumption. As many regions of the world are becoming chronically short of water, reducing water consumption is critical to satisfying future demand for electricity. Technologies that consume

15. A process of heating biomass (typically at temperatures ranging between 200°C and 320°C) to reduce moisture or impurities, which changes the biomass properties to obtain a much better fuel quality for combustion and gasification applications. Torrefaction leads to a dry product with no biological activity, such as rotting.

no water or less water are available, but many of them are less effective, lead to less efficient generation or are simply more costly to operate. Dry cooling, for example, reduces overall plant efficiency by 4 to 5 percentage points.

In flue gas treatment, it is not unusual for conventional flue gas desulphurisation (FGD) systems to use over 50 tonnes water per hour. Not surprisingly, interest is growing in dry technologies. Japan's Isogo Power Station Unit 2 provides an excellent example of a PC combustion unit that deploys dry technologies to achieve exceptionally low emissions of non-GHG pollutants (Topper, 2011). It uses dry desulphurisation technology to reduce SO_2 emissions; a combination of low-NO_X burners, overfire air and selective catalytic reduction to reduce NO_X emissions; and electrostatic precipitators to reduce emissions of particulate matter.

Flexibility to balance renewables

The projected growth of renewable energy technologies (RETs) will also affect the deployment of HELE technologies. As the share of RETs in power generation rises, so will the need for coal (and gas) technologies to balance the resultant variable generation. Future coal-fired units will need the flexibility to balance fluctuations in the power system with no major loss of efficiency. However, there will also be an economic element to consider: if a plant does not operate at a high capacity factor, the cost of generating each unit of electricity increases. This might reduce investment in more costly, high efficiency technology as a plant design is basically optimised at full load with high capacity factor. These dynamics are important. Flexibility and cost will be essential features of future development programmes.

Box 6: Reducing non-GHG pollutant emissions

By using currently available flue gas treatment systems, it is possible to reduce emissions of NO_X, SO_2 and PM below the most stringent levels demanded anywhere in the world (Figure 18). In Japan, OECD Europe and North America, emissions of air pollutants have been reduced dramatically, particularly over the past two decades (Figure 19). To bring emissions of NO_X, SO_2 and PM down to levels currently achieved by these front-runner countries, effective policy measures need to be put in place across a broader range of both OECD and non-OECD countries, with appropriately strict penalties for non-compliance. Market-based mechanisms to achieve least-cost compliance have been successful in several countries.

To minimise NO_X, generators use a combination of combustion technologies (including staged air and fuel mixing for low-NO_X combustion) and post-combustion technologies (usually selective catalytic reduction [SCR]). Particulates are removed by electrostatic precipitators or fabric filters, and SO_2 by using flue gas desulphurisation, usually scrubbing with limestone slurry. Dry SO_2 control systems that offer extremely high performance are deployed at some plants.

Other technologies available for NO_X and SO_2 control offer further potential for improving performance. For plants fitted with technology to capture CO_2, particularly those employing amine scrubbing, lower emissions of SO_2 and, to a lesser extent, NO_X would be favoured. Acid gases such as SO_2 and NO_X irreversibly degrade the amine solvent used to remove CO_2, preventing its regeneration and increasing significantly the costs of the overall process. Moreover, particulate matter can build up in the solvent and, if not filtered out, will require changing the solvent more frequently.

In CFBC, limestone is fed into the combustion system to control SO_2 emissions, typically achieving 95% abatement. Emissions of NO_X are intrinsically low because the combustion temperature is comparatively low. Additional SO_2 or NO_X capture systems can be added where very low emissions are required.

Mercury emissions from coal-fired power plants vary widely; much of the mercury released may be deposited (captured) on the fly ash, in the selective catalytic reduction system and/or in the flue gas desulphurisation unit. The highest levels of control are achieved with fabric filters fitted for particulate removal. In plants equipped with the full range of flue

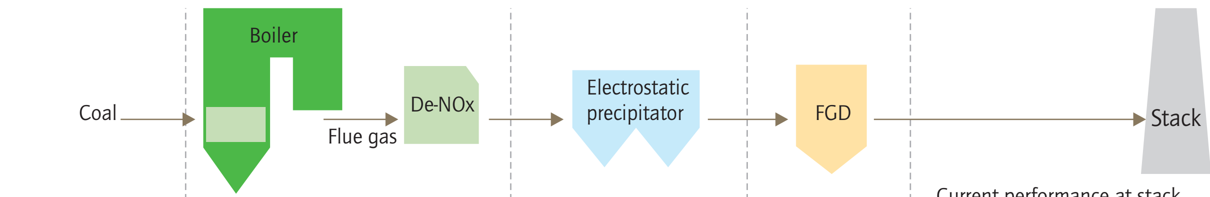
Box 6: Reducing non-GHG pollutant emissions (continued)

gas treatment systems, with no additional equipment for mercury removal, it is possible to reduce mercury emissions to less than 3 μg/Nm³. Mercury levels could be reduced still further by injecting activated carbon or by installing multi-pollutant removal systems.

In IGCC, stringent particulate control (via medium-temperature filtration) and desulphurisation (through liquid scrubbing) are carried out before the fuel gas is sent to the gas turbine. Most NO_X control is achieved by mixing the fuel gas with nitrogen or steam before combustion, but scrubbing ammonia from the gas also reduces NO_X emissions. Advanced ultra-low NO_X burners are being developed by gas turbine manufacturers with the aim of achieving extremely low emissions. An interim means of achieving ultra-low NO_X is to add selective catalytic reduction. Capturing sulphur gases from fuel gas at around 250°C using metal oxides in a transport reactor should increase efficiency and reduce costs (Gupta *et al*., 2009).

Ultimately, it is likely that environmental emissions could be reduced even further, to less than 10 mg/Nm³ for NO_X and SO_2, and less than 1 mg/Nm³ for PM (Henderson and Mills, 2009).

Figure 18: Capability of current flue gas treatment systems



NO_x (mg/Nm³)	<500 - 1 000 → <50 - 100		
SO_2 (mg/Nm³)	<1 000 - 5 000		< 20 - 100
$PM_{2.5}$ (mg/Nm³)	<20 000	< 50	< 10

Current performance at stack
<50 - 100
(<0.16 - 0.42 g/kWh)
<20 - 100
(<0.06 - 0.42 g/kWh)
<10
(<0.032 - 0.042 g/kWh)

Note: To convert mg/Nm³ into g/kWh, it is necessary to assume values for the plant efficiency and the flue-gas volume per unit of energy. In Figure 18, plant efficiency is assumed to range from 30% to 40% (LHV, net) based on regional average efficiencies. The flue gas volume is assumed to be 353 m³/GJ (LHV); this will vary with coal composition, but the fluctuation from this value is commonly less than 5%.

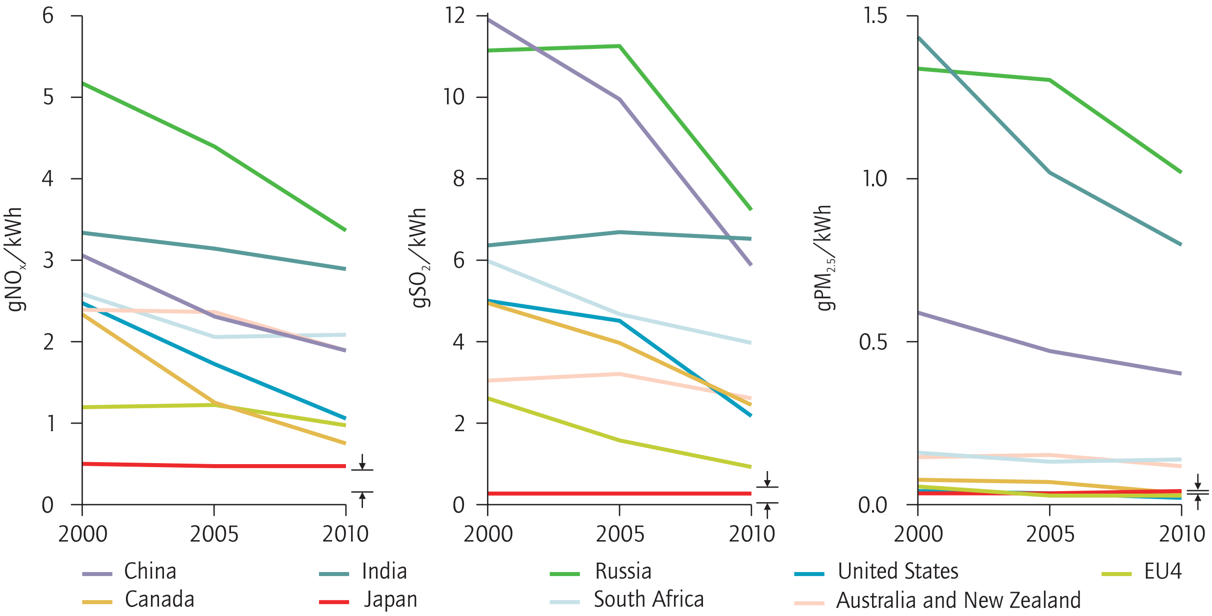
Summary of technology status

The range of high efficiency, low emissions (HELE) technologies highlighted in this roadmap are at various stages of development and/or deployment (Table 3), and offer different performance potentials for both improving efficiency and reducing emissions (both GHG and non-GHG).

PC and CFBC are technically mature: development of A-USC aims to raise their efficiencies further and reduce their CO_2 intensity factors to below 700 gCO_2/kWh. Maximum unit size is important, as certain advantages relate to scale; the capacity of a single PC unit can now reach 1 100 MWe (Nowack *et al*., 2011). Broader deployment is the primary means of achieving the potential of these technologies.

IGCC efficiency could be raised to the level of advanced USC by using 1 500°C-class gas turbines. Advanced fuel cells in an IGFC, a further development of IGCC, may offer even higher thermal efficiencies, reducing carbon emissions to around 500 gCO_2/kWh to 550 gCO_2/kWh. Reducing emissions of non-GHG pollutants and incorporating CO_2 capture are two more targets.

Figure 19: NO_x, SO_2 and PM emissions from coal-fired power plants



Note: EU4 includes France, Germany, Italy and the United Kingdom. Ranges sandwiched between the arrows indicate currently achievable performances from flue gas treatment systems.

Source: Includes data from Cofala *et al*, 2010.

These technologies require further development and demonstration, ultimately leading to widespread deployment.

Beyond HELE technologies, CCS is essential to make the deep cuts required to substantially reduce the CO_2 intensity factor of generation. At present, the capital and operating costs of CCS are high and a significant amount of energy is needed to operate CCS (particularly the capture facility), which reduces plant efficiencies by 7 to 10 percentage points. Technology development to reduce both the cost and the energy penalty is critical to the future of CCS.

Table 3: Performance of HELE coal-fired power technologies

Fuel type	Plant type	Emissions: CO_2 (g/kWh)	NO_x	SO_2 (mg/Nm³)	PM	Max. unit capacity (MWe)	Capacity factor (%)	CCS energy penalty (%-points)
Coal	PC (USC)	740	<50 to 100 (by SCR)	<20 to 100 (by FGD)	<10	1 100[3]	80	7 to 10 (post-combustion and oxy-fuel)
	CFBC	880 to 900	<200	<50 to 100 (in situ)	<50	460	80	
	PC (A-USC)[1]	670 (700°C)	<50 to 100 (by SCR)	<20 to 100 (by FGD)	<10	<1 000 (possible)	-	
	IGCC[1,2]	670 to 740	<30	<20	<1	335	70	7
	IGFC[1]	500 to 550	<30	<20	<1	<500	-	

[1] Under development.

[2] Only six IGCC plants currently in operation.

[3] In operation (sliding pressure-type).

Note: For the successful realisation of IGFC, the development of reliable fuel-cell technology is essential.
Source: Includes data from IEA, 2011a; Henderson and Mills, 2009; and VGB, 2011.Source: VBG, 2011.

HELE technologies for coal-fired power generation: actions and milestones

HELE technologies have an important contribution to make to the goal of halving energy-related CO_2 emissions by 2050. Essentially, existing HELE technologies must be deployed more quickly and the development of more effective technologies must be accelerated. Following consultation with stakeholders, time scales are offered that, if met, will facilitate the contribution to be made.

PC combustion

This roadmap recommends the following actions:	***Milestones***
PC - hard coal	
Deploy more supercritical and USC plants. Continue R&D on A-USC.	2012-20
Deploy more USC plants. Demonstrate A-USC. Test A-USC with post-combustion capture at pilot scale. Test oxy-fuel A-USC at pilot scale.	2021-25
Deploy A-USC. Demonstrate oxy-fuel A-USC.	2026-30
Deploy A-USC with integrated CCS. Deploy oxy-fuel A-USC.	2031-50
PC - brown coal	
Deploy more SC and demonstrate USC. Demonstrate lignite drying on full-scale power plant.	2012-20
Deploy lignite drying on full-scale power plant. Deploy USC plants. Demonstrate A-USC with partial CO_2 capture.	2021-25
Deploy USC with 100% fuel drying. Demonstrate A-USC with full flow dry-feed boiler. Demonstrate A-USC with full-flow CO_2 capture.	2026-30
Deploy A-USC incorporating drying with full CCS.	2031-50
PC – non-GHG emissions	
Mature, except for mercury control, and the best installations perform highly effectively: • NO_X — combustion measures (*i.e.* low-NO_X burners and air staging) plus SCR capable of meeting emission levels of 50 mg/Nm^3 to 100 mg/m^3; • Particulates — emissions reduced to 5 mg/Nm^3 to 10 mg/Nm^3, even with ESPs; and • SO_2 — limestone/gypsum FGD capable of reducing SO_2 to below 20 mg/Nm^3. Further reductions will be achieved mainly through development and deployment of these systems. Examples include: improved FGD with better reagent/flue gas contacting and the use of new additives; new, higher-performance SCR catalysts; and increased use of combined NO_X/SO_2 dry control systems.	2012-20

Growing awareness of the need for fuel efficiency – particularly as coal prices continue to rise – is encouraging major manufacturers to develop USC PC combustion plants. USC has become well established for new projects in OECD countries and in China. Several non-OECD countries are moving toward greater use of supercritical PC combustion for new plants, particularly for India and South Africa. After the initial move, and once familiarity with the technology is obtained, a move to USC is likely. The outlook is summarised as follows:

- eventual decrease to zero of new-build subcritical plants (for subcritical units >300 MWe);

- eventually, all new plants (>300 MWe) to achieve performance equivalent of USC;
- efficiency improvements achieved by testing and demonstrating improved plant designs;
- develop lignite plants with 4 percentage point efficiency gain over current design, for no net additional cost;
- achieve 5 percentage point efficiency gain over current best PC combustion plant from future A-USC plants;
- reduce non-GHG emissions to near zero, including for dry systems; and
- CCS marketed as inclusive system, using post-combustion capture or oxygen firing.

It is encouraging that China has mandated, starting in 2012, much tighter emission standards for SO_2, NO_X and particulates. Awareness needs to be raised that dry FGD and NO_X control systems are available, and that non-GHG emission controls are equally appropriate in regions or countries with low water resources. Development of dry systems could usefully be supported with the aim of reducing the efficiency penalty. A mechanism for recovering the additional cost to the power suppliers may be needed. There is also a need to show, perhaps through support for innovative systems, that reduced water consumption through dry cooling can still allow plants to operate in a highly efficient manner.

Looking further ahead, progress is needed in the development and deployment of A-USC plants operating at 700°C and above. Most groups involved in this area aim to advance to full-scale demonstration in around 10 years (2020-25). It is noteworthy that India and China have recently started their own programmes. In all regions, both public and private sector funding is supporting development. This clear commitment to improving plant efficiency needs to be maintained.

CFBC

This roadmap recommends the following actions:	***Milestones***
Deploy more supercritical and demonstrate USC.	2012-20
Deploy USC CFBC.	2021-25
Demonstrate A-USC CFBC. Test A-USC oxy-fuel at pilot scale. Initial deployment of A-USC.	2026-30
Deploy A-USC CFBC with full CCS – both post-combustion capture and oxy-fuel.	2031-50
• NO_X <200 mg/Nm^3; • Particulates <50 mg/Nm^3, with ESP and fabric filters; • SO_2 <50 mg/Nm^3. Additional systems (*e.g.* external FGD, ammonia injection) may offer even better performance with respect to SO_2 and NO_X.	2012-20

Supercritical CFBC is now mature technology. The first plant, a 460 MWe unit, was commissioned in Poland in 2009. The future outlook may be summarised as:

- CFBC will remain an important technology, with large units burning steam coals as well as others using biomass and wastes;
- steam conditions will increase for the largest units;
- the main target is a 5 percentage point efficiency gain over current best, by deploying A-USC technology; and
- deployment of CCS using flue gas scrubbing or oxygen firing.

Development of the next generation of CO_2 capture technologies (such as chemical looping), which are expected to lower the energy penalty, is closely related to the development of advanced CFBC technology. CFBC's fuel flexibility offers more options than PC combustion for CO_2 capture.

IGCC

This roadmap recommends the following actions:	***Milestones***
Deploy units with 1 400°C to 1 500°C gas turbines. Continue R&D to improve availability and performance with low-grade coals. Test at pilot scale dry gas cleaning and non-cryogenic provision of oxygen. Further develop and demonstrate gas turbines with turbine inlet temperatures higher than 1 500°C.	2012-20
Deploy units with 1 600°C gas turbines for high hydrogen fuel for CCS capability. Support R&D for dry syngas cleaning. Some application of non-cryogenic oxygen.	2021-25
Deploy units with 1 700°C gas turbines for high hydrogen fuel for CCS capability. Further application of non-cryogenic oxygen.	2026-30
Deploy units with 1 700°C+ gas turbines for high hydrogen fuel with full CCS. Deploy non-cryogenic oxygen option.	2031-50
• NO_X <30 mg/Nm^3, SCR will allow lower NO_X levels; ultra-low-NO_X combustors in development to achieve much lower levels; • Particulates <1 mg/Nm^3; • SO_2 <20 mg/Nm^3 for wet scrubbing; dry methods under development.	2012-20

Note: Temperatures quoted for gas turbines refer to turbine inlet temperatures.

The future outlook of IGCC may be summarised as follows:

- deployment must be increased;
- availability of 85% should be targeted (as for PC combustion units);
- efficiency should be raised to 50% (LHV, net) and beyond;
- cost differential against PC combustion must be reduced;
- components and cycles must be improved, *e.g.* advanced gas turbines, new gasifier designs, dry gas cleaning, novel cycles and non-cryogenic oxygen separation;
- dry gas cleaning systems should be made available at minimal or no cost penalty;
- polygeneration should be explored, *e.g.* with IGFC;
- CCS using pre-combustion capture should be deployed; and
- innovative, next-generation CCS systems to be developed.

Summary

Policies in favour of closing older, less-efficient subcritical PC combustion units should be maintained, despite the challenge of meeting the growing demand for power.

IGCC has been unable to take advantage of the present demand for power due to its relatively high cost, low availability and general performance characteristics, particularly when compared with SC and USC PC combustion. Mature IGCC technology could offer a solution to provide higher efficiency for lower capacity units. Ongoing RD&D support is needed to make IGCC more attractive to power suppliers, particularly because it provides an important alternative route to CCS. Expectations are that IGCC + CCS will have a lower energy penalty and offer a lower cost means to reduce CO_2 emissions than post-combustion CCS, but this needs to be demonstrated in practice.

Policy, finance and international collaboration: actions and milestones

Policy and regulatory framework

This roadmap recommends that governments implement policies to encourage action in the following areas:	***Milestones***
Retrofit of low efficiency units to higher efficiency (case by case).	2012-20
Reduce to a minimum generation from low efficiency plants (by setting lower limit of operating efficiency or higher limit of CO_2 emissions factor).	2012-20
Low-energy, lignite pre-drying.	2013
Dry FGD to minimise water consumption, particularly in dry regions (is likely to be dictated by economics).	2015
Dry gas cleaning for IGCC.	2020
All new PC combustion units >300 MWe should be USC. All CFBC units >300 MWe should be USC.	2020
Demonstration of 700°C steam conditions on PC combustion in early-2020s; with significant deployment from mid-2020s.	2025
Development of breakthrough technologies for next generation CCS, *e.g.* chemical looping and ion transport membrane.	2030
By 2030, emissions targets of: ● NO_X <10 mg/Nm^3. ● Particulates <1 mg/Nm^3 (0.1 mg/m^3 for IGCC); ● SO_2 <10 mg/Nm^3.	2030

A combination of policies are needed to halt the deployment of less efficient units, reduce CO_2 emissions and ensure the uptake of non-GHG pollution control measures, and thereby ensure that coal can continue to play an important role in meeting energy demand while also limiting emissions from coal-fired power generation. Some governments are beginning to adopt such policies, but implementation needs to accelerate if the "lock-in" of inefficient coal infrastructure is to be avoided (Table 4).

Table 4: Key policies that influence coal plant performance in major countries

Country or region	Summary of policies	Impacts and goals of policy
Australia	• Generator efficiency standards defined best practice efficiency guidelines for new plants: hard coal plant (42%) and brown coal (31%). Both have higher heating value net output. • Emissions trading will begin in 2015. • Carbon tax introduced in 2012.	• New plants are likely to be SC or USC technology.
China	• 11th Five-Year Plan (2006-10) mandated closure of small, inefficient coal-fired power generation units. • 12th Five-Year Plan (2011-15) caps coal production at 3.9 billion tonnes by 2015; from 2006, all plants of 600 MW or higher must be SC or USC technology. • Stringent emissions control for SO_2, NO_X and particulates are mandated on new units from 2012. SO_2 = 50 mg/Nm^3 NO_X = 100 mg/Nm^3 PM = 20 mg/Nm^3 New standards, including limits on mercury emissions, are applicable from 2014 for existing plants.	• From 2006-10, 70 GW of small, inefficient coal-fired power generation was shut down; in 2011, 8 GW were closed. • 17% reduction (compared with 2010) in carbon intensity targeted by 2015 (across all power generation) and a 40% to 45% reduction by 2020.
European Union	• Power generation covered by the EU Emissions Trading Scheme (ETS). The first two phases saw over 90% of emissions credits "grandfathered" or allocated to power producers without cost, based on historical emissions. In the third phase, beginning in 2013, 100% of credits will be auctioned. • Emission limit values according to the Industrial Emission Directive 2010/75/EU for new power plants are: SO_2 100-300 MWth = 200 mg/Nm^3 > 300 MWth= 150 mg/Nm^3 NO_X 100-300 MWth = 200 mg/Nm^3 > 300 MWth= 150 mg/Nm^3 PM 100-300 MWth = 20 mg/Nm^3 > 300 MWth= 10 mg/Nm^3	• GHG emissions reduction of 21% compared with 2005 levels under the European Union Emissions Trading Scheme (EU ETS). Credit auctioning will provide further incentive to coal plants to cut emissions.

Table 4: Key policies that influence coal plant performance in major countries (continued)

India	• 12th Five-Year Plan (2012-17) states that 50% to 60% of additional new coal-fired capacity should be SC. In the Thirteenth Five-Year Plan (2017-22), all new coal plants should be at least SC; with energy audits at coal-fired power plants to monitor and improve energy efficiency. The government expects 15% of power to come from SC by 2018. A policy plan for all post-2017 units to be SC, with progression to higher steam parameters in the future. An R&D programme is under way to raise steam temperatures to 700°C and beyond. • IGCC is being pursued using both indigenous and international technology suppliers. • A system to monitor and control emissions from thermal power stations is in place.	• The Twelfth and future Five-Year Plans will feature large increases in construction of SC and USC capacity.
Indonesia	• Emissions monitoring system has been put in place.	
Russia	• Unless action is taken, Russia's policy to increase indigenous coal use while exporting gas will inevitably lead to a rise in domestic CO_2 emissions.	• Conflicts likely between security of power supply and the environment. A policy and energy strategy are needed to address this.
South Africa	• To address the electricity shortages anticipated in the short-to-medium term, installation of new capacity will continue. • Emission policies are not yet in place.	
United States	• The US EPA's GHG ruling recommends use of "maximum available control technology". • Stringent SO_2 regulation will lead to expansion of FGD installation. • Advanced USC (760°C) R&D has USD 50 million of funding from the Department of Energy. Plans are under way for a 600 MWe design by 2015, with plant operating by 2021. • The US power system will retire as much as 70 GW of fossil-fired capacity over period 2013-17.	• New plants are likely to deploy best-practice HELE technology. • Pending EPA regulation, combined with low natural gas prices, suggests limited coal capacity additions in the future.

Some of these initiatives warrant further explanation:

- China's 12th Five-Year Plan (2011-15) explicitly called for the retirement of small, aging and inefficient coal plants and sent a strong message about the introduction of a national carbon trading scheme after 2020. In 2011, six provinces and cities were given a mandate to pilot test a carbon pricing system, which may go into effect as early as 2013. A shadow carbon price is likely to be implicit in investment calculations made by power providers.

- India's 12th Five-Year Plan (2012-17) contains a target that 50% to 60% of coal plants use SC technology (though significantly less is likely to be achieved in practice). Early indications of India's longer-term policy direction suggest that the 13th Five-Year Plan (2017-22) will stipulate that all new coal-fired plants constructed be at least SC.

- In Europe, the EU ETS and increasing government support for renewable sources of power have largely eliminated the construction of new coal plants.

- In the United States, if the EPA proposed coal emissions regulation is adopted and the shift to natural gas for power is sustained, construction of new coal power plants will be limited.

Financing innovation for R&D support

This roadmap recommends the following investing actions:	***Milestones***
RD&D on A-USC development will require support from public funds.	2012-20
Incentives to discourage installation of new combustion units <300 MWe capacity and to encourage retirement of combustion units of <300 MWe.	2021-25
RD&D for CO_2 capture will require support from public funds to commercialise large-scale CCS unit.	2026-30

Combustion units dominate existing capacity. The average efficiency of coal-fired power units varies markedly, depending on factors such as the ages of units, local climatic conditions, coal quality, operational factors, maintenance skills and uptake of advanced technologies. Many low-efficiency units remain operational. More than half of the global operating capacity is more than 25 years old, with unit sizes less than 300 MWe, which are not practical to apply supercritical conditions. More than 75% of the global operating fleet operates under subcritical conditions. Substantial potential exists to improve efficiency by phasing out generation from low efficiency units. Phasing out units before their commercial operational lifetime is reached will inevitably result in a loss of revenue. Low-carbon policies or internationally-agreed mechanisms would need to be implemented with appropriate incentives to offset these losses.

International collaboration in RD&D

Knowledge sharing. As is demonstrated by the extensive knowledge-sharing already underway among certain countries, international collaboration can reduce the time and resources needed to spread deployment of best practice worldwide. HELE technologies are available not only through direct supply, but also through licensing arrangements. Such arrangements have been successful, as exemplified by the large capacity of USC emerging rapidly in China. In India, the domestic manufacturer, BHEL, has embraced PC combustion with higher steam conditions through international collaboration, which led to deployment of SC technology. Great potential exists for China, India and other countries engaged in the development of A-USC technologies to work together to accelerate early deployment.

Community engagement. While technologies utilising coal continue to evolve and develop, governments and industry must ensure that communities are aware of the importance of coal in the world's energy future. History shows that communities are often opposed to the continued use and further development of fossil fuels, particularly coal, where they do not possess a complete understanding of:

- technological advances that have been made to achieve a HELE future; and
- the significance of having reliable and secure energy resources to underpin the global economy.

Thus, community engagement must be considered imperative in light of technology development to ensure that the role of coal in the energy sector is widely communicated.

Conclusion: near-term actions for stakeholders

This roadmap includes specific milestones that the international community can use to track progress of the deployment of HELE technologies against the efficiency and emission reduction targets needed by 2050 to limit the long-term global average temperature rise to between 2°C and 3°C. The IEA, together with government, industry and other key stakeholders will report regularly on this progress, and recommend adjustments to the roadmap as needed.

Recommended actions by key stakeholders are summarised below, and are presented to indicate who should take the lead in such efforts.

Lead stakeholder	Actions
Government	Implement policies to incentivise reduction in generation from less efficient coal-fired power units, replacing them wherever possible with low-carbon technology (including HELE coal technology).
Government	Facilitate RD&D programmes aimed at developing the next generation of HELE technologies, which will be critical to raising plant efficiency and reduce emissions.
Government	Continue investment in RD&D to demonstrate effective, large-scale CCS.
Government	Communicate clearly and effectively the role of HELE coal technologies as a key component of a low-carbon energy future.
Government	Implement policies and design mechanisms to encourage the demonstration and deployment, of HELE technologies with CO_2 capture in developing countries. Potential international carbon finance mechanisms should be evaluated and implemented.
Industry	Minimise generation from older, inefficient plants; improve the performance of existing plants; and install new highly efficient, state-of-the-art plants.
Industry	Develop the next generation of HELE technologies, including advanced-USC and reliable, highly-efficient IGCC technologies.
Industry	Continue RD&D on materials that will operate reliably and effectively under the challenging conditions to which they will be exposed in more advanced HELE technologies.
Industry	Continue RD&D to develop cost-effective, combined HELE and CO_2 capture technologies for commercial application.
Industry	Develop communications strategies and collaborate with key stakeholders to convey the importance of continued use of coal as a key contributor to a secure, reliable energy future.
Financial institutions	Implement financing mechanisms to encourage demonstration, and later deployment, of HELE technologies with CO_2 capture, particularly in developing countries. Possible options through global carbon finance mechanisms should be evaluated and implemented.

Abbreviations, acronyms and units of measure

Abbreviations and acronyms

2DS	*ETP 2012* 2°C Scenario
4DS	*ETP 2012* 4°C Scenario
6DS	*ETP 2012* 6°C Scenario
A-USC	Advanced ultra-supercritical
APEC	Asia-Pacific Economic Co-operation
BFBC	bubbling fluidised bed combustion
BoA	Lignite-fired power plant with optimised engineering (Braunkohlenkraftwerk mit optimierter Anlagentechnik)
CCS	carbon (dioxide) capture and storage
CCT	clean(er) coal technology
CFBC	circulating fluidised bed combustion
CO	carbon monoxide
CO_2	carbon dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSLF	Carbon Sequestration Leadership Forum
CV	calorific value
DICE	direct injection coal engine
EC	European Commission
ESP	electrostatic precipitator
ENCAP	Enhanced CO_2 Capture Project
EU ETS	European Union Emissions Trading Scheme
FGD	flue gas desulphurisation
GHG	greenhouse gas
H_2O	water
HELE	high-efficiency, low-emissions
HHV	higher heating value
HP	high pressure
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IGFC	integrated gasification fuel cell
ITM	ion transport membrane
LHV	lower heating value
LNG	liquefied natural gas
LP	low pressure
MCFC	molten carbonate fuel cell
MRC-DICE	Micronised Refined Coal – Direct Injection Coal Engine
NO_X	nitrogen oxides
NTPC	National Thermal Power Corporation
O_2	oxygen
PM	particulate matter
PC	pulverised coal combustion
PCC	post-combustion capture (of CO2)
RETs	renewable energy technologies
R&D	research and development
RD&D	research, development and demonstration
RDD&D	research, development, demonstration and deployment
RET	renewable energy technology
SC	supercritical (steam conditions)
SCR	selective catalytic reduction
SNCR	selective non-catalytic reduction
SNG	synthetic natural gas
SO_2	sulphur dioxide
SOFC	solid oxide fuel cell
UCG	underground coal gasification
US DOE	United States Department of Energy
US EPA	United States Environmental Protection Agency
USC	ultra-supercritical (steam conditions)
WEC	World Energy Council

Units of measure

kg	kilogram
kJ	kilojoule
kW	kilowatt
kWh	kilowatt hour
MPa	megapascal
MWth	megawatt-thermal
MWe	megawatt-electrical
GW	gigawatt
GWe	gigawatt-electrical
mg/Nm^3	milligrams per normal cubic metre
MJ	megajoule
MJ/Nm^3	megajoules per normal cubic metre
Mt	million tonnes
t	tonnes
tce	tonnes of coal equivalent
µg	microgram
µm	micrometre

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Technology Roadmap High-Efficiency, Low-Emissions Coal-Fired Power Generation

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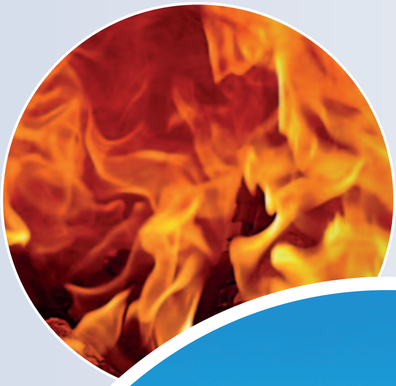

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