FORESIGHTING REPORT

Conventional Power Generation

Addressing power generation technologies that help improve emissions, operational efficiency and cost reduction

For Members Only

March 2006
V1.0

(Pending industry review)

TABLE OF CONTENTS

EXECUTIVE SUMMARY

This report captures the work that was performed by ITI Energy in its foresighting of Conventional Power Generation (CPG) for potential ITI Energy investment. Conventional Power Generation was identified as one of the five focus areas, mainly because of the large size of the market, the imminent market requirements and the strong Scottish R&D capability. It communicates the basis for ITI Energy's focus on certain areas of technology with application in fossil and nuclear-fuelled power generation. It also provides information which member organisations might find useful in developing their own business and technology development plans.

The core of the foresighting work was carried out with the assistance of Future Energy Solutions (FES).

Market

World primary energy demand is predicted to rise by almost 60% between 2002 and 2030. Developing countries will account for around two-thirds of this increase. To satisfy this demand, the projected increase in global energy supply will entail infrastructure development over the period to 2030 of over $500billion/year. The majority of this investment will be in the electricity sector.

Fossil fuels will dominate generation, and are likely to account for around 85% of the increase in world primary energy demand. Nuclear power is projected to decline progressively to 5% by 2030 from a 7% contribution to energy demand today. However, a potential renaissance in nuclear power is possible, driven by concerns over climate change and security of supply. Total hydropower, biomass and other renewables contribution will decrease to 25% in 2030.

With this predicted rise in world primary energy demand and the substantial increase in use of fossil fuels, the resultant rise in CO2 and other particulates emissions is of great concern to an increasing number of governments. Power generation is expected to contribute around half of the projected 39 billion tonnes CO2 emissions in 2030. Responding to this, governments are setting much more stringent emission targets and are pursuing other emission reduction methods, like CO2 trading schemes.

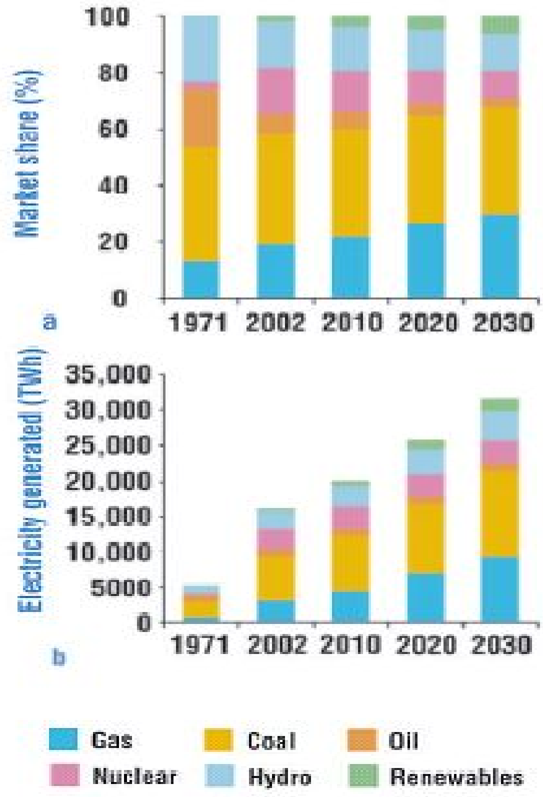


Figure 2. Global fuel market share and total amount of electricity generated. Source: IGU/IEA

Global Electricity Production by Fuel Type 1971-2030
(Source: IGU IEA)

The key drivers to the development of new CPG technologies are: the need for additional capacity, cost (both capex and operational), safety, status of existing plant, reliability, environmental impact and security of supply. Emphasis and interpretation of these drivers varies between coal, gas, and nuclear based technologies.

For fossil fuels, new technologies that address greenhouse gas emissions and that increase plant efficiency are in high demand. For nuclear energy, the development of fail-safe systems and of technologies that help towards reduce the cost of waste handling and decommissioning are mainly required. All plants will need technologies that increase reliability and reduce cost of electricity.

Technology Overview

CPG covers power generation from nuclear and fossil fuels, predominantly coal and natural gas. In the main, electricity is generated at large power plants which run on one of these fuels. These power plants need to be reliable, have very high availability and maintain high efficiency, which often means operating all year round virtually continuously whilst meeting the cycling and peaking demands placed on them.

The CPG technologies considered in this study include:

- Pulverised-Fuel (Coal)
- Fluidised Bed Combustion (FBC), including Circulating - (CFBC), Atmospheric- (AFBC), and Pressurised Fluidised Bed Combustion (PFBC)
- Combined Cycle plants, including Integrated Gasification Combined Cycle (IGCC) and Combined Cycle Gas Turbines (CCGT)
- Nuclear plants, of which the Pressurised Water Reactor (PWR), Boiling Water Reactor (BWR), Gas-cooled Reactor (Magnox) or Advanced Gas-cooled Reactor (AGR) and Pressurised Heavy Water Reactor, or CANDU (PHWR) are most common
- Distributed Generation, including Reciprocating Engines, Microturbines, Combustion Gas Turbines (e.g. Miniturbines) and Fuel Cells.

These technologies are at various stages of maturity and they each have their specific technology development opportunities, driven by market requirements and by their inherent functionality and (dis-)advantages.

Pulverised Fuel plants have been developed over many years and have reached efficiencies of 45% or more. Overall efficiency is constrained to that of the Rankine Cycle. A key advantage of PF plant is its ability to increase and decrease load quickly. Being coal based, emission control is a particular development area, as well as increase of plant efficiency, potentially by retrofit solutions.

In Circulating Fluidised-Bed Combustion (CFBC), the FBC technology receiving most attention, fuel and limestone are injected into the combustor and are suspended in a stream of upward flowing air. Circulation of the particles provides efficient heat transfer and better carbon and limestone utilisation. The process also inhibits thermal NOx emissions.

Integrated Gasification Combined Cycle (IGCC) was developed partly in response to the constraints of the Rankine cycle. Based on power generation using both steam and gas turbines, combined cycles offer the potential to achieve efficiencies in the 60%-70% range. The IGCC process produces syngas from fossil fuels. The gas turbine is driven by the combusted syngas, while the exhaust gases generate superheated steam to drive a turbine. Whereas IGCC is relatively new technology, CCGT is well established. Developments for both technologies aim at higher efficiencies and targeting zero emissions, burning hydrogen.

In a nuclear reactor, heat is produced when neutrons strike Uranium atoms causing them to divide in a continuous chain reaction. The heat is used to produce steam, which drives a turbine generator. All nuclear technologies will need to be competitive with fossil and other power generation technologies in terms of cost (off-setting the very high captial cost of a new nuclear plant), safety and impact on the environment. Although nuclear's contribution to CO2 emissions is virtually zero, economic, safe and clean disposal of waste and decommissioning are still largely unresolved issues. Furthermore, fail safe designs, like the pebble bed reactor, are mainly being considered for new build.

Distributed Generation technologies have various operational characteristics. Costs for these technologies vary significantly based on siting and interconnection requirements, as well as unit size and configuration. Fuel costs will vary significantly by region. The main disadvantages of DG are caused by lack of economies of scale: fuel efficiency, costs of fuel delivery and cost of emission reduction. Advantages include: ability to site generation close to demand, the potential for heat recovery (boosting overall efficiency), capability to deliver rapid response times and the potential for mobile or emergency use.

In addition to these system specific developments, there are an emerging set of enabling technologies. Through advancements in fundamental science, a number of enabling technologies have come to the fore over the last years including high temperature superconductivity, nanotechnology, information technology, semiconductor technology, catalysts, membrane technology and many other enabling technologies. We believe that two of them, namely Advanced Materials & Coatings and Condition Based Monitoring (CBM), will have a key impact on CPG. Advanced materials & coatings will enable plants to operate at the higher temperatures and pressures that are required to achieve higher efficiencies. They will also assist with improving corrosion resistance, heat transfer and plant reliability and operation. CBM can benefit operating and maintenence costs as well as help optimise plant burning efficiency, particularly where ramp up and ramp down rates are high.

Key Technology Development Areas

Opportunities exist across the range of CPG technologies to increase efficiency or to reduce cost, whilst meeting more stringent environmental standards. In discussing the status of each of the various technologies, many of these opportunities have become apparent. They are summarised below.

1. Increasing efficiency for both central and distributed generation by:
    - improving combustion efficiency
    - developing high-temperature materials
    - developing protective coatings for materials;
    - modelling the impact of the operating environment on materials.

2. Reducing emissions of SO2, NOx and Mercury by
    - improving coal preparation to reduce sulphur content
    - improving efficiency and operation of plant
    - reducing NOx formation during combustion
    - applying new technologies for reducing mercury emissions
    - integrating multi-pollutant control
    - specific emission reduction solutions for DG.
3. CO2 capture. The focus is on capture technologies, their application to combustion and gasification plant and the impact on the future mix of PF, oxyfuel firing and gasification.
4. Co-firing coal with biomass. Many problems need to be resolved before 20% thermal input of biomass can be reached.
5. O&M improvements. Condition-based monitoring can make a much greater contribution to planning maintenance and optimising the burning process. For DG technologies the emphasis is on bringing the costs down.
6. Ash utilisation, by
    - reducing carbon content in ash
    - developing novel uses for ash
    - studying the impact of biomass co-firing on ash properties.
7. Combustion of hydrogen. For gasification, hydrogen may be the fuel of the future. Modifications to current standard machinery are likely. Operating conditions are also likely to be different.
8. Nuclear operations and maintenance. Effective Condition-based monitoring would preclude the need for frequent inspection and contribute to extended life of plant. Solution areas include:
    - passive safety systems
    - smart sensors to allow power plant to base load operation
    - self diagnosis capabilities
9. Nuclear waste. Cost efficient and automated techniques for waste handling.

IP Landscape

Because of the breadth of technologies that are relevant to CPG, resulting in many thousands of existing patents, registered methods and other IP protection mechanisms, it is impossible to provide a comprehensive overview of the current IP landscape, other than to indicate specific areas where patent activity has been less intense.

However, a detailed analysis of the IP landscape for a specific technology area can provide useful insights into the current state of technology, the ‘hot’ technology interest areas and the competitive situation. When looking into specific CPG opportunities in more detail, ITI Energy has applied this analysis to improve its understanding of the commercial feasibility and risks related to the technology development.

Investment Strategy and Selected Technology Opportunities

ITI Energy must strive to optimise the impact of its investments on the Scottish economy. The study made a number of observations in this respect:

- The core CPG technologies are mature. Further technical improvements are likely to be incremental rather than disruptive.
- A number of drivers have created demand for a step improvement in technology to economically reduce emissions, provide alternatives to central gas-based generation, whilst continuing to generate power reliably and at acceptable cost.
- The industry is dominated by a relatively small group of large manufacturing companies, with their own R&D facilities, resources and budgets.
- However, there are also a large number of SMEs supplying into these manufacturers, who could benefit from R&D support.
- Globally, there are many sizeable R&D grants available (e.g EU, USA) for energy generation technologies. ITI Energy must take these into consideration when making investment decisions.
- The immense generation capacity increases that are required in the Far East, have created a risk taking attitude towards testing and installing new technologies which is in sharp contrast with the Western highly regulated and HSE-driven attitude.

ITI Energy believes that it should not focus on technologies that simply offer incremental improvement to existing systems. Instead, focus should be given to enabling technologies that can be applied to create step-change efficiency and emissions improvements.

In collaborating with industry, ITI Energy will encourage universities, other R&D organisations and SMEs, to come forward with novel ideas that are aligned with the opportunity areas outlined in this report. Furthermore, ITI Energy will encourage collaborations with Scottish and other globally leading R&D departments as well as with SMEs and corporates for testing & demonstration and to build an efficient channel into the market.

Utilities are the ultimate buyers of the new CPG technologies and as such ITI Energy will seek collaboration with utilities in the early stages to test ideas and design concepts and to increase the utility involvement in the testing & demonstration and commercialisation phases.

Working with industry, ITI Energy developed a prioritised list of 29 technology development opportunities, and rated them High (H), Medium (M), or Low (L) for each of the criteria:

- **Market**: Size and ease of the available market and speed to adoption
- **Technology**: Feasibility of the technology
- **IP**: Strength of IP / potential barriers

Area	Technology Opportunity	Market	Techn	IP
Gas				
1	Hydrogen fired gas turbine	M	L	L
2	Dual-fuel multi-burner	M	L	L
Emissions				
3	Retrofit of amine scrubbing	M	L	M
4	Low cost Sorbents for amine scrubbing	H	M	M
5	Membranes for amine scrubbing, NG fuel, CO2 flue gas, pure O2 manufacturing	H	M/H	H
6	Materials that can withstand high stresses in Oxyfuel burners	L	L	L
7	Coatings to prevent oxidation at hight T for Oxyfuel burners	L	L	L
8	Combined emission scrubbing (other than CO2) for particulates and metals	H	M	H
9	Fuel pre-treatment (e.g. microbial)	H	?	L
10	Alternative process that optimises combined (CO2 and other) emission reduction	H	M	L
Co-firing				
11	Multi-burner (optimise the process, using feedback from the burner)	M	M/H	M
Coal				
12	Solid waste opportunities	L	L	M
13	Pulverised Coal at 700C – materials	H	M	H
14	Pulverised Coal at 700C – components	H	H	M
15	Pulverised Coal at 700C - plant design	L	L	L
Distributed Generation				
16	DG use of standard aerospace turbines	L	L	L
17	DG Emission - making it economic (for 'mini' generation (1-5MW) in medium term and 'micro' (<1 MW) in longer term)	M	H	H
18	DG Operations and Maintenance	H	M	H
Operations & Maintenance				
19	Ensure ramp rates and cycling are not detrimental to asset life - low cost instrumentation (sensors/comms)	H	M	M
20	Ensure ramp rates and cycling are not detrimental to asset life - data handling and interpretation	H	H	M
Enabling Technologies				
21	Smart coatings, e.g. that include sensors	M	M	H
22	Solutions that allow a better understanding of the material state at mulecular level (e.g. MRI alternative)	M	H	M
23	Low cost, high temperature sensors (wireless comms)	M	H	H
24	Alternatives to super alloys – coatings & pipelines	H	H	M/H

Area	Technology Opportunity	Market	Techn	IP
25	Corrosion prevention, particularly in small scale turbines	L	M	M
Nuclear				
26	Condition Based Monitoring for rotating plant and fuel conditions (radiation measurements)	M/H	M	L
27	Nuclear waste volume reduction	H	L	L
28	Monitoring of decommissioning (radiation)	M	L	L
29	SiC and/or GaNitrite for power electronics	M	H	L

Qualified and Reviewed List of Technology Opportunities
Source: ITI Energy analysis

Conclusions and Next Steps

In addition to the above ranking, we considered in how far Scottish capability could be created in the development of these new technologies and where ITI Energy could make a material difference. From this assessment, the technology opportunities have been categorised ‘A’, ‘B’, or ‘C’ as follows:

Category (A): The principal focus of ITI Energy effort and financial commitment in CPG technologies will be to opportunities in this category.

Category (B): Although opportunities in this category are of particular interest and ITI Energy may commission research and market assessments for opportunities in this category, this will not be a main focus for ITI Energy at this time.

Category (C): ITI Energy will respond to parties to bring forward specific project proposals.

The following table shows this in practice:

		PROACTIVE		REACTIVE
		A) Pursue Specific Projects	**B) Explore Possibilities & seek 3rd Party Proposals**	**C) Respond to 3rd Party Proposals**
5	Membranes	🟦		
24	Alternatives to super alloys – coatings and pipelines	🟦		
8	Combined emission scrubbing		🟦	
11	Multi-burner for co-firing		🟦	
13	HT pulverised coal – materials		🟦	
14	HT pulverised coal – components		🟦	
17	DG emissions		🟦	
18	DG Operations and Maintenance		🟦	
20	Ramp rate and cycling management – data management		🟦	
23	Low cost HT sensors		🟦	
	Other 19 Technologies			🟦

This categorisation is based on a thorough analysis. It forms ITI Energy's judgment at this point in time. ITI Energy recognises that external forces may change and that new ideas will emerge, that may change the above prioritised list of opportunities. We therefore remain open to 3rd parties bringing forward proposals in areas outside the list of opportunities.

FOR FURTHER INFORMATION ON THIS STUDY AND ITI ENERGY PLEASE CONTACT CHRIS DEGOEY, ACTING TECHNOLOGY & MARKETS DIRECTOR ON TEL +44 (0)1224 701207 OR EMAIL CHRIS.DEGOEY@ITIENERGY.COM.

ACKNOWLEDGEMENT

ITI Energy wishes to thank Future Energy Solutions (FES) for their dedication and hard work in conducting this foresighting study and in developing this report.

Future Energy Solutions
Caledonian Rd
Lochshore Industrial Estate
Glengarnock
KA14 3DD

HTTP://WWW.FUTURE-ENERGY-SOLUTIONS.COM/

1 INTRODUCTION

1.1 Document purpose and structure

This report captures the work performed by ITI Energy in its foresighting of Conventional Power Generation (CPG). It explains the basis for ITI Energy's focus on certain areas of technology with application in fossil and nuclear fuelled power generation. It provides information which member organisations might find useful for their own business and technology development plans. This report does not intend to provide a complete, comprehensive overview of the power generation sector. Instead, it highlights the drivers and developments that have led ITI Energy to identify certain areas of technology development that may be considered as potential areas for future ITI programmes. This report:

- Provides a summary of the market and technology information gathered and analysed through the foresighting process;
- Communicates the areas of technology that emerged as priorities from the foresighting work;
- Allows members to comment on the resulting technology priorities and to consider if they have particular project proposals or ideas they would like to bring forward for assessment by ITI Energy for potential investment.

The document is arranged in five main sections:

- Background to the foresighting work;
- Overview of the Conventional Power Generation market;
- Overview of the Conventional Power Generation technologies;
- Prioritised technology opportunities;
- Conclusions and recommended actions

The main report provides a summary and distillation of the knowledge that was gathered and developed through the study. A set of appendices provides additional information upon which the report is based.

1.2 ITI Foresighting into Conventional Power Generation

ITI Energy performed a high level study across the whole energy spectrum to identify those areas that were most suitable for ITI Energy investment, in order to allow for some initial focus of effort and resources. This work, supported by PA Consulting and Charles River Associates, assessed the various energy technology areas against three success criteria: market attractiveness; feasibility and Scottish fit. Conventional power generation was identified as one of the five initial focus areas for ITI Energy, mainly because of the large size of the market and some specific strong Scottish R&D capability.

The foresighting took place in earnest during the period July-November 2005.

The aim was to identify some of the more promising technology opportunities for investment, based on anticipated medium to long-term market needs and technology trends. The foresighting work has used a nominal time horizon of 2020 to try to also incorporate more fundamental technology developments, rather than purely focusing on incremental developments.

Given that this is a mature industry with incremental technological advancements and large investments from established players, the study has taken a more narrow focus from the start looking into areas where ITI investment could potentially make a difference:

- Increased efficiency of existing generation technologies
- Reduced Capital Expenditure and/or Operating Cost
- Cleaner power generation
- Mini and large power generation

ITI has tried to avoid studying areas where an annual £15M investment fund would be insufficient to have a significant impact on technology development, such as the next generation of gas turbines.

Furthermore, for the purpose of this study the following topics are considered out-of-scope:

- Fuel sourcing, logistic handling and preparation technologies
- Biomass, except for co-firing
- In situ coal gasification / coal bed methane technologies
- Carbon transport and storage technologies (carbon capture is included)
- Micro generation of power (< 10kWe)

An attempt was made to provide an overview of the Intellectual Property (IP) landscape with the objective to identify:

- Technology areas that have relatively received a lot versus little attention
- Technology areas where activity has reduced/increased over the past years
- Entities that have been most active in IP/technology development

Overall, the foresighting programme has had direct engagement (through workshops, visits and other events) with more than 45 experts throughout the Power Generation Sector in the UK and across Europe. Over 35 different organisations have been involved, including equipment manufacturers, suppliers, utilities, and universities. More information regarding industry engagement is provided in the appendix.

2.0 FORESIGHTING APPROACH

The approach for this study has been slightly different from previous ITI Energy foresighting work in that an initial set of hypotheses have been developed in combination with expert input from industry and academia to investigate a limited set of technology developments. Furthermore, this study has relied more extensively on input from external events (in particular the Power-Gen Europe conference in Milan) and from our consultant Future Energy Solutions (FES).

The structure of the foresighting process is shown in Figure 2.1, and comprised 5 main activities:

1. Develop initial views on market drivers and related technology developments;
2. Develop a long-list of opportunities through team brainstorming;
3. Test the views and opportunities by means of consultant research, workshops and lessons from the Milan conference;
4. High-level assessment and prioritisation of long-list of opportunities;
5. Selection of priority areas for further investigation and ITI Energy investment

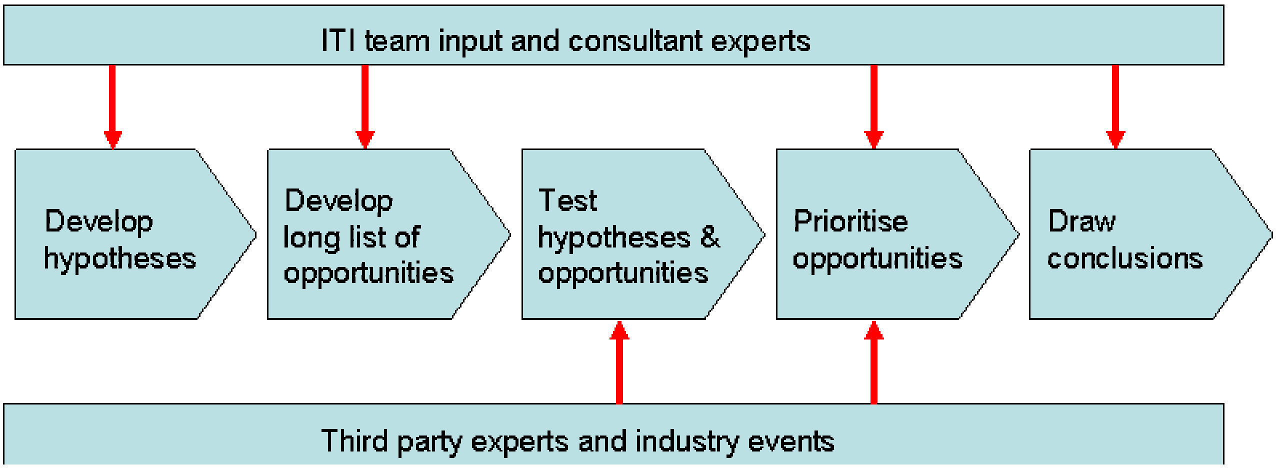


Figure 2.1 – CPG foresighting approach
(Source: ITI Energy)

The study has incorporated the outcomes of a workshop that was organised jointly by ITI Energy and IPA. Furthermore, ITI Energy has made use of a number of high quality, hugely relevant studies that have served as background material. In particular, but not exclusively:

- DTI energy white paper
- The APGTF Carbon Abatement Strategy green paper: “A vision for clean fossil power generation”, 2004
- Scottish Enterprise: “Carbon Capture and Storage Market Opportunities, 2005”

3 CONVENTIONAL POWER GENERATION MARKETS

3.1 Market overview

There are several established sources for high-level market data and energy projections. For this study the two main sources of reference were the IEA's World Energy Outlook 2004 and the EIA International Energy Outlook. Though subject to a wide range of uncertainties, projected trends do not appear to differ markedly from source to source.

In both developed and developing countries, the vast majority of electricity is distributed to consumers via high-voltage grids. Grids are supplied with electricity from large, central power stations, fuelled in the main by fossil fuels, nuclear and large hydro. After boosting voltage from about 25kV to up to 400kV volts, high voltage transmission lines carry electricity long distances to a substation. Transformers in the substations change the very high voltage electricity back into the medium and lower voltage electricity that powers businesses, factories and homes. This system of supplying consumers is well established and works effectively, but does have drawbacks, including transmission costs and distribution losses.

Over the last decade interest in distributed generation has been on the rise. Distributed generation involves the production of electricity at an electricity consumer's site or at a local distribution utility substation and the supply of that power directly to the on-site consumers or to other consumers through a distribution network. This has some advantages over power from the high-voltage grid, overcoming transmission costs and distribution losses, and offers the potential to provide more flexibility in matching power supply and demand. Market liberalisation increases significantly the flexibility of the distributed generator. In a liberalised market, excess production may be sold to any consumer in the same distribution network. With the drive to increase the contribution from renewables, this greatly enhances the attractiveness of distributed generation. In practice, however, the higher generation costs, higher fuel delivery costs and lower efficiency of distributed generation units form significant barriers to its uptake. Moreover, there is an additional cost for connection to the network which is often much higher than for central transmission-connected generation.

3.2 Market Size

The global population now stands at around 6 billion. Of this, more than 25% have no access to electricity. A number of countries are experiencing rapid economic growth – China and India in particular – and this in turn drives significant growth in energy demand. As a result, world primary energy demand is predicted to rise by almost 60% between now and 2030. To satisfy this demand, the projected increase in global energy supply will entail infrastructure development over the period to 2030 of over $500billion/year. The majority of this investment will be in the electricity sector.

Developing countries will account for around two-thirds of the increase in world energy demand by 2030. In these countries, coal plants will produce more CO2 in 2030 than the entire power sector in OECD countries. Figure 3.1 illustrates the EIA estimate that total world consumption of marketed energy is expected to expand from 412 quadrillion British thermal units (Btu) in 2002 to 645 quadrillion Btu in 2025, or a 57% increase over the period.

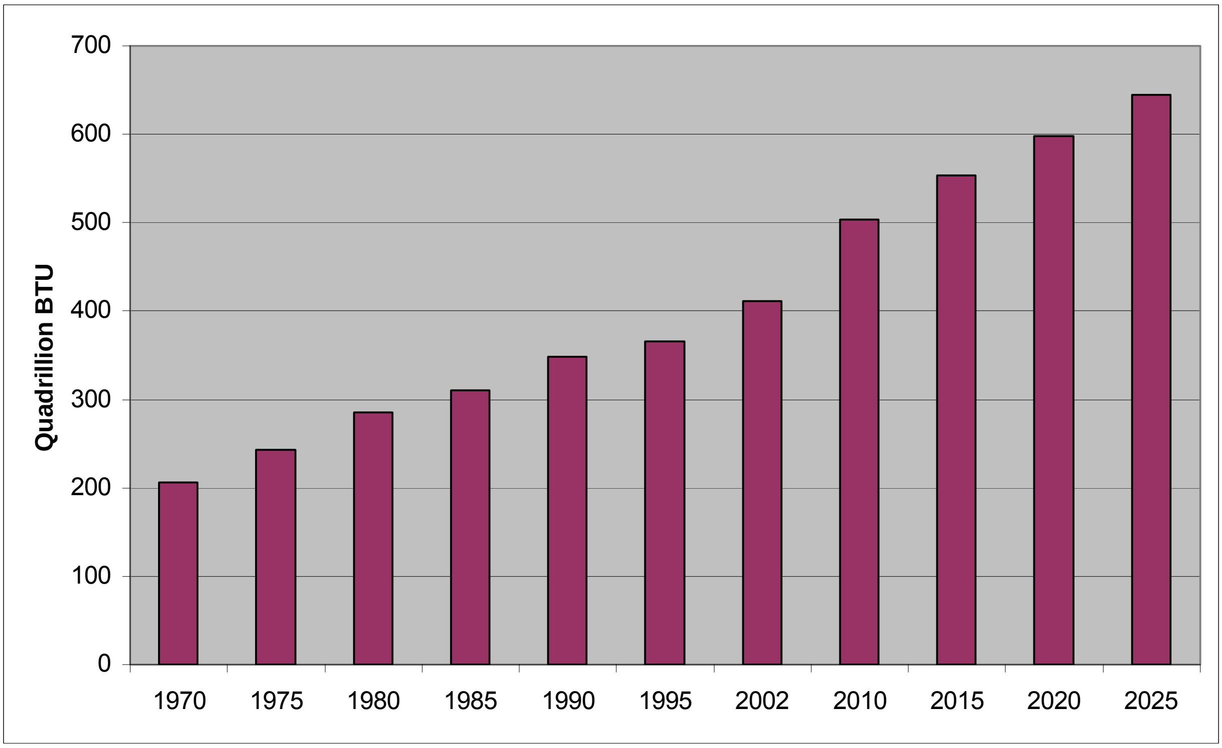


Figure 3.1 World Marketed Energy Consumption 1970-2025
(Source EIA International Energy Outlook 2005)

Fossil fuels will dominate generation, and are likely to account for around 85% of the increase in world primary energy demand. As a result, the share provided from fossil fuels will also increase slightly from 80% in 2002 to 82% in 2030. Figure 3.2 illustrates this prediction. Oil is expected to remain the dominant energy source, with its share of world energy consumption declining only slightly, from 39 percent in 2002 to 38 percent in 2025.

Coal and natural gas will provide the majority of incremental demand for electricity between now and 2030. The share of oil in electricity production is currently small and will decline further. Globally, coal-fired plants provided 39% of the world's electricity in 2002. This is projected to fall to 38% by 2030, but in absolute terms coal consumption for electricity generation will be substantially higher than at present.

Though subject to considerable uncertainty, e.g. future government policies and public attitudes, nuclear power is projected to decline progressively to 2030. Contributing 7% at present, 6% in 2010 and 5% by 2030, nuclear is expected to peak, in absolute terms, soon after 2010. The recent discussions in some countries about a potential nuclear renaissance may influence these projections somewhat.

The contribution from hydropower will decrease from 16% in 2002 to 13% in 2030, and that from biomass and waste from 11% in 2002 to 10% in 2030. Other renewables are projected to increase their contribution from 1% in 2002 to 2% in 2030. Figure 3.4 illustrates global electricity production and fuel mix over the period 1971-2030.

With this predicted rise in world primary energy demand and the substantial increase in use of fossil fuels, the resultant rise in CO2 emissions is of great concern. Power generation is expected to contribute around half the projected CO2 emissions to 2025, with 70% of the increase expected to come from developing countries.

Figure 3.3 shows worldwide CO2 emissions by fuel type. Emissions in 2025 are projected to total 38,790 million metric tons, exceeding 1990 levels by 81%. Combustion of petroleum products contributes 5,454 million metric tons to the projected increase from 2002, coal 5,353 million metric tons, and natural gas 3,540 million metric tons. As coal is a more carbon-intensive fuel than natural gas, the projected increment in carbon dioxide emissions from coal combustion is larger than the increment in emissions from natural gas.

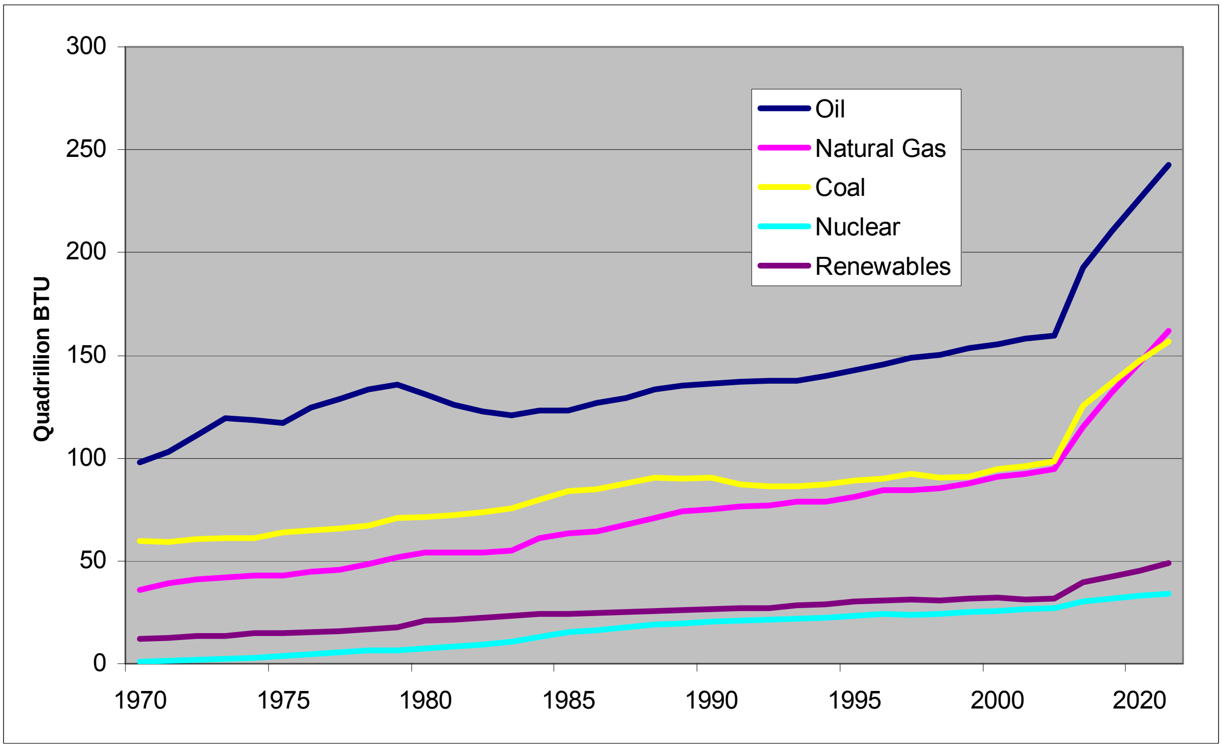


Figure 3.2 World Marketed Energy Use by Fuel Type 1970-2025
(Source EIA International Energy Outlook 2005)

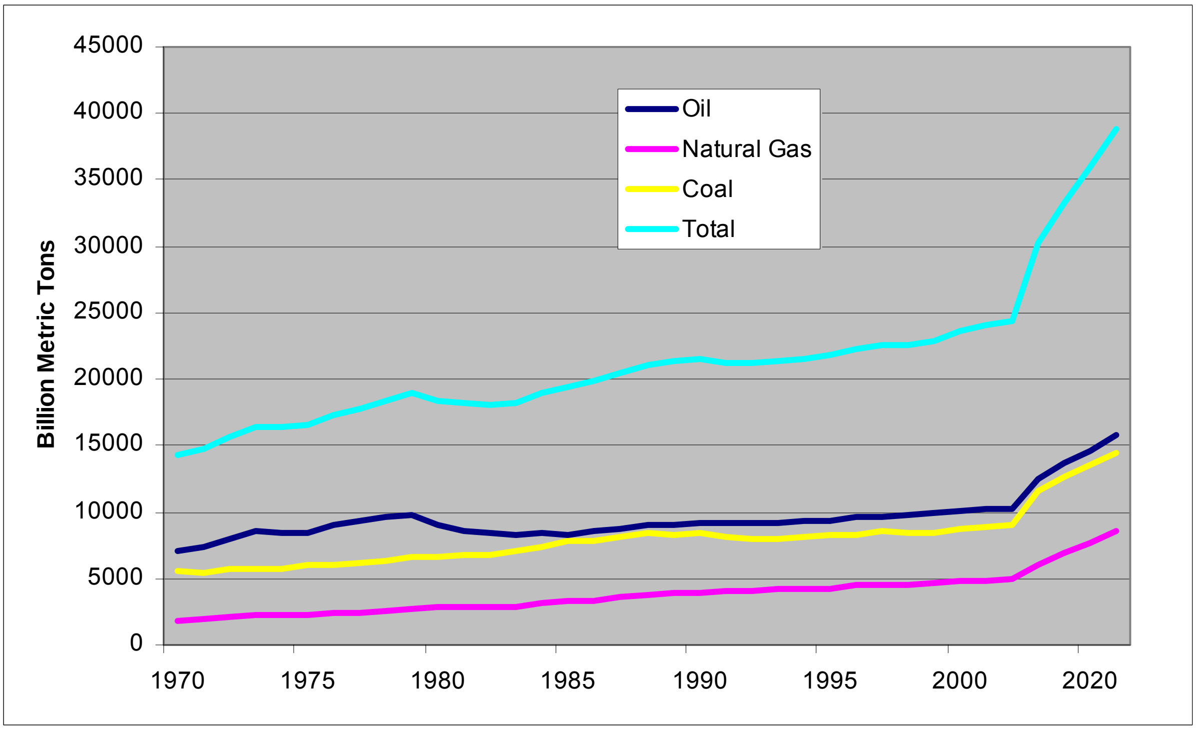


Figure 3.3 World Carbon Dioxide Emissions By Fuel Type 1970-2025
(Source EIA International Energy Outlook 2005)

3.2.1 China

World electricity production is projected to rise from 16,074 TWh in 2002 to 31,657 TWh in 2030, growing at an average of 2.5% per year. This is a massive rise and the largest increase will take place in China. China is the world's most populous country, it has the second largest economy and is the second largest consumer of primary energy after the USA. It accounts for 12% of global GDP and primary energy demand.

With 12% of total proven global reserves, it is not surprising that coal remains the dominant fuel in China and it that will do so for many years to come. Coal production in China is projected to rise from 1.4 btonnes in 2002 to 2.5 btonnes in 2030, which is 35% of the world total. The power sector will account for more than 73% of total coal consumption by 2030 compared with 52% in 2002. China's investment requirement for electricity to 2030 is estimated at $2 trillion. At present, it is adding between 30 and 40GW of new capacity each year.

It is planned that nuclear capacity will meet 4% of total capacity by 2030. This is by no means trivial - in absolute terms, nuclear capacity would have to increase tenfold from current levels. The share of gas and nuclear power in electricity generation is projected to increase from 1% to 6% and from 2% to 5%, respectively, by 2030.

China's share of global CO2 emissions is projected to increase from 14% to 19% by 2030. While the largest absolute amount of CO2 emissions will arise from power generation sector, the transport area will see fastest growth.

3.2.2 India

Coal is also the dominant fuel in India, with electricity production accounting for around 73% of coal consumption. Though coal resources are plentiful, they are of low quality. Nevertheless, production is projected to rise from 364 Mtonnes in 2002 to 705 Mtonnes in 2030.

Natural gas use is expected to increase rapidly from 4% in 2002 to 9% in 2030. A small number of nuclear plants are planned, which would lead to a tripled increase in the nuclear share of fuel consumption.

The share of coal and renewables in total final energy consumption will likely decline, while that of oil, electricity and gas is due to increase. Electricity output is projected to grow by 4.4% per annum to 2030, which will have the effect of raising electrification from 44% of the population to 68% by 2030.

If these projections are met, CO2 emissions will more than double by 2030, reaching 2,254 Mtonnes.

3.2.3 USA

The USA has very substantial reserves of fossil fuels, ranking eleventh worldwide in reserves of oil, sixth in natural gas, and first in coal. It is the second largest coal producer after China, with production in 2002 of over 1 btonnes. Over 90% of that coal is consumed by the electric power sector.

Coal-fired plants accounted for 53% of generation in the electric power sector in 2002, whilst nuclear power provided 21%, natural gas 15%, hydroelectricity 7%, oil 3%, geothermal and 'other' 1% making up the balance.

The future for nuclear is unclear. Since 1977, no orders have been placed for new nuclear units, and none are currently planned.

The stated goal of the USA's 'Clear Skies' initiative is to reduce power plants' emissions of sulphur dioxide, nitrogen oxide, and mercury, by approximately 70% over the next 15 years. Though proposed in the 108th Congress, this initiative has not yet passed into law.

The USA remains the world's largest single source of anthropogenic greenhouse gas emissions. Current projections indicate that emissions of CO2 will reach almost 6 Mtonnes in 2005, an increase of over 1 Mtonnes from that emitted in 1990, and around 25% of total world energy-related carbon emissions.

3.2.4 EU

Primary energy demand was only marginally higher in 2003 than in 2000. In fact, primary energy demand in the EU is predicted to grow by only 0.7% over the period 2002 to 2030. Oil remains the predominant energy source.

The IEA anticipates that most of the new fossil fuel power plants will be gas-fired. As a result, the consumption of coal is predicted to drop by 10% to 2030. The share of nuclear power is also predicted to drop sharply, from 14% in 2002 to 7% in 2030. Gas, on the other hand, is projected to increase from the current 23% to 32% in 2030. Though recently, due to higher cost of gas, some power producers switched back to coal, this is not expected to have a significant bearing on these longer-term trends. Imports of fossil fuels will increase substantially as indigenous production dwindles and demand edges up.

In 2002, excluding hydro, renewables contributed 5% of total power generation capacity. This is expected to exceed 20% by 2030.

Energy-related CO2 emissions are expected to be 9% higher in 2010 than in 1990. CO2 emissions trading began in 2005.

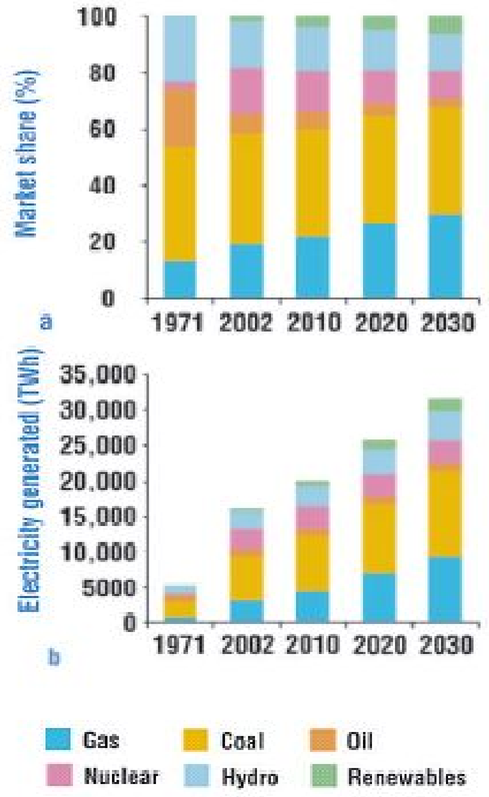


Figure 2. Global fuel market share and total amount of electricity generated. Source: IGU/IEA

Figure 3.4 Global Electricity Production By Fuel Type 1971-2030
(Source: IGU IEA)

3.3 Market Drivers for Technology Development

Meeting the additional power capacity needs of the next 25 years will be an enormous challenge. Thousands of new power plants (nearly 1,400 GW) will have to be built to meet the demand. A choice of fuels to power this demand will need to be made, i.e. to use coal, gas, nuclear and/or one of several renewables. And a choice will need to be made of the technologies to deploy.

Costs for new and replacement capacity will be met in a background of tightening emissions regulations, particularly with regards to CO2 and other greenhouse gases. As fossil fuels will predominate over this period, technology development will be absolutely paramount. The twin goals of reducing costs whilst meeting the emissions constraints that will inevitably be placed will foster technology innovation.

There are several factors that will govern which new technologies or technology improvements will be installed, or existing plant retrofitted or refurbished, e.g. safety, need for additional capacity, status of existing plant, cost, reliability and environmental impact.

Driver	Description
Capacity	Need for additional capacity in existing plant
Cost	Relative cost of technology in generation mix. This can be split into: - installation cost (mainly Capital cost), and - cost of use (mainly fuel cost and O&M cost)
Safety	e.g. Nuclear failsafe systems
Status of existing plant	Age and condition which impacts on retrofitting/replacement decisions.
Reliability	Reliability of operation (i.e. uptime)
Environmental Impact	GHG and other emissions
Security of Supply	Drive to reduce dependency on imports, or on reliance on a single fuel.

Figure 3.5 Market Drivers for Technology Development
(Source: ITI Energy analysis)

Dependent on the fuel, these different factors may attract different weightings. For example, for fossil fuels, emissions of greenhouse gases to the atmosphere will need to be addressed. For new build nuclear plant, the development of fail-safe safety systems will be important. The age and condition of installed plant will determine whether new components might be retrofitted or replacement plant be required. For all plants, high reliability, low environmental impact and competitive cost will remain essential. Figure 3.5 provides an indication of how specific market drivers influence the need for new technologies for each fuel. For instance, the demand for new generation capacity is a key driver for technology improvements for all CPG fuels. Likewise, the need to reduce capital cost is more important for nuclear and renewables than for coal or gas fired stations. The requirement to improve the effects on the environment are most urgent for coal (CO2 emissions) and for nuclear (waste and decommissioning).

	Coal	Gas/Oil	Nuclear	Renewables
Need for new capacity	☺ ☺	☺ ☺	☺ ☺	☺ ☺
Capital cost			☺ ☺	☺ ☺
O&M cost	☺	☺	☺	☺
Safety	☺	☺	☺ ☺	
Status of plant	☺ ☺	☺	☺ ☺	
Reliability	☺	☺	☺	☺ ☺
Environment	☺ ☺	☺	☺ ☺	
Supply security	☺		☺ ☺	☺ ☺

Figure 3.6 Impact of drivers on various power technologies
(Source: ITI Energy analysis)

Cost and environmental impact are often related through legislation. In most cases, reducing significantly the environmental impact of a plant incurs costs. To ensure environmental good practice, countries or regions often enact legislation. An example of this is the legislation enacted by the EU governing emissions to the atmosphere from power generation plant. Known as the Large Combustion Plant Directive, it was originally intended to set emissions standards for new plants larger than 50 MWth, irrespective of the fuel used. It now sets out newly revised emissions limits for existing plants and tightens up the requirement for new plants. Its most recent legislation forces generators to make commercial decisions on whether and to what extent they intend to operate their plant in future, essentially demanding that new technology is installed or that the plant is closed.

3.4 Impact of emissions

Since the beginning of the industrial revolution, emissions from fossil fuels, particularly coal, have been a major drawback. Some of these were recognised at an early stage and some are only just becoming apparent. The dirt and grime caused by particulates were apparent from the beginning, then smogs and acid rain and, now, global warming. Emissions of the pollutants that bring smogs and acid rain have been reduced to very low levels in Western countries, largely as a result of legislation. Technologies have been developed that can remove the pollutants from the gases emerging from a furnace or gasifier effectively. Examples of the approach of various countries to control emissions from power plant are described below.

The impact of Greenhouse Gases, in particular, CO2, on global warming and climate change has only relatively recently been recognised and formally debated. Different countries are taking different approaches to controlling or reducing their emissions of

CO2. Some, e.g. the Kyoto signatories, are applying targets and applying measures to try to meet these targets. Others, e.g. the USA and Australia, are attempting to tackle the problem through the development of technology. Developing countries, by and large, have other more pressing priorities in the short term, though they have provided indications that they are starting to recognise CO2 as a problem.

Country	Effect of Implementation of Kyoto Protocol
UK	12.5% reduction of 1990 level in 2008 – 2012 period. More stringent 20% unilateral target.
EU	EU-15 collective target of 8% cut in emission level in 2008-2012 period. Over 1990 levels.
US	Has not ratified the Kyoto protocol but has scheme focused on reducing GHG intensity by 18% over 02-12 period.

Figure 3.7 – Effect of Planned Implementation of Kyoto Protocol
(Source: ITI Energy analysis)

In Europe, the primary environmental legislation addressing emissions from industrial processes is Integrated Pollution Prevention and Control (IPPC), which is embodied in EC IPPC Directive of 1996 (96/61/EC). To operate, all industrial installations require a permit based on the concept of Best Available Techniques (or BAT). In many cases BAT means radical environmental improvements and installations are allowed an eleven-year transition period to achieve compliance. Failure to comply results in closure of the installation.

Air pollutants included in the IPPC Directive are:

- SO2 and other sulphur compounds
- NOx and other nitrogen compounds
- Carbon monoxide
- Volatile organic compounds (VOCs)
- Metals and their compounds
- Dust (particulate matter)
- Asbestos (suspended particulates, fibres)
- Chlorine and its compounds
- Fluorine and its compounds
- Arsenic and its compounds
- Cyanides
- Substances and preparations which have been proved to possess carcinogenic or mutagenic properties or properties which may affect reproduction via the air
- Polychlorinated dibenzodioxins and polychlorinated dibenzofurans.

For coal-fired power generation, the legislation governing emissions to air is the Large Combustion Plant Directive (LCPD). The Directive includes emission ceilings and reduction targets for plant in each Member State, specifically for emissions of particulates, SO2 and NOx.

The UK has chosen a twin track strategy for implementing the LCPD to regulate pre-1987 plants, an option allowable within the directive. This allows plant operators the option over whether to comply with the Emission Limits Values (ELV), or to join the National Emissions Reduction Plan (NERP). If the NERP approach were taken, plants would operate within a ‘national plan’ that would set a ceiling for each pollutant. Under a national plan emissions trading for NOx and SO2 could operate, which would allow operators additional flexibility in their investment decisions. Operators of post 1987 plant are required to comply with the relevant ELVs.

For the recent accession countries to the EU, it would be unreasonable to expect compliance with the LCPD within the same timeframe as other member countries. Each of the new accession countries have been allocated a period, dependent on the state of its economy and its energy profile, over which it is expected to comply.

The European Union Greenhouse Gas Emission Trading Scheme is the largest multi-national, greenhouse gas emissions trading scheme in the world. It commenced operation in January 2005 and all 25-member states of the European Union participate in the scheme. Under the scheme, each participating country proposes a National Allocation Plan (NAP) including caps on greenhouse gas emissions for power plants and other large point sources. The NAP must subsequently be approved by the European Commission. The scheme has created a new market in carbon dioxide allowances estimated at some €35 billion per year.

In the United States, a highly regulated country in respect of emissions, environmental laws are policed by the Environmental Protection Agency (EPA). The EPA works to develop and enforce regulations that implement environmental laws enacted by Congress and is responsible for researching and setting national standards for a variety of environmental programmes. It delegates to states and tribes the responsibility for issuing permits and for monitoring and enforcing compliance. Where national standards are not met, the EPA can issue sanctions and take other steps to reach the desired levels of environmental quality.

One important aspect of the framework in the USA is the piloting and development of a number of emissions trading schemes – with suitable rules emission trading can help deliver emissions reductions at significantly lower costs than direct regulation of individual plants.

The development of emissions trading in the USA includes:

- The early EPA Emissions Trading programmes which began in the 1970’s;
- The Lead trading programme for petrol, implemented in the 1980’s;
- The acid rain programme for electric industry sulphur dioxide emissions;
- The federal mobile source averaging, banking and trading (ABT) programmes that began in the early 1990’s;
- The Los Angeles based RECLAIM programme;
- The Northeast NOX Budget trading programme, which began in the late 1990’s.

Australia recently introduced a National Pollutant Inventory (NPI) in the form of an internet database, to provide the community, industry, and the government with reliable information regarding the emission of pollutants into the atmosphere. In most cases, Australia's concentrations of common pollutants meet World Health Organization guidelines and are low by world standards.

Japanese environmental policy is not based on prescriptive legislation, but instead on 'administrative guidance', where the government gives advice, setting standards for different companies. These requirements are voluntary but include emission standards to be met. Fines are set for breaches of these regulations, but are rarely policed. Instead, the high importance attached to social responsibility in Japan works to ensure that any company violating regulations will lose their reputation and public credibility.

In developing countries, environmental regulations vary significantly. In South Africa, for example, more than 90% of electricity is generated from the combustion of coal that contains approximately 1.2% sulphur and up to 45% ash. Though most townships are exposed to high levels of air pollution, South Africa lacks any legally binding air pollution regulations, only non-binding guidelines and no enforcement authority. In China, the existing emission standard of air pollutants for thermal power plants was issued jointly by the State Environmental Protection Authority and the State Technical Supervisory Bureau in 1996. This standard is applicable for new coal/oil fired utility boilers (i.e. those approved after 1 January 1997) with a capacity above 45.5 MWth. It is applicable for the management and environmental evaluation, design, acceptance and operation of new power projects for air pollutant emissions from coal-fired utility boilers with various capacities. The Environmental Protection Authority is responsible for monitoring emissions, for serving improvement notices and for collecting the taxes and fines.

After years of neglect under the Soviet Union, the environment has become an important issue in today's Russia. Soviet policies that encouraged rapid industrialisation and development left a legacy of air pollution and nuclear waste. Cleanup has been slow, and environmental protection has not been a priority for the Russian government. Russia has a comprehensive legal and regulatory framework, but government institutions responsible for environmental protection lack the authority and capability to enforce legislation. Russia increasingly has come under international pressure, particularly from the European Union, to improve its environmental conditions. Neighbouring countries are concerned with cross-border pollutants, nuclear waste, and water pollution.

3.5 Nuclear power

Following the events at Three Mile Island Unit 2 nuclear power plant near Middletown, Pennsylvania, USA on 28 March 1979 and at Chernobyl Unit 4 nuclear power plant, Chernobyl, Ukraine on 26 April 1986, public perceptions of nuclear power indelibly changed. Instead of the safe provider of power for the future, public fear and distrust made future provision of electricity from nuclear power plants very difficult to imagine. For many in the West, the issues around safety and the problems of waste disposal attracted much attention. From an investor perspective, the huge up front capital requirements, combined with an uncertain, fluctuating electricity price (in a liberalised industry), make for an unattractive investment. As a result, no new nuclear power plant has been commissioned in the US since 1979 and, since 1986, a number of European countries have taken the decision for no new build and/or to decommission their existing plants.

There are also advantages to nuclear power generation. For instance, it may be attractive for security of supply. Uranium can be obtained from 'friendly' countries and stockpiled. Gas, on the other hand, is increasingly dependent on geopolitically unstable parts of the world. According to the Uranium Information Association (www.uic.com.au), if used only in conventional reactors, there are sufficient reserves of Uranium worldwide to last for half a century. Of the 3.1 million tonnes of known recoverable resources of Uranium, over a quarter lies in Australia (28%), with 15% in Kazakhstan, 14% in Canada, 10% in South Africa, 8% in Namibia, 6% in Brazil, 3% in the USA and 3% in Uzbekistan.

Furthermore, concerns over climate change and global warming have brought a recognition that nuclear may have a part to play as one of a portfolio of technologies that could contribute to a low carbon future.

Thirdly, if the capital costs of the nuclear plant and the cost of waste disposal and decommissioning can be contained and written-off over a 50-60 year design life, then nuclear is a technology with one of the lowest costs-of-electricity.

Over the past 20 years there have been considerable efforts on the part of the nuclear industry to improve plant safety, to deal with the waste problem and to make the technology cost competitive. The barriers to deployment of nuclear power are being addressed and there is a growing lobby for it to be embraced once again. For example, the UK Government's 2003 Energy White Paper did not endorse a programme of new nuclear power stations, but it did recommend that 'at some point in the future new nuclear build may be necessary if we are to meet our carbon targets'.

At present, nuclear power generates about 25% of the electricity in the UK. The lifetime of its nuclear stations, however, is limited. Closure and the start of decommissioning of all the first generation Magnox stations will be completed by 2010 and all but three of the remaining stations by 2014. Heysham 2 and Torness (each with a capacity of 1250MW) are due to be closed in 2023, and Sizewell B (1188MW) in 2035. If this timetable is adhered to, the contribution to electricity generation provided by nuclear would fall to 7% at most by 2020.

Recently, the Government has committed to review its policy with regard to nuclear build within the life of the present parliament. If the outcome of the review leads to new nuclear capacity build, there are three designs that are likely to contend. One is based on the Canadian (CANDU) reactor manufactured by Atomic Energy of Canada

Ltd (AECL) and the other two are based on Pressurised Water Reactor (PWR) technology and manufactured by BNFL/Westinghouse and Framatome. None of these designs have yet been built. Two of the designs use novel passive safety systems that do not require active intervention of operators.

Issues that will need to be addressed before new build could be started include:

- Economics
    - The high initial capital cost of building a nuclear power station (and subsequent low operating costs) make it difficult to compare the overall costs with conventional plants leaving the investor to carry the financial risk
- Knowledge base for nuclear technology
    - A survey by HSE found that overall nuclear education and training was in a 'fragile state'.
    - Research and development is mostly funded by the industry and the Research Councils, who fund work on general nuclear technology through their research programme 'Towards a Sustainable Energy Economy'
    - Many experienced staff within the industry are approaching retirement
- Waste management: what is acceptable?
- Planning and licensing timing and issues
    - Streamlining of the public enquiry process
    - Licensing of new design of reactor

The future of nuclear power depends on public acceptance that it is a safe, economical and necessary source of generation. Interesting to note also, is that there are no technology related barriers to building new nuclear capacity, although technology may assist with further reducing the waste and safety issues.

The UK position is not unique: a large fraction of the nuclear power plants in France are aging, having been constructed following the oil crisis in the 1970's. Finland's government has announced the construction of a new nuclear power station. China has started a very substantial build programme to meet its growing electricity demand. Nonetheless, there are significant nuclear legacy and decommissioning tasks that need to be undertaken in the Former Soviet Union, as well as in the USA**.** Whether or not nuclear turns around its public image, it is clear that nuclear power plants will continue to be deployed in many parts of the world.

4 TECHNOLOGY OVERVIEW

CPG covers power generation from nuclear and fossil fuels, predominantly coal and natural gas. In the main, electricity is generated at large power plants which run on one of the fuels just mentioned. These power plants need to be reliable, have very high availability and maintain high efficiency, which often means operating all year round virtually continuously whilst meeting the cycling and peaking demands placed on them.

The efficiency of a plant usually refers to its overall fuel to power efficiency. Except for gas turbines, all large fossil fuel power plants are steam-electric power plants. Simply put, heat is used to raise steam, which, in turn, is expanded through a steam turbine generator to produce electricity.

Above the critical point for water of 374°C and 22.1 MPa, there is no phase transition from water to steam. Plants operating at temperatures above the critical point can take advantage of increased thermodynamic efficiency available at the higher temperatures. Power plants that operate below and above this critical point are referred to as sub-critical and supercritical, respectively.

Nuclear power plants generally cannot reheat process steam due to safety requirements for isolation from the reactor core. This limits their thermodynamic efficiency to the order of 34–36%[1]. Subcritical fossil fuel power plants can achieve 36–38% efficiency. Supercritical designs have efficiencies in the low to mid 40% range, with new 'ultra supercritical' designs using pressures of 30MPa and dual stage reheat reaching about 48% efficiency.

An important class of fossil power plant uses a gas turbine, sometimes in conjunction with a steam boiler "bottoming" cycle. The efficiency of a combined cycle plant can approach 60% in large (500+ MWe) units. Such turbines are usually fuelled with natural gas or light fuel oil. While highly efficient and very quick to construct, the economics of such plants is heavily influenced by the volatile cost of natural gas.

Simple-cycle gas turbine plants, without a steam cycle, are sometimes installed as emergency or peaking capacity; their thermal efficiency is much lower. The high running cost per hour is offset by the low capital cost and the intention is usually to run such units for only a few hundred hours per year.

4.1 Power generation from fossil fuels

There are several power plant technologies for fossil fuels at various stages of maturity. These consist of what might be referred to as mainstream technologies through to niche technologies that have more limited application. For coal, the

---

[1] In this report efficiency figures are reported on a Lower Heating Value/Net Calorific Value basis.

mainstream technologies are based on pulverised fuel (PF) combustion, fluidised bed combustion (FBC) and integrated gasification combined cycle (IGCC).

4.1.1 Pulverised Fuel plant

The boiler of a PF plant is a rectangular furnace about 40m tall, with walls made of a web of high-pressure steel tubes. Coal injected into the furnace from fuel nozzles rapidly combusts, forming a large fireball at the centre. This heats the water that circulates through the boiler tubes. As the water in the boiler circulates it absorbs heat and changes to steam, which is separated from the water by parallel plates inside a drum at the top of the furnace. Saturated steam is introduced into superheater tubes hanging in the hottest part of the combustion gases as they exit the furnace. Here the steam is superheated to above 540 °C to prepare it for the turbine.

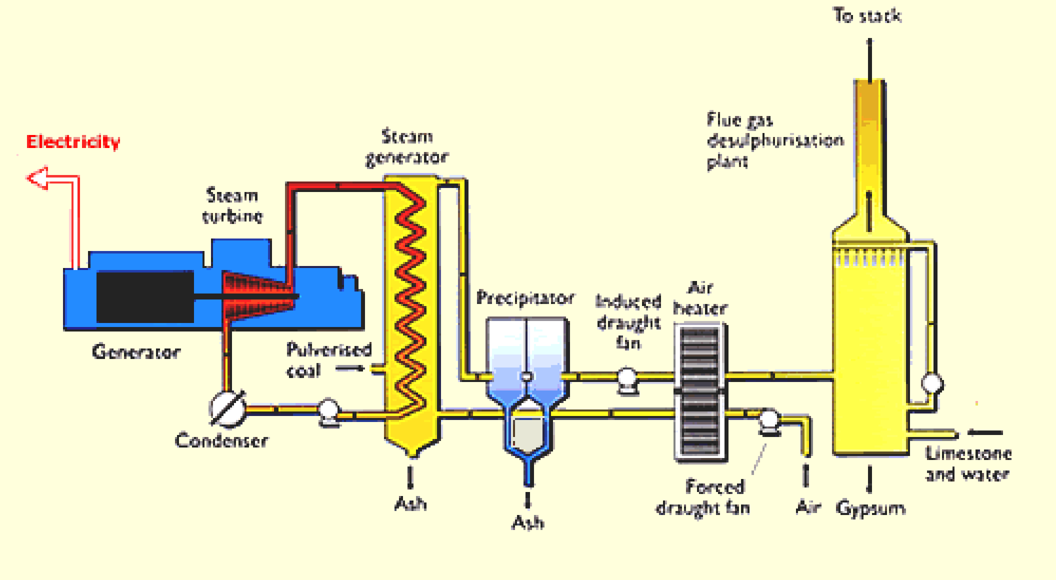


Figure 4.1 : Illustration of Pulverised Fuel Plant
(Source: www.australiancoal.com.au)

The superheated steam from the boiler passes to the high-pressure turbine, where it reduces in pressure and passes back into the boiler where the temperature of the steam is raised in the reheater tubes. The hot steam is conducted down to the intermediate-pressure turbine where it falls again in both temperature and pressure, and exits directly to the large bladed low-pressure turbines, and finally enters the condenser. An illustration of a typical PF power generation process is shown in Figure 4.1.

Fly ash removed from the gas exiting the boiler using bag filters or electrostatic precipitators may be sold, e.g. to be used in cement production. Most of the emissions of sulphur and NOx are removed from the exit stream leaving the stack.

Development over many years has led to the construction of coal-fired PF plants, of which the best achieve overall net cycle efficiencies of more than 45%. The efficiency of conventional PF systems is constrained by the limitations of the Rankine Cycle as illustrated in Figure 4.2. The Rankine Cycle refers to the cycle of operations in a heat engine. It more closely approximates to the cycle of a real steam engine than does the Carnot cycle. With advances in materials to allow higher steam temperatures, efficiencies over 50% are being pursued.

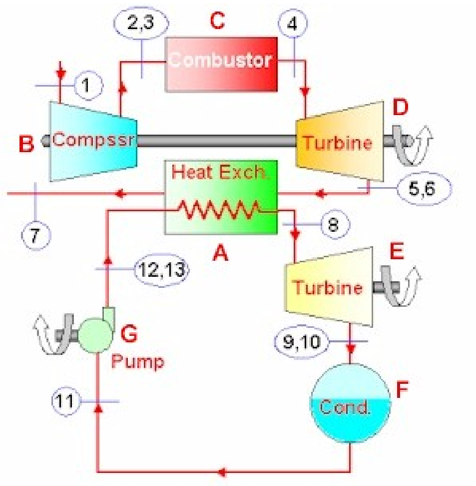


Figure 4.2 Illustration of a Rankine cycle
(Source: www.kahuna.sdsu.edu)

A key advantage of PF plant is its ability to increase and decrease load according to the demands of the grid. This allows it to back up intermittent renewable energy generation.

4.1.2 Fluidised-bed combustion

Of the fluidised-bed combustion (FBC) technologies, circulating fluidised-bed combustion (CFBC), as illustrated in Figure 4.3 has received most attention. In circulating fluidised bed combustion plant, fuel and limestone are injected into the combustor. These particles are suspended in a stream of upwardly flowing air, which enters the bottom of the combustor through air distribution nozzles. The balance of combustion air is admitted above the base of the furnace as secondary air. While combustion takes place at 840-900C, the finer particles are elutriated out of the furnace with a flue gas velocity of 4-6m/s. The particles are then collected by the solids separators, usually cyclones, and circulated back into the furnace.

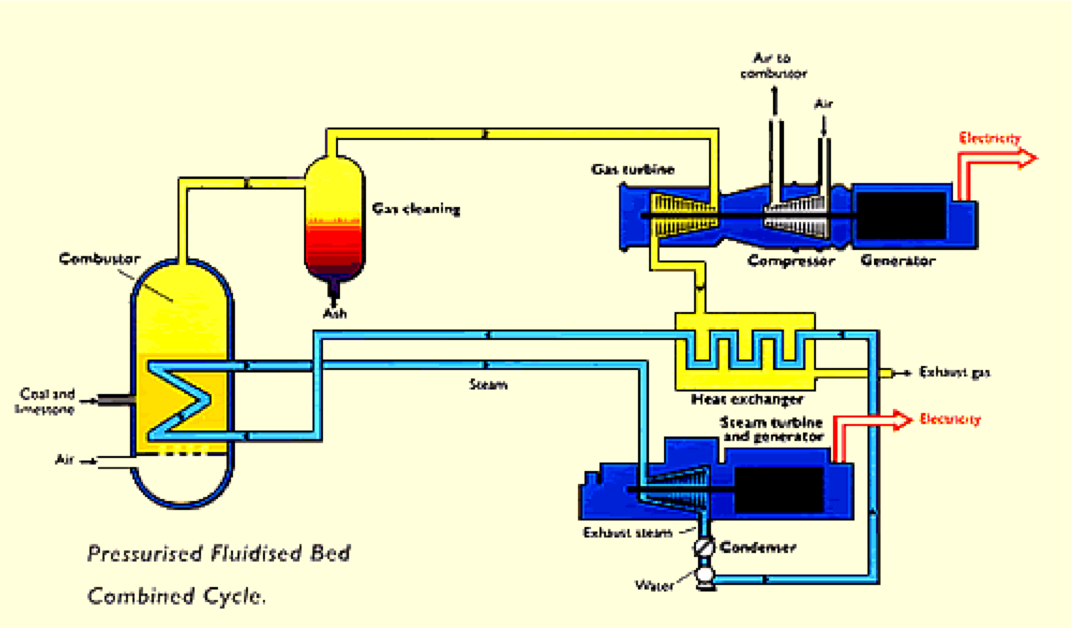


Figure 4.3 : Illustration of the CFBC process
(Source: www.australiancoal.com.au)

Circulation of the particles provides efficient heat transfer to the furnace walls and a longer residence time for carbon and limestone utilisation. The longer residence time offers the opportunity for high combustion efficiency and for more of the sulphur dioxide released to react with and be captured by the limestone. The lower combustion temperature reduces emissions of NOx, as it inhibits production of thermal NOx. In addition, as the temperature remains below the ash melting temperature, it reduces the risk of ash sintering and fouling.

There are a small number of large-scale power plants operating worldwide, notably in France. With support from the EU, the French constructed two large CFBC plants during the 80s and 90s. Though both the Emile Huchet plant (125MW) and the Gardanne plant (250MW) remain operating, CFBC plants are largely considered a niche product, and mainly for low quality fuels.

Atmospheric fluidised-bed combustion (AFBC) or bubbling fluidised-bed combustion plants operate under a similar principle to CFBCs, except that they operate at lower fluidising velocities, often lower than 1m/s. The atmospheric bubbling variant is usually considered less suitable for power generation, largely due to the cross-section of the vessel required for a reasonable output.

There are also pressurised variants of both the AFBC and the CFBC, known as pressurised fluidised bed combustion (PFBC) and pressurised circulating fluidised-bed combustion (PCFB), respectively.

4.1.3 Combined Cycle power plants

Integrated gasification combined cycle (IGCC) and PFBC plants are both examples of coal-fired combined-cycle technologies, and were developed partly in response to the constraints of the Rankine cycle. Based on power generation using both steam and gas turbines, combined cycles offer the potential to achieve efficiencies well in excess of 50% by optimising the parameters of both the Brayton and Rankine Cycles. [The Brayton Cycle, as illustrated in Figure 4.4, is an ideal air standard cycle for the closed cycle gas turbine unit. Both the heat supplied and rejected from the cycle occur at constant pressure, i.e. it is a constant pressure cycle.] Furthermore, processes to reduce the environmental impact of a technology may be integrated into the combined-cycle, resulting in more compact power generation plants.

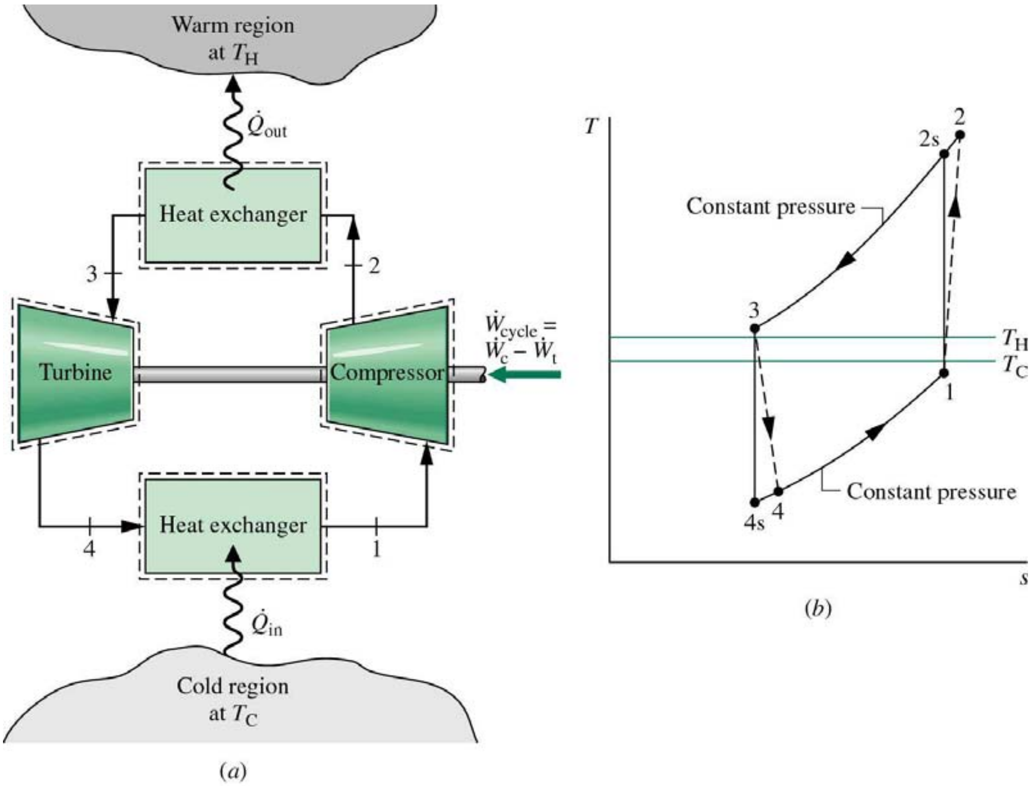


Figure 4.4 Bryton cycle
(Source: www.kahuna.sdsu.edu)

PFBC and PCFB were developed to take advantage of the higher efficiencies possible from employing combined cycles. Both received much attention through the 1970s, 80s and early 90s, and there are a small number of PFBC plants operating worldwide, particularly in Japan. Interest in these technologies, however, has largely been superseded by the development of supercritical conventional technologies and by the promise of IGCC. Issues such as the constraint on combustion temperature, tube-bank erosion, and the lack of effective hot gas particulate removal and consequent sub-optimal gas turbine design (for PFBC, only around 20% of the power comes from the gas turbine) have resulted in these technologies having niche applications only.

IGCC, as illustrated in Figure 4.5, is a power generation system which produces synthesis gas (syngas), mainly of CO and H2, converted from fossil fuels, such as coal, vacuum residue, heavy oil, petroleum coke and orimulsion by a partial oxidation process and then burned to generate electricity from the syngas in a combined cycle.

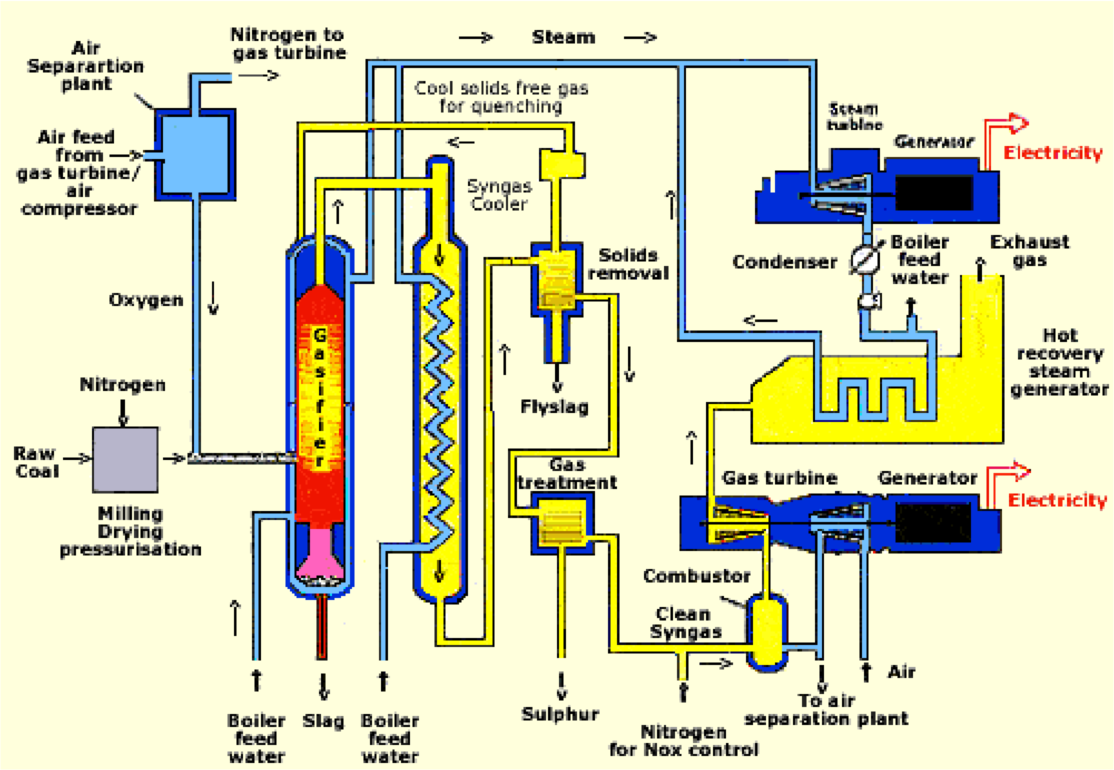


Figure 4.5: Typical IGCC process
(Source: www.australiancoal.com.au)

In IGCC, the gas turbine is driven by the combusted syngas, while the exhaust gases are heat exchanged with water/steam to generate superheated steam to drive a steam turbine. Using IGCC, 60-70% of the power comes from the gas turbine.

Coal gasification takes place in the presence of a controlled low concentration of air/oxygen, thus maintaining reducing conditions. The process is carried out in an enclosed pressurized reactor, and the product syngas a mixture of CO + H_2. The syngas is cleaned and then burned with either oxygen or air, generating combustion products at high temperature and pressure. The sulphur is present mainly as H_2S, with a little COS. The H_2S can be more readily removed than SO_2. Although no NOx is formed during gasification, some is formed when the syngas is subsequently burned. IGCC's can achieve efficiencies in the order of 45-46%.

Unlike IGCCs, combined–cycle gas turbines (CCGTs) use natural gas as fuel and are well established. Achieving efficiencies of 60% or higher, power generated from

CCGTs is significantly lower cost than from other conventional sources and, as such, its contribution to the mix has risen very substantially over the past ten years. Even though gas prices have been volatile of recent, raising operating costs quite significantly, CCGTs remain the preferred technology of the power utilities. Developments in the technology, particularly in more advanced materials such as single crystal blade technology, is leading to even higher efficiencies and lower emissions. Ultimately, as we move towards the hydrogen economy and target zero emissions, gas turbines capable of burning hydrogen must be developed. These technologies are already under investigation as intermediate stages to achieving the hydrogen economy are sought.

4.2 Nuclear power generation

Nuclear power could potentially significantly reduce national carbon emissions. In a nuclear reactor, heat is produced when neutrons strike Uranium atoms causing them to divide (fission) in a continuous chain reaction. The reactor core contains the Uranium fuel, formed into cylindrical ceramic pellets about one-half inch in diameter, which are sealed in long metal tubes. Control rods, or moderators, made of materials that absorb neutrons, are placed among the fuel assemblies. When the control rods are pulled out of the core, more neutrons are available and the chain reaction speeds up, sustaining the chain reaction and producing more heat. When they are inserted into the core, more neutrons are absorbed, and the chain reaction slows or stops, reducing the heat. The heat produced is used to convert water into steam, which drives a turbine-generator to produce electricity. The type of reactor described is known as a thermal reactor. Figure 4.6 and 4.7 illustrate variations in reactor core design.

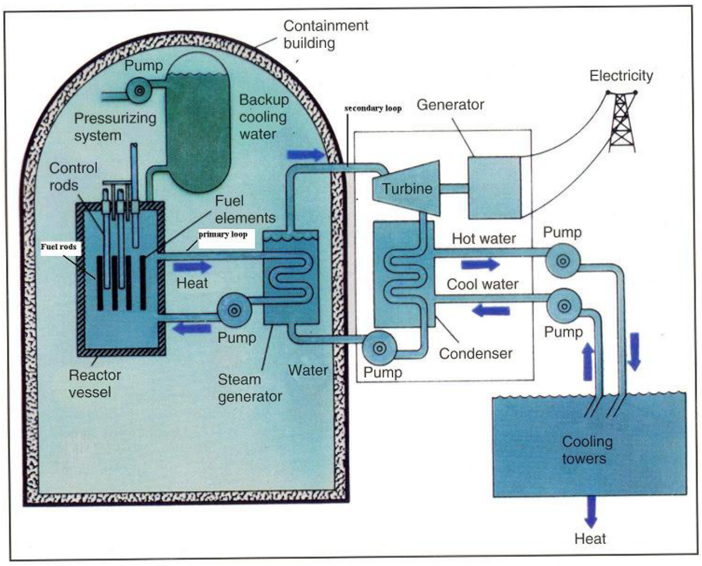


Figure 4.6 Nuclear reactor typical design
(Source: www.wikipedia.com)

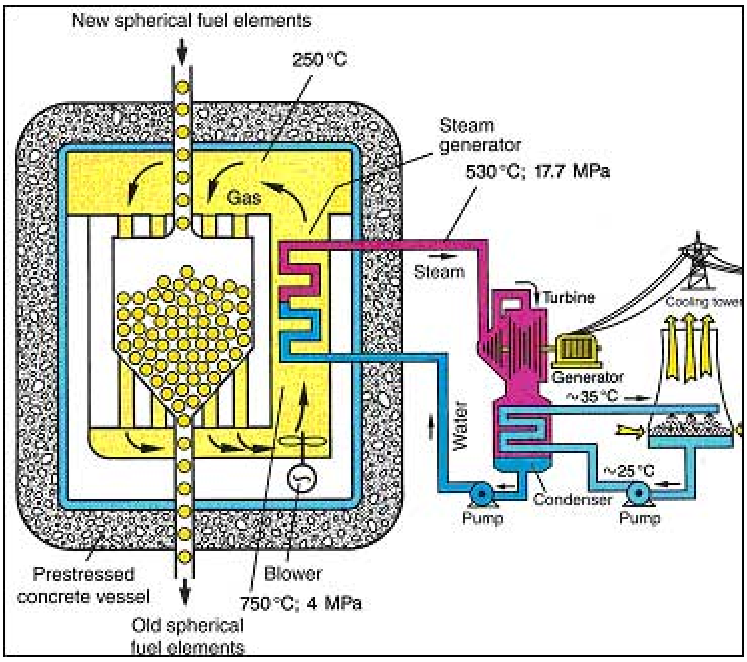


Figure 4.7 Nuclear reactor typical design
(Source: www.wikipedia.com)

Figure 4.8 provides a summary of the deployment of the main nuclear power generation technologies, starting with the most numerous reactor types. This figure also provides a summary of the key features of each reactor type.

Reactor type	Main Countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised Water Reactor (PWR)	US, France, Japan, Russia	268	249	Enriched UO$_2$	water	water
Primary cooling circuit flows through core of reactor under high pressure (Water reaches 325C at ~150atm). Lower pressure secondary cooling circuit generates steam in the heat exchanger (with primary circuit) to drive the turbine.						
Boiling Water Reactor (BWR)	US, Japan, Sweden	94	85	Enriched UO$_2$	water	Water
A single water cooling circuit (at lower pressure (~75atm) than in a PWR) generates steam in the core at about 285C. Reactor operates with 12-15% of the water in the top part of the core as steam, so providing less moderating capacity and therefore less efficiency						
Gas-cooled Reactor (Magnox & AGR)	UK	23	12	natural U (metal), enriched UO$_2$	CO$_2$	Graphite
Advanced Gas Cooled Reactors are the second generation of UK designed reactors (Magnox being the first). Carbon dioxide gas cools the core at 650C and then past steam generators outside the core (but still in the concrete and steel pressure vessel). Gas cooled reactors have a high thermal efficiency but are more expensive to build than conventional water cooled reactors.						
Pressurised Heavy Water Reactor 'CANDU' (PHWR)	Canada	40	22	natural UO$_2$	heavy water	heavy water

This Canadian designed reactor type uses natural uranium fuel that needs a more efficient moderator – heavy water. The heavy water moderator is contained in a large tank (callandria) penetrated by several hundred horizontal pressure tubes that form the channels for the fuel, cooled by heavy water at high pressure (at 290C). As in the PWR the primary circuit generates steam in the secondary circuit to drive the turbines.						
Light Water Graphite Reactor (RBMK)	Russia	12	12	Enriched UO_2	water	Graphite
Soviet design developed from plutonium production plants. It employs long vertical pressure tubes, containing the fuel, running through the graphite moderator. Coolant is provided by water that boils in the core at 290C (like the BWR). Since the moderation largely due to the fixed graphite, excess boiling, reduces the cooling and neutron absorption without inhibiting the fission reaction, and a positive feedback can occur.						
Fast Neutron Reactor (FBR)	Japan, France, Russia	4	1	PuO_2 and UO_2	liquid sodium	none
One reactor in commercial service generates electricity does not use a moderator but sustains the fission reaction using fast neutrons. While fast reactors generate more than 60 times as much energy from the original uranium compared to conventional reactors they are expensive to build.						
TOTAL		**441**	**381**			

Figure 4.8 Overview of Nuclear Reactor Types
(Source: Nuclear Engineering International Handbook 2005, World Nuclear Association)

All nuclear technologies will need to be competitive with other power generating technologies in terms of:

- Cost: recent studies have indicated that the capital, operating and fuel costs of base-load generation for new nuclear plant compare closely with those of new coal-fired power generation plant with CO2 capture and storage. Estimates of the costs associated with decommissioning and (current means of) disposal of radioactive waste products, when discounted over the period until disposal will be required, have only a small impact on the costs of generation[2].
- Safety: recently, the drive has been to develop passively safe reactors, i.e. nuclear reactors that do not require operator action in order to shut down safely in the event of a 'loss of coolant accident' or other emergency. Such reactors use the laws of physics to keep the nuclear reaction under control rather than use engineered safety systems. The pebble bed reactor is an example of a passively safe reactor - it uses 'pebbles' of uranium encased in graphite to moderate the reaction - the more heat produced, the more the pebbles expand, causing the reaction to slow down.
- Environment: solutions to decommissioning of nuclear facilities and long-term disposal of nuclear wastes will both be required to pass public scrutiny.

---

[2] BNFL presentation at IPA Seminar “Powering a Sustainable Scottish Economy” 26-27 October 2005, slide 15 states that “decommissioning cost” and “spent fuel management cost” make up 2% each only out of the total cost of electricity (typically £20-25/MWh)

4.3 Distributed generation

The portfolio of Distributed Generation (DG) technologies includes reciprocating engines, microturbines, combustion gas turbines (including miniturbines), fuel cells, and renewable sources such as photovoltaics and wind turbines. Each technology has varying characteristics and emission levels. Costs for these technologies vary significantly based on siting and interconnection requirements, as well as unit size and configuration. Fuel costs will vary significantly by region.

A subset of DG is formed by micro generation technologies, which is defined as generation with a capacity below 10 kWe. ITI has conducted a separate foresighting exercise into microgeneration and therefore those specific technology challenges and opportunities are not dealt with in this report. Similarly forms of distributed generation that use renewable energy are outside the scope of this foresighting report.

This leaves four main types of distributed generation technology that are used with conventional fuels: reciprocating engines, combustion gas turbines, microturbines and fuel cells. Figure 4.9 summaries key size, efficiency, capital cost and operating cost of each of these:

Prime Mover	**Open Cycle Gas Turbine**	**Spark Ignition Engine**	**Microturbine**	**Fuel Cell**
Fuel	Natural Gas Biogas Propane Distillate Oils	Natural Gas Biogas Propane Liquid Fuels	Natural Gas Biogas Propane Distillate Oils	Hydrogen Natural Gas Propane
Size Range MW	0.25 - 500	0.08 - 20	0.025 - 0.5	0.01 - 10
Electrical Efficiency (%)	25 - 42	25 - 43	20 - 30	30 - 70
Overall efficiency with cogeneration (%)	65 - 87	70 - 92	Up to 85	Up to 85
Installed Cost ($/kW)	800 - 1800	900 - 1500	1300 - 2500	3500 - 5000
O&M Costs ($c/kWh)	0.3 - 1	0.5 - 2	1	0.5 - 5

Levelized Costs (in Cogeneration mode) 8000 hrs/year	4.0 - 5.5	4.5 - 5.5	5.0 - 7.0	9.0 - 11.5

Figure 4.9: comparison of DG technologies
(Source: AEA Technology FES, 2006)

The advantages and disadvantages of DG are well documented. The main disadvantages are that costs of generation are higher, costs of fuel delivery are higher and that unit efficiency is lower. Advantages include generation close to load, potential for heat recovery, rapid response time and potential for mobile or emergency use. Costs of meeting the more stringent environmental targets of the future will be higher for some DG technologies, compared to economy of scale for abatement technologies that can be achieved on large plants.

DG technologies are relatively new and some of the disadvantages are being addressed. Fundamentally, DG does not suffer from transmission costs and distribution losses which add to the overall cost, efficiency, and emission reduction potential of DG. Furthermore, using the appropriate infrastructure, DG will enable more flexible balancing of power supply and demand. Market liberalisation increases significantly the flexibility of the distributed generator.

4.3.1 Reciprocating Diesel or Natural Gas Engines

Reciprocating engines, developed more than 100 years ago, were the first among DG technologies. Both Otto (spark ignition, as shown if Figure 4.9) and Diesel cycle (compression ignition, as shown in Figure 4.10) engines have gained widespread acceptance in almost every sector of the economy. They are used on many scales, with applications ranging from fractional horsepower units that power small tools to enormous 60MW baseload electric power plants. Smaller engines are primarily designed for transportation and can usually be converted to power generation with little modification. Larger engines are most frequently designed for power generation, mechanical drive, or marine propulsion.

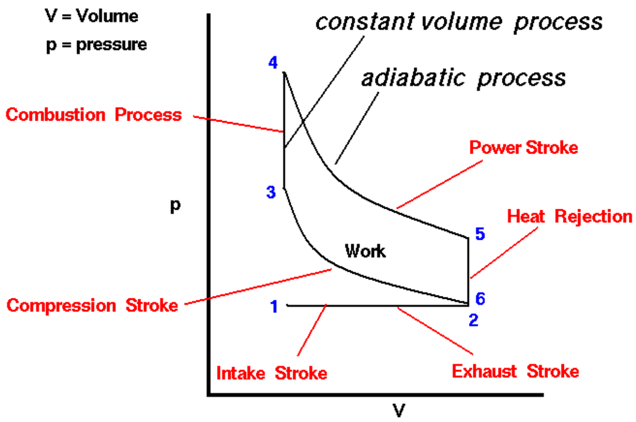


Figure 4.9: Otto Cycle
(Source: www.grc.nasa.gov)

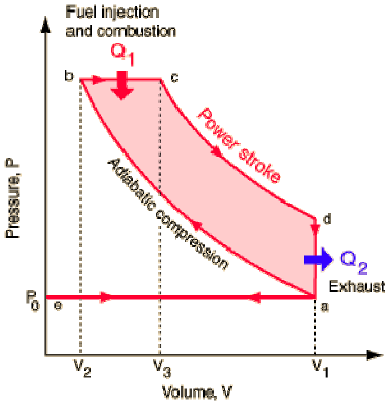


Figure 4.10: Diesel Cycle
(Source: http://www.hyperphysics.co.uk/)

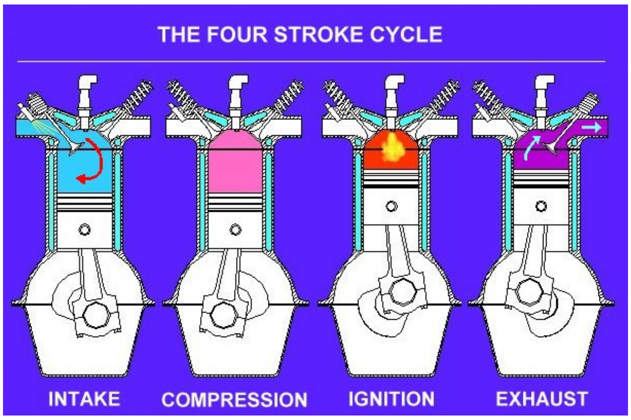


Figure 4.11: The four Stroke Cycle
(Source: http://calvin.phys.columbia.edu/teaching/Otto.jpg)

Reciprocating engines can be fuelled by diesel or natural gas, with varying emission outputs. Almost all engines used for power generation are four-stroke and operate in four cycles (intake, compression, combustion, and exhaust, as illustrated in Figure

4.11). The process begins with fuel and air being mixed. In turbocharged applications, the air is compressed before mixing with fuel. The fuel/air mixture is introduced into the combustion cylinder and ignited with a spark. For diesel units, the air and fuel are introduced separately with fuel being injected after the air is compressed. Reciprocating engines are currently available from many manufacturers in all size ranges. They are typically used for either continuous power or backup emergency power. Cogeneration configurations are available with heat recovery from the gaseous exhaust. In CHP applications high temperature heat can be recovered from the exhaust gas, while low temperature heat can be recovered from the engine cooling jacket.

4.3.2 Microturbines

Microturbines are an emerging class of small-scale distributed power generation in the 30-400kW size range. The basic technology used in microturbines is derived from aircraft auxiliary power systems, diesel engine turbochargers, and automotive designs. A number of companies are currently field-testing demonstration units, and several commercial units are available for purchase.

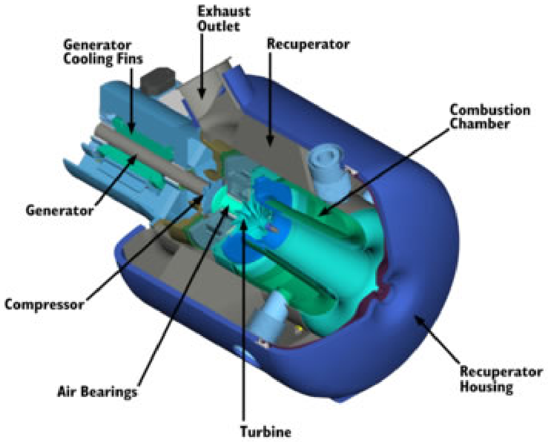


Figure 4.12: Illustration of a Microturbine
(Source: www.energieprojecten.nl)

As illustrated in Figure 4.12, microturbines consist of a compressor, combustor, turbine, and generator. The compressors and turbines are typically radial-flow designs, and resemble automotive engine turbochargers. Most designs are single-shaft and use a high-speed permanent magnet generator producing variable voltage, variable frequency alternating current (AC) power. Most microturbine units are designed for continuous-duty operation and are recuperated to obtain higher electric efficiencies.

4.3.3 Combustion Gas Turbines

Combustion turbines range in size from simple cycle units starting at about 1MW to several hundred MW when configured as a combined cycle power plant. Units from

1-15MW are referred to as industrial turbines, or sometimes as miniturbines, which differentiates them both from larger utility grade turbines and smaller microturbines. Microturbines smaller than 1MW are produced, but few have been installed. Industrial turbines are currently available from numerous manufacturers. Historically, they were developed as aero derivatives (as illustrated in Figure 4.13), spawned from engines used for jet propulsion. Some, however, are designed specifically for stationary power generation or compression applications in the oil and gas industries. Multiple stages are typical and, along with axial blading, differentiate these turbines from the smaller microturbines described above.

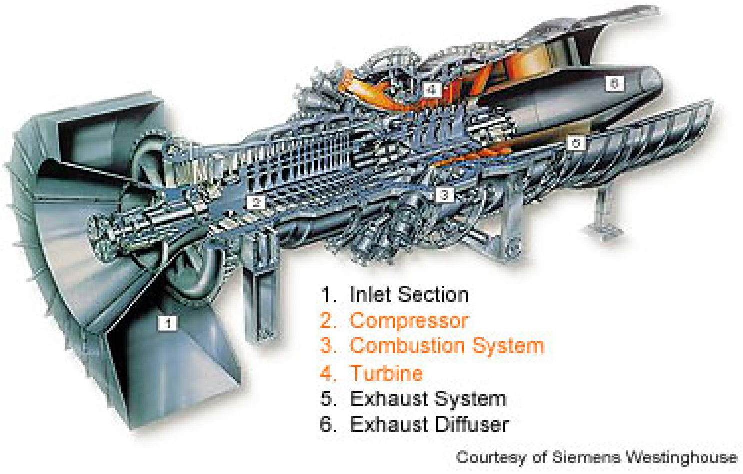


Figure 4.13: Combustion Gas Turbine
(Source: www.fe.doe.gov)

Combustion turbines have relatively low installation costs, low emissions, and infrequent maintenance requirements. However, their low electric efficiency has limited turbines to primarily peaking unit and combined heat and power (CHP) applications. The high temperature heat available from the exhaust is ideal for steam raising in a heat recovery steam generator. Cogeneration DG installations are particularly advantageous when a continuous supply of steam or hot water is desired and this form of CHP is found for instance in the process industries, chemical, paper and food industries.

The lower electrical efficiency is generally a complexity versus cost issue. For instance greater efficiency could be gained by introducing multi-stage turbines, but this is often not cost effective. In some DG applications, mismatching of plant capacity to highly variable load demands may result in plant operating far from its optimum operating point for a significant proportion of the time. Achieving overall efficiency improvements provides many challenges in this regard.

4.3.4 Fuel Cells

Although the first fuel cell was developed in 1839 by Sir William Grove, it was not put to practical use until the 1960's when NASA installed this technology to generate electricity on Gemini and Apollo spacecraft. There are many types of fuel cells currently under development in the 5-1000+ kW size range, including phosphoric acid, proton exchange membrane (illustrated in figure 4.14), molten carbonate, solid oxide, alkaline, and direct methanol.

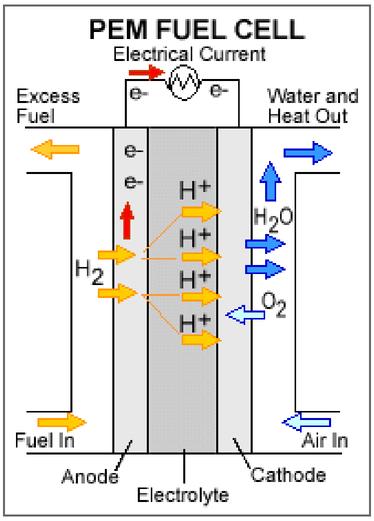


Figure 4.14: Proton Exchange Membrane fuel cell
(Source: www.news.cornell.edu)

Although the numerous types of fuel cells differ in their electrolytic material, they all use the same basic principle. A fuel cell consists of two electrodes separated by an electrolyte. Hydrogen fuel is fed into the anode of the fuel cell. Oxygen (or air) enters the fuel cell through the cathode. With the aid of a catalyst, the hydrogen atom splits into a proton (H+) and an electron. The proton passes through the electrolyte to the cathode and the electrons travel in an external circuit. As the electrons flow through an external circuit connected as a load they create a DC current. At the cathode, protons combine with hydrogen and oxygen, producing water and heat. Fuel cells have very low levels of NOx and CO emissions because the power conversion is an electrochemical process. The part of a fuel cell that contains the electrodes and electrolytic material is called the "stack," and is a major contributor to the total cost of the total system. Stack replacement is very costly but becomes necessary when efficiency degrades as stack operating hours accumulate.

Fuel cells require hydrogen for operation. However, it is generally impractical to use hydrogen directly as a fuel source; instead, it must be extracted from hydrogen-rich sources such as gasoline, propane, or natural gas. Cost effective, efficient fuel reformers that can convert various fuels to hydrogen are necessary to allow fuel cells increased flexibility and commercial feasibility.

5 KEY TECHNOLOGY DEVELOPMENT AREAS

As indicated previously, global power demand is projected to increase 60% between now and 2030 and the biggest contribution will come from conventional, fossil and nuclear fuelled power generation technologies. It is imperative that further technology developments are deployed to bring down the costs, to reduce the environmental impact and to ensure that power is delivered in a secure and sustainable manner. This chapter summarises some of the most likely technology opportunities.

5.1 Fossil fuels technologies

For fossil fuel-fired power generation technologies, which mean predominantly coal and gas, the main drivers for development are the twin goals of reducing costs whilst meeting emissions constraints. Within the fossil fuels area, the key development areas lie in raising efficiency, reducing emissions and improving availability.

5.1.1 Efficiency

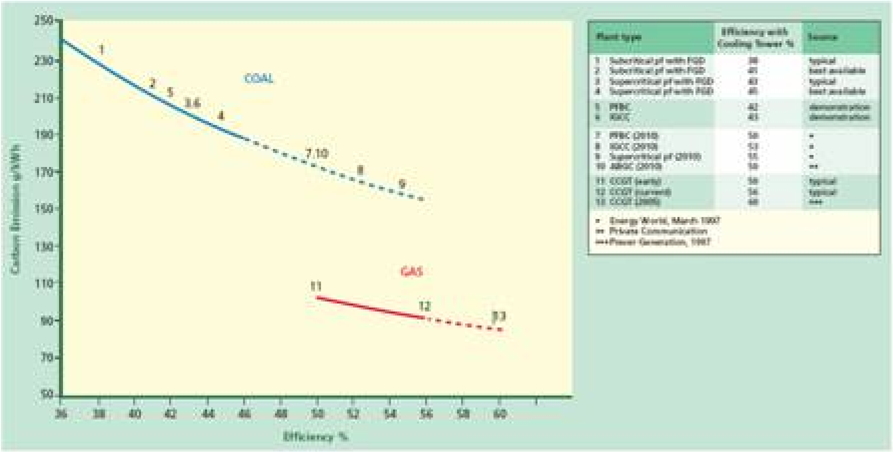
The main approach to reducing the costs has been to improve the efficiency of the power generation process itself. If efficiency were improved, it would have a twofold impact:

- The size of plant required to provide a given output would be smaller. This would reduce equipment costs significantly and would also reduce the plant footprint.
- It would require less fuel to generate the same output, potentially leading to significant cost savings over the lifetime of the plant

Furthermore an increase in efficiency would result in a net reduction of emissions per MWh of electricity generated. Figure 5.1 depicts the impact of increased efficiency on CO2 emissions for a number of coal and gas technologies.

Though technologies have progressively increased in efficiency over the years, there are still opportunities for further improvement. For any particular technology, these may include:

- Employing enhanced control and monitoring technologies e.g. to improve carbon burnout in a furnace and raise combustion efficiency.
- Developing advanced materials, e.g. to enable operation at higher temperatures and higher pressures, often in highly oxidising or reducing conditions.



Plant type	Efficiency with Cooling Tower %	Source
1 Subcritical pf with FGD	38	typical
2 Subcritical pf with FGD	41	best available
3 Supercritical pf with FGD	43	typical
4 Supercritical pf with FGD	45	best available
5 PFBC	42	demonstration
6 IGCC	43	demonstration
7 PFBC (2010)	50	*
8 IGCC (2010)	53	*
9 Supercritical pf (2010)	55	*
10 ABGC (2010)	50	**
11 CCGT (early)	50	typical
12 CCGT (current)	56	typical
13 CCGT (2005)	60	***

* Energy World, March 1997
** Private Communication
*** Power Generation, 1997

Figure 5.1: Efficiency improvements and impact on CO2 emissions
(Source: APGTF "a vision for clean fossil power generation, 2004")

5.1.2 Reliability, Availability, Maintainability and Operability (RAMO)

To reduce operating costs, there has been much improvement in the areas of RAMO in recent years. Efforts to make improvements in these areas can appreciably reduce costs by, e.g. allowing plants to operate for longer periods between shutdowns, reducing the length of time required for shutdowns, having scheduled maintenance plans and having to store less equipment/spares on-site. Condition-based monitoring is now widely employed but is still an area in which further developments are needed.

5.1.3 PF plant

Current improvements on PF plants are focused largely on developing and adapting the technology to meet current and anticipated emissions criteria, whilst maintaining a competitively priced product.

Since the introduction of low-NOx burners, more unburnt carbon escapes the furnace, leading to lower combustion efficiencies. With concentrations greater than around 4% carbon-in-ash, the ash becomes unsaleable and, unless treated, must be discarded to landfill. This can lead to a loss of revenue for the plant, inefficient combustion, environmental pressures and higher fuel consumption. Combustion efficiency may be increased through a combination of improved low-NOx technologies and improved control and monitoring of the fuel injected into the furnace.

Increases in process efficiency are principally being addressed through the development of advanced materials that are suitable for operation at the higher steam temperatures and pressures required and have the favourable creep and fatigue performance under such HPHT conditions. For example, to reach temperatures above 480°C in the water walls, much attention is being directed towards the 9% and 12% chromium steels such as T91/P91, X20CrMoV121 and HCM12.

There is a significant European project (AD700) with the objective to improve the materials of various components such that an efficiency of 50% may be exceeded. Raising the plant efficiency to 50% or higher will require materials capable of handling steam at 700°C and pressures exceeding 30Mpa. At present, the best ultra-supercritical PF plants can reach 46% efficiency. High efficiency, ultra-super-critical plant would provide an excellent basis for integration of CO2 capture technology for new build plant of the future.

Other developments relating to PF plants are concerned with the impact of burning biofuels, in all their various forms, effectively and without detriment to the plant. Many of the PF stations in the UK inject or have injected 3-10% biomass. However, there are many remaining concerns with this practice before the 20% target can be safely reached. Biomass is much less dense than coal and handling, milling and injection of biomass all present their challenges to the generator. Explosion hazards are not trivial. Corrosion resulting from the high alkali content of some biofuels presents problems with metallic components. It is clear that to reach the stage where 20% of the fuel is biomass will require a great deal more effort.

In the UK, around 11 Mtonnes of fly ash are produced annually. Globally, the quantities are orders of magnitude higher. To be suitable for commercial use the fly ash must meet certain quality control criteria. Commercially attractive solutions to the following issues would benefit the environment enormously:

- Reduction of fly ash production
- Alternative uses of fly ash
- Impact on changing fuels (e.g. co-firing) on fly ash production and its uses

5.1.4 Fluidised-bed combustion

With fluidised-bed combustion occupying niche markets in today's power generation technologies mix, significant effort is spent on testing and improving its performance various fuels, ranging from Orimulsion to Olive pips. Each fuel brings its own problems, relating to handling, storage, feed to combustor, ash properties and emissions. Some fuels present particular difficulties, e.g. if they are high in alkalis, they may cause corrosion.

The disposal of ash from FBC may present difficulties as it can have a high free lime content as a result of the limestone added to reduce emissions of SO2. If the free lime content is high, the waste may be treated as a hazardous or controlled waste and special provisions may apply.

The erosive and corrosive nature of the fluidised-bed can also wear the in-bed tube banks, there to raise steam to drive the steam turbine. A well-designed combustion chamber and tube bank can reduce this to manageable levels. This is the case for both atmospheric circulating bed combustion plants (CFBCs) and for pressurised fluidised-bed combustion plants (PFBCs).

For PFBC, it is important to reduce the particulates entering the gas turbine to sufficiently low levels that erosion will not occur. In most existing plants, high efficiency cyclones, operating at the limits of their performance, are used. Through the 1980s and 90s, much effort was placed into the development of particulate filters that would operate reliably at high temperatures and pressures. Ceramic filters that would operate at temperatures of around 850°C and metal filters at lower temperatures, with limited success. Compared with the scale of effort in the past two decades, current activity appears modest. This may reflect the case that, whereas PFBC was then anticipated as a future mainstream power generation technology, this is no longer the case. Existing problems remain largely unresolved.

5.1.5 Combined cycle power plants

For the past 15 years, a major breakthrough has been anticipated, with IGCC to become mainstream and compete with PF technology. The Buggenum plant in the Netherlands was commissioned in late 1993, with Puertollano in Spain coming on stream a couple of years later. The US commissioned a number of IGCC plants as part of their demonstration programme through the 90s. Japan demonstrated IGCC. The efficiencies of these plants are generally around 42-43%, which is low and needs to be raised significantly for it to both reduce costs and emissions.

As a result, the predominant technology for power generation remains PF. Utilities and others with the responsibility for installing power generation plant have been unwilling, to date, to accept the risk of installing IGCC as a commercial technology.

However, IGCC is now being promoted as a potential route to the hydrogen economy. When coal is gasified, it produces syngas. The main constituents of syngas are hydrogen and carbon monoxide, together with small amounts of other contaminants. The hydrogen and carbon monoxide can be shifted, using steam, to hydrogen and CO2. If the CO2 and other contaminants are separated, hydrogen remains. The hydrogen can then be used to power a gas turbine or, perhaps a little further in the future, a fuel cell to produce electricity.

Syngas is also a valuable feedstock for chemicals production and hydrogen is in demand for use in refineries. IGCC, therefore, has the potential for polygeneration, i.e. it can be used to produce electricity, hydrogen for refineries or feedstocks for chemicals production. The technology challenge exists to design a plant that can flexibly switch products, depending on demand.

Similarly, natural gas can be treated to produce hydrogen and CO2. In both these cases, if the CO2 is permanently stored in geological formations (CO2 sequestration), there is potential for both coal and gas to be used as a source of power with near zero CO2 emissions. This is an area that has attracted much international interest over the past couple of years. BP, in conjunction with Scottish and Southern Energy, Royal Dutch Shell, and ConocoPhillips recently announced plans to develop – at Peterhead – the world's first industrial scale plant to generate electricity from hydrogen. The planned project would convert up to 70 million cubic feet of natural gas a day into hydrogen and CO2. The hydrogen would be used to fuel a 350MW power station, while the CO2 would be exported through existing pipelines to a North Sea oil reservoir (the Miller oilfield, 240 kilometres offshore) for increased oil recovery and ultimately storage. The plant would capture and store around 1.3 million tonnes of CO2 per year.

To commercialise these technologies, means to effectively and cheaply remove the CO2 are sought. Furthermore, solutions are required to cost effectively transport CO2 to the geological formations where they can be stored and monitored.

5.2 Emissions from fossil fuels

This section covers emissions from the use of coal, oil and gas for power generation. Though the proportions may vary, the constituents of these fuels are very similar. Where emissions of certain elements or compounds need to be reduced, the methods employed are similar.

Most countries are already taking steps to reduce substantially emissions of the so-called traditional pollutants, SO2, NOx and particulates. Much work has been done and remains to be done to further reduce the impact of these pollutants. Trace elements release, in particular mercury, has recently been the focus of attention and, in the USA, legislation has been brought to bear.

5.2.1 Sulphur dioxide

Sulphur appears in coal as pyritic sulphur (FeS2), organic sulphur, sulphur salts and elemental sulphur. Pyritic and organic sulphur account for the vast majority of sulphur in coal and both types are responsible for SOx formation. The sulphur is released when the coal is burnt, mainly oxidised to SO2. Usually less than 1-2% of the total sulphur is released as SO3. Visible emissions of SO3 are not a feature of modern coal-fired power stations. Indeed a small amount of SO3 is beneficial to the precipitation of dust particles, and hence some power plants burning low sulphur coals are equipped with SO3 injection systems, to promote more efficient dust precipitation.

For continuous measurement of SO2 in flue gases, the following types of systems are commercially available for SO2:

Extractive systems:	In-situ systems:
• Simple non dispersive infrared (NDIR)	• Differential optical absorption spectroscopy (DOAS)
• Luft detector NDIR	• Derivative spectroscopy
• Photoacoustic detector	• Gas filter correlation (GFC) NDIR
• Gas filter correlation (GFC) NDIR	• High temperature electrochemical cells
• Differential optical absorption spectroscopy (DOAS)	
• Fourier transform infrared spectroscopy (FTIR)	
• Non dispersive ultraviolet (NDUV)	
• Ultraviolet fluorescence	
• Electrochemical cells	
• Flame photometric	
• Conductivity analyser	

Flue Gas Desulphurisation (FGD) technologies are widely used to control the emissions of sulphur dioxide and sulphur trioxide from large stationary sources such as coal- and oil-fired power stations and refineries. A variety of FGD processes are available, most of which use an alkali sorbent to recover the acidic sulphur compounds from the flue gas. The most widely used process is the limestone gypsum process, which produces a saleable gypsum by-product, variants of the limestone process that produce a disposable sludge, and the spray dry process, which produces a mixed solid waste.

For FGD, most development work is focused on limestone gypsum and other wet scrubbing systems, since these represent the most common types used worldwide. Specific areas for improvement include higher desulphurisation efficiencies, lower capital and operating costs and better reliability. As reliability improves, user confidence increases and the need for redundancy reduces. Consequently, larger unit size is the target, dispensing with the multiple absorbers favoured in the past. Another area of interest is to reduce the dimensions of the absorber, both in height and diameter. A better understanding of the processes involved may lead to more efficient systems, offering shorter gas and particle residence times. Aerodynamic modelling and computational fluid dynamics simulations have contributed to this understanding of the processes. To make the units more reliable, further developments of corrosion-resistant materials are required. Gypsum slurry and recycle pumps often suffer erosion or corrosion, which might be avoided if better materials were available.

5.2.2 Oxides of Nitrogen

NOx comprises predominantly NO and NO2. It plays a major role in the formation of the ozone. NOx is formed from both oxidation of nitrogen compounds in the fuel (fuel NOx) and from oxidation of nitrogen in the combustion air (thermal NOx). The amount of fuel NOx is fixed by the properties of the fuel, while the amount of thermal NOx is controlled by the complex reactions that take place in the high temperature firing zone. 80 to 90% of NOx emitted from coal is formed from the nitrogen in the fuel. Thermal NOx, contributing less than 20%, is dependent on combustion temperature. Excess air and high temperatures found in some firing configurations encourage the production of thermal NOx.

Technologies for the measurement of NOx in flue gases are well developed. Most measurement technologies measure NO alone with the exception of some UV-based techniques, which are capable of measuring both NO and NO2. Regulators both in the UK and elsewhere accept that, if it can be demonstrated that the NO2 content represents less than 5% of the total NOx, measurement of NO alone may be acceptable. If full on-line measurement of NOx is required, catalytic converters are used to convert NO2 to NO. These converters are based on stainless steel or molybdenum catalysts. The stainless steel converters operate at 650°C and at this temperature any NH3 present in the flue gas will also be converted to NO and hence can interfere with the measurement. Molybdenum converters operate at lower temperatures of around 450°C, and will not convert NH3. NH3 may be present in the flue gas if control measures for NOx utilising NH3 injection are used. Problems have been reported with the conversion efficiencies of both stainless steel and molybdenum converters, and it is generally accepted that the conversion efficiency is less than 100%. Also molybdenum converters are limited to NO2 concentrations of less than 30ppm and must be recharged after dealing with a specified mass throughput of NO2.

Problems associated with the measurement of NOx are selectivity and the design of the sampling system for extractive systems. NO2 is highly water soluble, whereas NO is much less soluble. Heated sampling lines are normally used in extractive systems. Analytical systems for the continuous measurement of NOx concentrations in flue gases have been in existence for many years. Performance standards and specifications for analyser systems are given in Germany and the USA.

The following types of measurement systems are commercially available:

Extractive systems:	**In-situ systems:**
• Chemiluminescence analysers	• Differential optical absorption spectroscopy (DOAS)
• Simple non dispersive infrared (NDIR)	• Derivative spectroscopy
• Luft detector NDIR	• Gas filter correlation (GFC) NDIR
• Photoacoustic detector	• High temperature electrochemical cells
• Gas filter correlation (GFC) NDIR	
• Differential optical absorption spectroscopy (DOAS)	
• Non dispersive ultraviolet (NDUV)	
• Fourier transform infrared spectroscopy (FTIR)	
• Electrochemical cells	

Control of NOx emissions can be by combustion control measures or abatement. Combustion control measures include:

- burner optimisation
- air and/or fuel staging
- flue gas recirculation
- low NOx burners.

Burner optimisation techniques and low NOx burners are used to minimise the formation of NOx during combustion. In air staging and flue gas recirculation technologies, reducing the oxygen availability helps reduce NOx formation and complete the combustion. In fuel staging, previously formed NOx is reduced to nitrogen and oxygen within the furnace.

Primary measures for NOx control are integral parts of new build power plant and only retrofitted to existing units when required to meet regulatory requirements. Selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) are the proven options to achieve high NOx removal efficiencies. Incremental improvements in this technology are aimed at reducing the size and cost of these systems.

5.2.3 Particulates

Particulate matter (PM) entrained in flue gases is produced by the combustion of fuels or wastes. The size and quantity of particles released depends on the type of fuel and the design of the plant.

Residual PM following a bag house filter would be expected to have a different particle size distribution than that following a multi-cyclone due to the different separation methodologies employed, and the relative efficiency of the particulate abatement devices.

Commercial PM measurement systems can be classified as follows:

- Opacity monitors or transmissometers
- Scintillation or received light modulation
- Light scattering
- Beta-radiation attenuation
- Loaded oscillator
- Contact charge transfer
- Contact accoustical
- Electrodynamic induction.

Of the methods listed, opacity monitors, Beta-radiation attenuation and light scattering techniques have had the greatest application and success in meeting continuous monitoring requirements in the EU at the low particulate levels required. The other methods, with the exception of the loaded oscillator tend to be more qualitative, and are frequently used as alarm monitors, or as PM monitors in less demanding applications.

Particulate removal systems consisting of electrostatic precipitators, bag filters or multi-cyclones are used to reduce particulate concentrations to the required level prior to release to atmosphere.

Substantial progress has been made over the past 20 years and technologies to control emissions of all SOx, NOx, and particulates are now widely deployed. Systems are able to meet the strictest legislation currently in force. The challenge is to reduce the costs of these systems.

5.2.4 Trace Elements

Most releases of trace elements to the atmosphere come from a whole range of industrial processes. They are generally in the form of airborne particulate material, but a proportion of the more volatile species such as mercury (Hg) may exist in the vapour phase, even under ambient conditions.

Concentrations of emitted trace elements in flue gas are extremely low – dust emissions at coal-fired plant in the UK are required to be 50mg/m3 or lower and vapour phase concentrations of most trace elements are of the order of tens of microgrammes per cubic metre.

The vast majority of sampling systems for trace elements are designed for flue gas sampling. The majority of published information, particularly for vapour phase determinations and continuous emissions monitoring, covers sampling methods for mercury. It is possible to determine trace element concentrations further upstream in the boilers and furnace system, but this is rarely undertaken. Studies have also taken place of trace element behaviour in the plume and ground level concentrations of certain trace elements are often routinely monitored.

The ideal trace element control option would be removal from the fuel, but this appears not to be technically or economically feasible. Once trace elements have been introduced into the boiler, the most appropriate control options will depend on their physical state at the boiler exit. With the exception of mercury, combustion conditions do not affect the partitioning of the majority of trace elements to any great extent and most trace elements are present on particulate matter at typical flue gas exit temperatures. Current particulate abatement technologies are efficient and the continuous pressure to reduce particulate emissions is resulting in improvements and upgrades to existing equipment as well as new installations. Specialist polishing devices are designed to remove very fine aerosols and installation of such devices will assist in reduction of trace element emissions to atmosphere. Finally, the increasingly widespread application of flue gas desulphurisation technology also assists in particulate removal.

Given the high degree of co-control of trace element emissions by existing pollution control devices and their continual improvement, combined with the application of new technologies such as polishing devices, it is likely that no further action may be required in terms of abatement specifically for trace elements, with the exception of mercury.

Mercury

Due to its toxic effects on the environment and human health, mercury is one of the more significant trace elements emitted to the atmosphere. Once deposited on land or in water, bacteria can act to change the metal into an organic form called methyl mercury (MeHg), which can bioaccumulate in the food chain. At the upper reaches of the food chain, some fish and other predators can contain mercury levels many times higher than those in the surrounding environment and these concentrations can be harmful. Mercury emission is currently an important environmental issue, particularly in the United States.

Mercury is more complicated due to its behaviour within the combustion system and its high degree of volatility at flue gas exit temperatures. Mercury capture efficiency in existing flue gas cleaning equipment is entirely dependent on its speciation. Major factors that affect mercury speciation are the fuel composition (chlorine, sulphur), the combustion conditions (carbon-in-ash), and the type of flue gas cleaning methods used. Mercury associated with particulate material will be effectively removed by the ESP or fabric filter installation. Vapour phase mercury can exist in two forms; elemental Hg0, which is unreactive and insoluble and oxidised Hg2+, which is reactive and soluble and therefore easier to capture on both particulate matter and within an Flue Gas Desulferisation (FGD) facility.

Combustion modifications such as low NOx burners, overfire air and reburn may result in increased carbon-in-ash levels which have been demonstrated to result in increased mercury capture on particulate material. Fuel modifications such as coal blending and fuel spiking with chloride salts offer the potential for increased oxidisation of mercury and/or increased carbon-in-ash for subsequent capture in downstream ESP and/or FGD. These strategies are at an early stage of development but do show some promise as low cost control technologies.

In terms of mercury specific removal techniques, injection of a sorbent prior to the flue gas treatment system is the leading technology at present. Many such sorbents are under development and demonstration at full-scale in the USA, but as yet none are commercially deployed. Commercial sorbents are expensive and significant effort is going into developing alternatives at lower cost. The impact of such sorbents on stack opacity and byproducts is likely to be significant.

It is clear that, as yet, there is no proven technology that has been successfully demonstrated to achieve very high levels of mercury control under all conditions, and given the complications of the systems involved, it is unlikely that such a technology will appear in the short term. Research indicates that the most cost-effective approach to high levels of mercury control may be an integrated multipollutant (SO2, NOx, particulate and mercury) control technology. A number of these technologies are in the pilot-scale development stage in the USA, but have generally not yet been demonstrated at full-scale. It is not clear whether multi-pollutant technologies can be retrofitted at existing plant.

5.3 CO2 emissions

Internationally, climate change is now a dominant power industry issue. For example, in June 2005, the UK DTI launched its Carbon Abatement Technology (CAT) strategy, where the case was made for a range of generic options to reduce the CO2 emissions from fossil fuel combustion. These options are mirrored by the approaches being followed or suggested in other countries and international bodies. The UK options are:

a) To develop higher efficiency conversion processes
b) To switch fuel to lower carbon alternatives
c) To develop and apply CO2 capture and storage
d) To reduce power consumption per capita, by improving power efficiency. (this option is not further elaborated)

5.3.1 Higher efficiency conversion processes

The amount of fuel consumed, and the associated emission of CO2, is reduced when conversion processes (e.g. power generation, oil refining) are made more efficient. This can contribute emissions reductions of 10-30% depending on the performance of the old and replacement plant. For example increasing the efficiency of coal-fired power generation plant from 36% (typical current UK PF plant) to 45% reduces CO2 emissions by 20%.

For coal, the most mature and most commonly employed technology is based on pulverised fuel (PF) combustion. The state-of-the-art efficiency in Europe is >45%, based on supercritical steam plant operating at about 600°C. To increase efficiencies further, systems need to be developed that will withstand yet higher pressures and temperatures. The key technology development required for this is in materials that can withstand these pressures and temperatures. Similarly, for gas, efficiency increases rely on improving the performance of the gas turbine, where again, application of more advanced materials is crucial.

5.3.2 Fuel switching to lower carbon alternatives

Over the last decade, the main route taken in the UK is the replacement of coal-fired power generation with natural gas, which reduces emissions by about 50% per unit of output. However, there are other options such as replacement of fossil fuels with biomass (which is CO2-neutral), or co-firing coal with up to 5-10% biomass.

There is no widely adopted definition of materials classified as biomass. The category generally includes organic-based materials such as straw, wood, bark, grasses and animal wastes. Though biomass co-firing offers some advantages, it also throws up some disadvantages. Consistent supply of biomass of appropriate grade and quality is the most critical factor in ensuring adequate operational performance. Additionally, biofuels are generally much more expensive than conventional fuels, and have significantly different properties with respect to storage, bulk handling, volume flow, milling, combustion, slagging, corrosion, and gaseous emissions.

There are two main options available for utilising biomass as a renewable energy source in the generation industry: construction of 'stand-alone' dedicated biomass plant, or co-firing biomass with other fuels in existing combustion plant.

With regard to the design of mechanical, gravity flow and pneumatic handling systems, the most important properties of powders or bulk materials are considered to be:

- Bulk density
- Particle size distribution
- Moisture content
- Abrasiveness
- Angle of repose

However, biomasses add further properties such as:

- Combustibility
- Explosion severity
- Flammability
- Thermal properties
- Hygiene
- Toxicity.

It is therefore important to know what range of biomass materials the plant is to be designed for. Problems may be encountered at any stage with bulk handling, e.g. in transportation, silos, bunkers, hoppers, and so on. Then, for other plant operations, such as milling and pneumatic feeding to the combustor, there is also the potential for problems to arise. In the burner, the biomass content will change firing properties that will need to be better understood, particularly at co-firing quantities higher than 10%. Lastly, emissions in the flue gases and ashes will require attention. This waste treatment can take place in the fuel preparation phase (e.g. torefaction) as well as during and after combustion in ways similar to those described in 5.1 - 5.3.

5.3.3 CO2 capture

The carbon in fossil fuels is captured (as CO2) either during pre-combustion or post-combustion and can subsequently be reused, sold as feedstock to the chemical industry, or committed to long-term storage in geological formations. With the methods currently available, this approach can capture over 90% of emissions.

a. Post-combustion capture

CO2 is emitted to the atmosphere in the flue gases of power stations. The CO2 concentration in power station flue gas is ~4% (by volume) for NGCCs, 9% for coal-fired IGCC plant and ~14% for PF-fired boilers. A variety of techniques can be used to capture CO2 from power station flue gases. The preferred technique at present is to scrub the flue gas with an amine solution. The amine from the scrubber is subsequently heated by steam to release high-purity CO2 and the CO2-free amine is then re-used in the scrubber. Amine scrubbing has been deployed at small scale for a number of years. However, current technologies reduce overall plant energy efficiency by 6-8%. The major challenges are to reduce the cost of the amines, by increasing their effectiveness and improving their regeneration performance, and to develop other capture technologies to compete against amine scrubbing both for cost and performance.

Post-combustion capture can be applied to coal-fired power stations but some additional measures are needed to prevent the impurities in the flue gas from contaminating the CO2 capture solvent. In many respects, post-combustion capture of CO2 is analogous to FGD, which is widely used on coal- and oil-fired power stations to reduce emissions of SO2.

Post-combustion capture might be more efficient if the concentration of CO2 in the flue gas was much higher. This is the idea behind oxyfuel firing, described below.

b. Pre-combustion capture

The low concentration of CO2 in power station flue gas means that a large volume of gas has to be handled. This results in large equipment sizes and high capital costs. A further disadvantage of the low CO2 concentration is that powerful solvents have to be used to capture CO2 and regeneration of the solvents, to release the CO2, requires a large amount of energy. If the CO2 concentration and pressure could be increased, the CO2 capture equipment would be much smaller and different solvents could be used, with lower energy penalties for regeneration. This can be achieved by pre-combustion capture.

In a gasifier, the fuel is reacted with oxygen or air, and in some cases steam, to give mainly CO and hydrogen. The CO is reacted with steam in a catalytic reactor, called a shift converter, to give CO2 and more hydrogen. The CO2 is separated and the hydrogen is used as fuel in a gas turbine combined cycle plant. The process is, in principle, the same for coal, oil or natural gas, but when coal or oil are used there are more stages of gas purification, to remove particles of ash, sulphur compounds and other impurities. Similar to post-combustion technologies, application of pre-combustion capture is likely to lead to a 6-8% points on efficiency. This needs to be addressed.

Although pre-combustion capture involves a more radical change to the power station design, most of the technology is already well proven in ammonia production and other industrial processes. One of the novel aspects is that the fuel gas fed to the gas turbine is essentially hydrogen. It is expected that it will be possible to burn hydrogen in an existing gas turbine with little modification but this is not yet commercial technology. Large gas turbine manufacturers are undertaking tests with the objective of establishing criteria for the combustion of hydrogen-rich fuels, particularly for turbine start-up and shutdown where hydrogen flame control is important and challenging.

The hydrogen produced in pre-combustion capture processes could alternatively be used to generate electricity in a fuel cell. Fuel cells are currently not economically competitive with gas turbines, but they may become more competitive in future, particularly for small-scale distributed power generation. The technology of capture and storage is therefore expected to be suitable for future as well as current power generation technologies.

c. Oxyfuel firing

Oxyfuel firing involves burning fuel in an oxygen/CO2 mixture rather than air to produce a CO2 rich flue gas. The oxygen is derived from an air separation unit and the oxygen/CO2 mixture is produced by recirculating some flue gas to the combustor. The oxygen/CO2 mixture is needed to control flame temperature, which would be too high if combustion took place in pure oxygen. Some novel processes seek to avoid the need for the cryogenic air separation unit, which has a high-energy demand. For example chemical looping uses a metal oxidation reaction to separate oxygen, with subsequent reduction of the metal oxide to provide the oxygen needed to burn the fossil fuel. Oxy-fuel combustion can be applied to boilers and gas turbines, although a different design of gas turbine would be needed to work with highly concentrated CO2, which rules out retrofit to existing GTCC stations.

Oxy-fuel combustion produces a highly CO2 enriched flue gas that in principle enables simple and low cost CO2 purification methods to be used. Also, because combustion occurs in a low nitrogen environment, the formation of nitrogen oxides (NOx) is greatly reduced. The advantage of oxygen-blown combustion is that the flue gas has a CO2 concentration of typically >90%, compared to 4-14% for air-blown combustion, so only simple CO2 purification is required. Disadvantages are that current forms of oxygen production are expensive in terms of capital cost and energy consumption, as well as the requirement for high temperature materials.

Capture technologies include solvent scrubbing, cryogenics, gas separation membranes and adsorption. The near-term priority is to reduce the penalty of using CO2 capture in power plant. In the case of absorption technology there is scope for the development of improved solvents, starting at the laboratory scale and leading to demonstration. Improved separation processes (e.g. membranes or cryogenic separation) and novel concepts (e.g. enriched oxygen combustion or a combined reactor/membrane separator for the decarbonisation of fuel gases) should also be investigated. Development of more efficient, low-cost oxygen separation processes, such as ion transport membranes, could greatly reduce the overall cost of CO2 capture. Process integration could also provide significant cost and performance improvements. Small footprint systems would facilitate retrofit to existing plants.

5.4 Distributed Generation technologies

Distributed Generation (DG) technologies in this report include mini genaration (<50MW), but exclude microgeneration (<10kWe) and renewable generation, which are captured in other ITI Energy studies. To meet the challenges for increasing the amount of electricity supplied from DG, R&D needs to be focused on:

- **Decreasing costs**. At present, the cost per unit of electricity supplied from the various DG technologies is not competitive with the cost from large-scale grid-based generation. Further development to improve electric and overall efficiency, to reduce the capital cost, or to reduce operating and maintenance cost will facilitate increased penetration of DG.
- **Reduced emissions**. Fossil fuel-based DG technologies (e.g. turbines) are inherently less efficient than their larger-scale counterparts. The specific cost of emissions reduction is higher. Particular attention to NOx control.
- Increased flexibility. Where DG plants are used for CHP, there is a need to increase the flexibility of electrical output (versus heat output) to meet demand.
- **Operations and maintenance**. Economies of scale mean that costs assigned to operation and maintenance of DG is high relative to large-scale power generation plant. Technologies and designs that reduce (unscheduled) maintenance requirements, monitor operations, or reduce the cost of repair or upkeep can help to bring the overall O&M cost down. An additional area of investigation is in remote diagnostics and control.
- **Distribution systems**. An important factor that will have a significant impact on DG uptake is the way in which DG is integrated into distribution systems. There is much scope for evaluating the impact of increased DG on the design requirements for distribution systems, including metering and local power management solutions.

Improvements in product performance or cost tend to filter down from other industries:

- Improvements in reciprocating engines tend to originate in transport applications.
- Improvements in large-scale gas turbines or aero turbines filter down into DG scale turbines.
-

This said, there are unique elements to the operation of these technologies in DG applications, for instance: remote and un-manned operation, high load factors in CHP mode and part load operation.

For microturbines and fuel cells, the designs and technologies are being designed with DG applications in mind from the outset. Hence there are more opportunities to influence the development of these technologies in response to the needs and potential for growth in DG applications.

5.5 Nuclear

The key drivers for technology development in nuclear power generation are:

- Plant life extension
- Safety
- Nuclear Waste Management and Decommissioning
- Improving efficiency, uptime and CBM

5.5.1 Plant Life Extension

It was possible to significantly extend the working lives of the first generation Magnox nuclear stations by expert technical assessment that included mechanical and physical assessment of specimens taken from the cores of the reactors. This required the availability of technical experts and highly specialised nuclear facilities. Much of this work was carried out at Berkeley and Harwell nuclear laboratories. These facilities are no longer available and many of the experts have been dispersed, however this capability, together with a set of diagnostic tools (e.g. neutron embrittlement), will be required for life extension assessments. Also, there may be technologies that can be deployed that allow old stations to be upgraded to current standards, including monitoring. Lastly, the potential for retrofit of new stations in existing plants needs to be investigated.

5.5.2 Operational / Safety issues

Operation and safety are primary issues for all countries that operate or plan to operate nuclear power plants. The approach taken by the UK HSE illustrates the areas to be covered:

HSE safety areas:	
• Plant Life Management o Steel components o Civil Engineering	• Chemical Processes
• Fuel and Core	• Radio-nuclides
• Nuclear Physics	• Plant Modelling
• External Events	• Control and Instrumentation
• Human Factors	• Probabilistic Safety Assessment
• Radiological Protection	• Waste and Decommissioning
• Nuclear Systems and Equipment	• Graphite

The HSE Programme is aimed at general issues of nuclear safety. Nuclear plant operators carry out their own work to improve operational efficiency and plant specific issues. In new build plants, the application of passive safety systems is now preferred. These systems must be designed to operate in fail-safe mode under all conditions.

5.5.3 Nuclear Waste Management and Decommissioning

The satisfactory long-term disposal of radioactive wastes generated by the operation and decommissioning of nuclear power stations is a key issue for the public acceptability of nuclear generation.

While modern nuclear plant is now built with decommissioning in mind, the early nuclear programme worked in a very different environment with the result that plant design and operational information are more limited.

Currently High Level and Intermediate Level wastes are stored at various locations. All aspects of the disposal of radioactive wastes including, geology, chemistry and physical containment of wastes have been intensively investigated over the years. Nevertheless, if specific routes are recommended, further work may be required to robustly demonstrate that these are adequate and provide public reassurance that they are acceptable.

The decommissioning of a large number of nuclear reactors and other nuclear facilities is furthermore generating a very large volume of Low Level Waste. Over a timescale in excess of 100 years a wide variety of plant will have to be decommissioned ranging from large-scale power and research reactors and fuel processing plants to small-scale manufacturing and experimental facilities. This will involve the development of innovative solutions requiring, according to the UK Committee on Radioactive Waste Management (CoRWM):

- Scientific, technical and engineering services.
- Advances of basic science and technology.
- Adaptation of technologies from areas outside of the nuclear industry.
- Knowledge of regulatory and environmental issues.
- Business experience of building and maintaining strong safety cultures and managing large and complex programmes.

For example, the damaged unit at Chernobyl Nuclear Power Station is being decommissioned. To do this an international effort costing many billions of US dollars, is building a large concrete housing at a location adjacent to the power station. The housing will be moved on rails into a position to completely encapsulate the damaged unit. When complete, the housing will be the largest man-made moving structure. In this type of undertaking, there are enormous challenges to reducing costs and developing technology, whilst maintaining the most rigorous safety levels.

5.5.4 Improving efficiency, uptime and CBM

As a base load technology, nuclear power plants need to improve their availability by reducing outages. The application of condition-based monitoring can improve reliability and contribute to minimising downtime significantly. Examples of CBM that could be explored are the development of wireless chips that may be used to monitor rotating plant, core conditions and fuel conditions. In the decommissioning phase, non-intrusive wireless CBM could also be used to monitor radiation in the core.

Improving the efficiency of the 'steam side', i.e. of the steam raising plant, the steam turbine and the heat exchanger, could markedly improve efficiency. Similar to PF technology, this is dependent on the development of new materials that can tolerate high temperatures and pressures.

5.6 Enabling technologies

The ongoing advancements in fundamental sciences, like physics and chemistry, have over the years resulted in a number of “enabling technologies”. These enabling technologies can form the basis for technology developments in a whole range of industries and applications, including energy. Enabling technologies that have come to the fore over the last years include high temperature superconductivity, nanotechnology, information technology, semiconductor technology, catalysts, membrane technology and many other enabling technologies. However, in this report we focus on the two technologies that we believe will have the largest impact on CPG: Advanced Materials & Coatings and Condition Based Monitoring.

5.6.1 Advanced Materials & Coatings

Plant performance is often restricted by materials limitations, preventing it meeting the exacting standards required. There are many activities ongoing worldwide to develop the advanced materials required for the power generation plant of the future. Advanced materials are materials or materials systems (e.g. combined alloys with coatings) that improve the efficiency and reduce the environmental impact of power plants. They may be either newly developed or traditional materials in a new application, i.e. the term 'advanced' relates to the application as much as to the materials themselves.

These materials range from ferritic alloys for boilers to ceramics for filter elements or coatings for the protection of gas turbine blades. They are the result of extensive research programmes, supported by the necessary long-term mechanical and environmental performance data. As indicated in a recent technology status report on advanced materials undertaken for the DTI, current priorities for fossil fuel-fired power plant covers three main R&D areas:

- High temperature materials for boilers, steam turbines, gas turbines, gasifiers, high temperature heat exchangers, as well as functional materials such as sorbents, catalysts and membranes;
- Protective systems/coatings for the same technology areas as high temperature materials; and
- Modelling of materials processing, component manufacture and life assessment.

The in-service performance and durability of these materials is fundamental to the reliability of power plants, which directly impacts on the cost of electricity. Improved materials and fabrication methods provide opportunities to reduce plant manufacturing costs as well as providing for many spin-off applications in other industrial sectors.

a. Boilers

- T23 and 7CrMoVTiB1010 appear to be the most likely materials of choice for the waterwall tubes in super-critical plant operating up to 625°C and 325 bar, but stronger materials will be required for higher steam conditions. The candidate materials at the most advanced stage of development at present are P92, P122 and E911, but all three currently require post-weld heat treatment during fabrication.
- Current materials are available for the manufacture of steam separating vessels for steam conditions of up to 625°C and 325 bar. Where limitation of wall thickness criteria apply, stresses in the walls of these components may be reduced to acceptable levels by increasing the number of separators and reducing their duty. Stronger materials will be required for operation above 625°C and 325 bar, with T91/P91 being a strongly favoured candidate.
- Austenitic stainless steels which possess adequate creep rupture strength and fireside and steamside corrosion resistance are available for use in the final super heater tubes of advanced PF-fired plant operating with steam parameters up to 290bar/580°C, provided the inherent flue gas corrosivity (Cl content) is low. However, it is unlikely that the fireside corrosion resistance of these steels will be sufficient to operate much above 620°C.
- More highly alloyed steels are under development, which may allow operation at steam temperatures of up to 630°C. However, more work is required to extend the creep rupture data for these steels out to longer times and longer-term fireside corrosion data, collected under more realistic conditions, will be required before these materials can be used with any degree of confidence.
- ASTM/ASME approval P92 and P122 should allow construction of thick-section components and steam lines for advanced PF-fired plant operating with steam parameters of up to 325bar/610°C. However, welds in thick-section headers and pipework are likely to be susceptible to Type IV cracking and allowable stresses will ultimately be limited by the need to account for this phenomenon. Similar consideration will also need to be paid to the performance of transition joints.
- The higher creep strength of the austenitic steels and the somewhat lower metal temperatures expected in headers and pipework mean that less expensive grades such as X3CrNiMoN1713 with lower chromium contents, can be considered.

b. Steam turbines

To reduce the 10-12 years development time often required before a material enters commercial service, computer-aided design is used as a major development tool. However, models are not yet sufficiently accurate or robust to remove the need for long-term testing.

The major emphasis of development is focused on improved materials for high temperature cylinders. According to the DTI report, the following are required to support development:

- Modelling of microstructural evolution of oxidation during processing and in service and of the behaviour of oxidation-resistant coatings.
- Test capacity for short and long-term mechanical property characterisation, covering creep testing, low cycle fatigue and cyclic hold testing, fracture toughness testing, creep crack initiation and growth testing.
- Test capacity for environmental (steam oxidation) testing, including the influence of thermal cycling on oxide layers and coatings.
- Manufacturing capacity for trial melts and more significantly for prototype components including weldments where appropriate.
- Capacity for development of welding consumables.
- Capacity for coatings resistant to steam oxidation.

c. Gasifiers

In advanced coal gasification systems, there are a number of unique critical components in the hot gas path, for example, the fuel gas cooler, hot gas filter and gas ducts. Materials for these components need to have adequate, reliable and have predictable lives. From a process perspective, the duties are similar to those of a pulverised coal boiler and so similar materials would be applied if the fuel gas environment was not so aggressive. Once generated, the fuel gases need to be cooled and cleaned before being burnt in gas turbines. The heat exchanger to cool the raw fuel gas is generally the first major component downstream of the gasifier vessel. Gas coolers can be either 'water-tube' or 'shell-boiler' in type, depending on the required duty in terms of water/steam temperature and pressure. Most now use the cheaper shell-boiler approach, which is suitable for modest steam conditions but increases the risk of fouling and blockages of the gas.

In the gas cooler, the presence of particles cause erosion, abrasion or deposition, while gaseous species (e.g. H_2S, COS, HCl) cause corrosion and further deposition through the condensation of vapour-phase species such as alkali and trace metal chlorides/sulphides. The performance of materials in various simulated and real coal-gasification gases have been investigated for more than 25 years. The initial generic studies investigated the performance of materials in a range of highly reducing atmospheres with varying levels of sulphidation at high temperatures. Later studies have tended to concentrate on higher alloyed materials and/or lower exposure temperature. More recent studies have been targeted at increasingly realistic exposure simulations to match the degradation morphologies observed in practise.

d. Gas turbines

Current gas turbine power generation systems are performance-limited by the alloys used for the hot gas path components for these engines. For future engine technology this will continue to be an increasing need and will only be addressed with the development of alloys capable of providing the requisite mechanical property, corrosion resistance and stability levels using cost-effective manufacturing. Further development of high strength alloys (steel and nickel based) and dual alloy technologies for compressor and turbine rotors will continue to be a priority. The development of computational tools to predict the effects of alloying additions on the phase stability, processing and properties is crucial to these objectives and to limit the excessive costs currently associated with alloy development programmes.

Low density materials (intermetallics and composites) still possess the potential to provide step-change materials solutions to reducing rotor mass, whilst enabling harder working, more efficient stages within both the compressor and turbine. Also, the thermo-physical and mechanical property characteristics of ceramic composite materials have yet to be exploited fully in providing solutions for components such as combustors. This technology is at a more advanced stage in the USA.

Developing an improved understanding of the mechanical properties and behaviour of substrates and coatings under service-representative loading conditions and environments continues to be a key requirement. Combined with these activities is the development of more advanced life assessment methods for hot section components operating under creep-fatigue-corrosive loading environments and improved methods for data analysis and database systems. This could result in more accurate lifetime prediction and thereby fuller utilisation of expensive materials and components.

Development of advanced Non Destructive Inspection (NDI) techniques and the further development of remnant life assessment and repair/overhaul methods are also required. This is particularly true for high strength fracture critical rotating parts, such as discs and shafts, and hot section components and protective coatings exposed to high temperatures for long periods. Methods for in-service inspection of, for example, thermal barriers such as optical spectroscopy that can be linked to the health and usage monitoring systems are seen as key for life-usage management.

New, improved coating systems are required that use cheaper more efficient, non-line-of-sight deposition methods, providing high integrity protection from oxidation and corrosion. Coatings capable of withstanding the aggressive environment within coal-gasification plant, as well as “smart” multi-layer coatings that modify their phase development to meet the local environment-temperature loadings are needed. In addition, future coatings will be required that can act as sensors for CBM, for example, that emit fluorescent or spectroscopic signals for life management detection systems. Improved thermal barriers are needed that are capable of providing increased thermal protection and more reliable integrity for longer periods than are currently achievable (thicker layers, strain-tolerance, reduced thermal conductivity, increased phase stability and resistance to sintering).

5.6.2 Condition based monitoring

Condition based monitoring (CBM) is an effective form of predictive maintenance where the condition of specific areas of plant and equipment is monitored. This can be done automatically with the use of instrumentation such as machinery vibration analysis and thermal imaging equipment or manually. In automatic CBM when any monitored and predefined condition limit is exceeded, a signal or output is turned on. This is particularly suited to continuous process plants such as in CPG, where plant failure and downtime is critical.

Increasing competition has forced power producers to switch from traditional time-based maintenance strategies to condition based methods, based on the plant's operating conditions.

One effect of the deregulation of electricity markets throughout Europe and beyond has been the increasing demand on the maintenance and operation of power plants. Units designed for base-load now have to cycle to meet peak demand and this has an enormous effect on their availability and reliability. A second consequence of market liberalisation is that plant availability must be maximised in order to react to price changes in electricity markets. In periods of high price, shutdowns must be avoided and it may be meaningful to use all the engineering reserves of the machine and to operate it closer to its design limits for a limited period of time, in order to tap maximum profit.

As such, the operation of the complete power plant – turbine, generator, boiler and auxiliaries must be optimised and operating requirements can be summarised as follows:

- Reliability and flexibility are vital elements;
- Maximum cycling flexibility in order to follow market demand;
- Reliable and quick ramp-up and ramp-down capabilities;
- Optimisation of component life usage;
- Extension of maintenance intervals and reduction of duration of maintenance downtime;
- Optimised proactive maintenance to reduce unplanned outage frequency and allows component change-out in next outage.

Next to this, the earlier-mentioned monitoring of emissions and of firing conditions and their influence on emissions and overall plant efficiency are key CBM elements that will need to be integrated in the overall running of operations.

Implementation of CBM Technology

The drivers for the adoption of CBM listed above create demand for technology:

- The development of software for data handling/data mining and interpretation, leading to historical statistical trending and plant control optimisation;

- The development of smart sensors, and other low-cost on-line monitoring systems that will permit the cost-effective continuous monitoring of key equipment items;
- The increasing provision of built-in vibration sensors as standard features in large motors, pumps, turbines and other large equipment items;
- Increasingly sophisticated condition monitoring software, with rapidly developing "expert" diagnosis capabilities;
- Further, this "expert" software allowing less skilled personnel to conduct "first pass" condition assessment and overcome operator conservatism in plant operation.

Most plant and equipment manufacturers have developed some form of CBM technology. However, it is envisaged that there are still significant improvements to be made in areas mentioned.

5.7 Summary of technology opportunities

Opportunities exist across the range of CPG technologies to increase efficiency or to reduce cost, whilst meeting more stringent environmental standards. In discussing the status of each of the various technologies, many of these opportunities have become apparent.

Fossil Fuels

- Increasing efficiency of power generation technologies fuelled by coal or gas. The development of 'advanced' materials, capable of operating in more aggressive environments, will be central to the success of this ambition:
  - Improve combustion efficiency
  - Develop high-temperature materials
  - Develop protective coatings for materials
  - Model effectively the impact of the operating environment on materials

- Reducing emissions of SO2, NOx and mercury. SO2 and NOx are subject to ever more stringent legislation. Mercury, important in the US, is very likely to be controlled in other parts of the world in the future.
  - Improve coal preparation to reduce sulphur content
  - Improve efficiency and operation of FGD plant
  - Reduce NOx formation during combustion
  - Better monitoring technology for mercury
  - Technologies for reducing mercury emissions
  - Integrated multi-pollutant control

- CO2 capture. The focus is on capture technologies, their application to combustion and gasification plant and the impact on the future mix of PF, oxyfuel firing and gasification.

- CO2 capture technologies. Regenerable sorbents, membranes and other novel processes
- Impact reduction of other species, eg SO2, on capture technologies
- Design of capture plant and scaling-up issues
- Integration of capture technology with main plant to reduce efficiency penalty

- Co-firing coal with biomass. Many problems need to be resolved before, say, 20% thermal input of biomass can be reached.
  - Transport, handling and milling of biomass
  - Preparation for combustion and gasification
  - Consistency of chemical and physical properties
  - Address corrosion of plant due to use of biomass

- O&M improvements. Condition-based monitoring can make a much greater contribution to planning. CBM, located strategically, where the environment is particularly aggressive, would preclude the need for frequent inspection, which has previously been the option to reduce catastrophic events.
  - Develop condition-based monitoring equipment
  - Develop software for data interpretation
  - Develop self diagnosis capabilities

- Combustion of hydrogen. For gasification, hydrogen may be the fuel of the future. Modifications to current standard machinery are likely. Operating conditions are also likely to be different.
  - Model H2 combustion in gas turbine combustors
  - Establish conditions for effective and efficient combustion

Nuclear

- O&M improvements. To be more economically competitive, nuclear power plants typically operate at base load. Effective condition-based monitoring would preclude the need for frequent inspection and contribute ultimately to extended life of the plant.
  - Develop passive safety systems
  - Develop smart sensors to allow power plant to base load operation
  - Develop software for data interpretation
  - Develop self diagnosis capabilities

- Waste. More effective or novel processes to treat high and low level waste products from nuclear plant would be of great value. Development might also be undertaken on automated techniques for waste handling.
  - Solutions for publicly acceptable means of long-term storage of nuclear waste
  - Novel solutions to reduce problems associated with nuclear waste

6 INTELLECTUAL PROPERTY LANDSCAPE

Many of the core CPG technologies have been around for a long time and have seen continuous, incremental developments as well as more fundamental breakthroughs. As a result, most technologies are well understood and the Intellectual Property (IP) landscape is likely to be crowded, potentially leaving less fruitful ground for new, commercially useful IP. On the other hand, recent developments have created a demand for new technologies.

Because of the breadth of technologies that are relevant to CPG, resulting in many thousands of patents, registered methods and other IP protection mechanisms, it is impossible to provide a comprehensive overview of the IP landscape. Instead, this chapter, intends to give an example of how ITI Energy can analyse a more specific technology development area. The examples chosen are in the area of treatment of emissions from fossil fuels.

6.1 Benefits of IP landscaping

Arguably the most powerful IP right for a technology-based company is the patent, which, in return for public disclosure of one’s invention, confers time- and geographically-limited rights on the patent owner (patentee) to prevent others from, for example, manufacturing a patented material or copying a patented process. This can clearly give a tangible competitive advantage to the patentee.

Prior to embarking on any technical research project, it is wise to undertake a review of relevant existing patents, as:

- It avoids ‘re-inventing the wheel’
- It can provide information on competitor activity
- It can assist in the inventive process itself

IP landscape analysis can assist in giving insight into the competitive landscape in a specific technical field. For example, a focussed patent search can reveal information on similar work by other parties of which the inventor was unaware. Furthermore, a close existing patent is a good source of technical information, and the filing strategy chosen can give an indication of the markets in which the patentee wishes to exploit his invention.

6.2 IP landscaping software tools

Rather than ploughing through thousands of databases and patent documents, there are a number of useful software tools in the market that can electronically search through these databases and documents. ITI Energy uses Micropatent’s Aureka™, a web-based tool.

Aureka is fundamentally both a patent search and patent information analysis tool. It can be used to find patents:

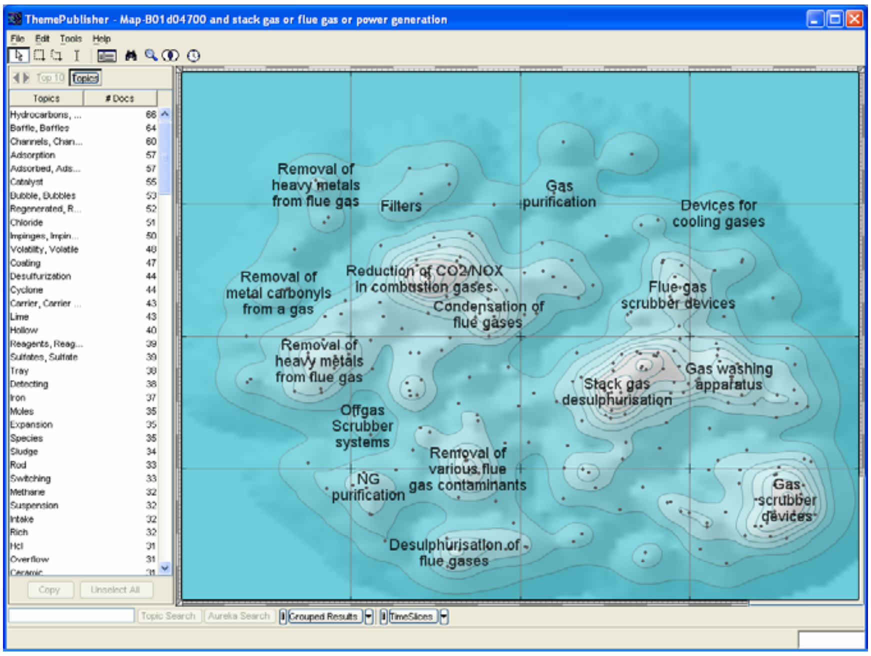
- on a particular subject,
- by a particular inventor,
- by a particular organisation,
- over a certain time period.

This produces a patent list that can be looked at in detail. Full copies of relevant patents can be printed or saved. There is also a reporting function that automatically generates reports based on the information in a selected patent list. This can give a handle on how much money is being spent on patenting in a given subject area (generally a good indication of R&D spend).

Lastly, the application can graphically plot patents on a 3-D map such that patents sharing a large number of 'topics' (considered words or catch-phrases) are situated close together on the map, and patents that share few topics are plotted far apart. On the basis that patents sharing a high proportion of topics will likely be in the same technical area, the map can divide a patent list into patents in different technical areas. The map can be interrogated so as to generate new patent lists and has drill-down functionality to see the actual patent detailed wording.

6.3 Example: Emission control in CPG

In order to obtain a list that includes most relevant, whilst excluding most non-relevant patents, it is important to choose a search string of specific keywords. In this case: "stack gas" or "flue gas" or "power generation". This search string results in 296 patents. The map in Figure 6.1 below is based on this patent list.

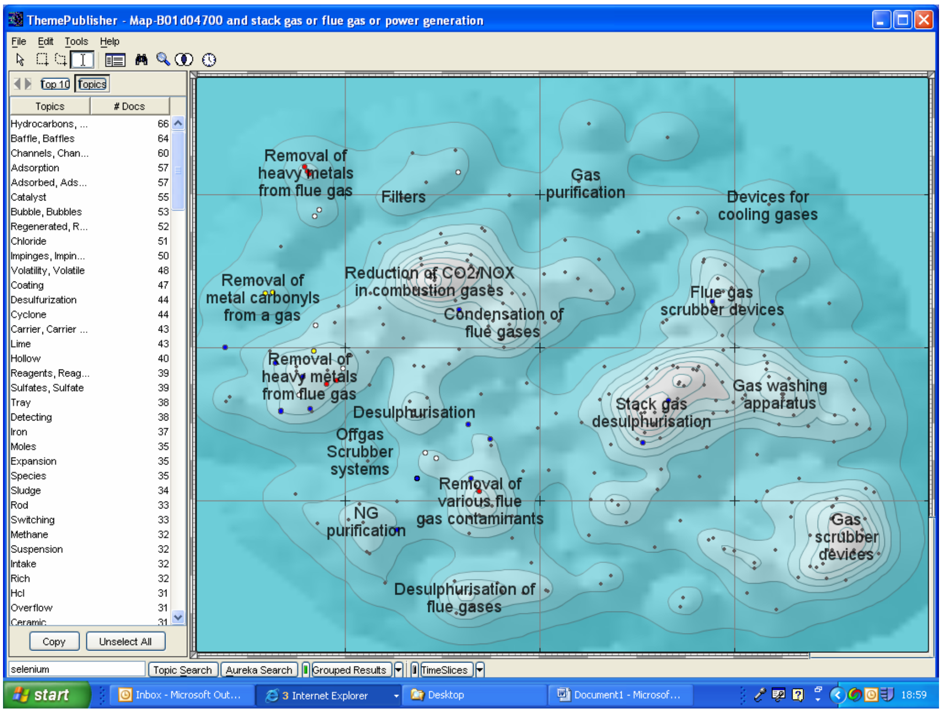


Topics	# Docs
Hydrocarbons, ...	66
Baffle, Baffles	64
Channels, Chan...	60
Adsorption	57
Adsorbed, Ads...	57
Catalyst	55
Bubble, Bubbles	53
Regenerated, R...	52
Chloride	51
Impinges, Impin...	50
Volatility, Volatile	48
Coating	47
Desulfurization	44
Cyclone	44
Carrier, Carrier ...	43
Lime	43
Hollow	40
Reagents, Reag...	39
Sulfates, Sulfate	39
Tray	38
Detecting	38
Iron	37
Moles	35
Expansion	35
Species	35
Sludge	34
Rod	33
Switching	33
Methane	32
Suspension	32
Intake	32
Rich	32
Hcl	31
Overflow	31
Ceramic	31

Figure 6.1: Aureka map for emission control patents, using key words "stack gas", "flue gas", or "power generation" (Source: ITI Analysis on Aureka™)

The areas of high patent density on the map are shown as “islands” with contours giving an indication of patent density. On the left-hand side is the topic list with the number of occurrences of each topic in the entire patent set. It is possible to label certain areas of the map according to the subject of the majority of patents in that area.

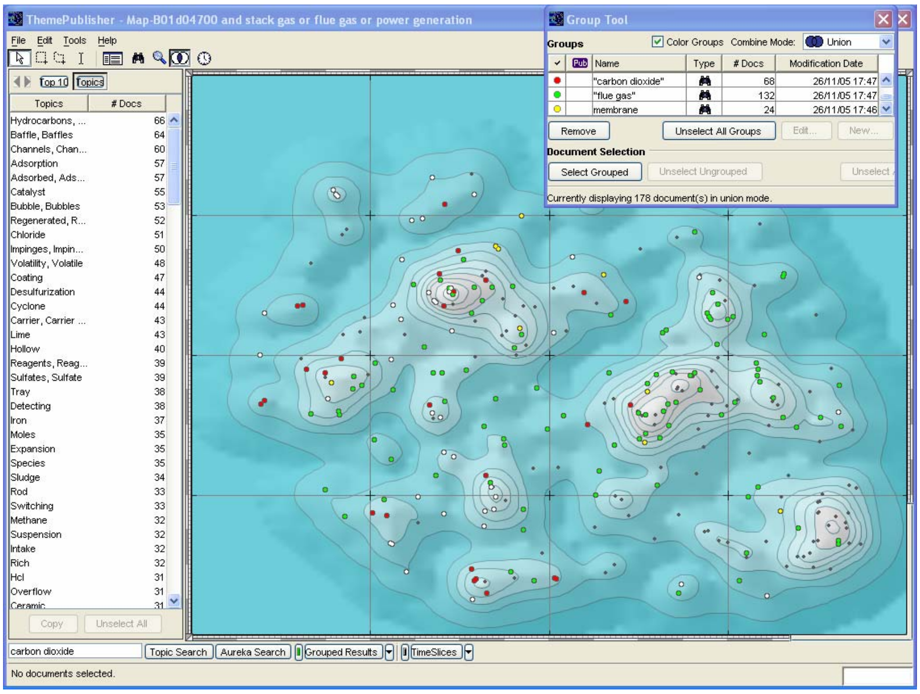
The map can be interrogated further by performing sub-searches, which highlight any patents in the map containing a certain keyword or combination of keywords. As an example, patents dealing with removal of the heavy metals mercury, cadmium and selenium are identified on the map by separately searching for these topics. In Figure 6.2, patents on “mercury” removal are highlighted in blue, those mentioning “cadmium” and “selenium” are in yellow and red respectively. A full analysis on any of the subsearch results can then be undertaken if desired.



Topics	# Docs
Hydrocarbons, ...	66
Baffle, Baffles	64
Channels, Chan...	60
Adsorption	57
Adsorbed, Ads...	57
Catalyst	55
Bubble, Bubbles	53
Regenerated, R...	52
Chloride	51
Impinges, Impin...	50
Volatility, Volatile	48
Coating	47
Desulfurization	44
Cyclone	44
Carrier, Carrier ...	43
Lime	43
Hollow	40
Reagents, Reag...	39
Sulfates, Sulfate	39
Tray	38
Detecting	38
Iron	37
Moles	35
Expansion	35
Species	35
Sludge	34
Rod	33
Switching	33
Methane	32
Suspension	32
Intake	32
Rich	32
Hcl	31
Overflow	31
Ceramic	31

Figure 6.2: Aureka map for emission control patents, subsearch
Source: ITI Analysis on Aureka™

As another example, Figure 6.3 below shows patents on the treatment of carbon dioxide from stack gases using membranes, based on a combination of separate searches using the terms: “carbon dioxide”, “stack gases” and “membrane”.



Topics	# Docs
Hydrocarbons, ...	66
Baffle, Baffles	64
Channels, Chan...	60
Adsorption	57
Adsorbed, Ads...	57
Catalyst	55
Bubble, Bubbles	53
Regenerated, R...	52
Chloride	51
Impinges, Impin...	50
Volatility, Volatile	48
Coating	47
Desulfurization	44
Cyclone	44
Carrier, Carrier ...	43
Lime	43
Hollow	40
Reagents, Reag...	39
Sulfates, Sulfate	39
Tray	38
Detecting	38
Iron	37
Moles	35
Expansion	35
Species	35
Sludge	34
Rod	33
Switching	33
Methane	32
Suspension	32
Intake	32
Rich	32
Hcl	31
Overflow	31
Ceramic	31

carbon dioxide

No documents selected.

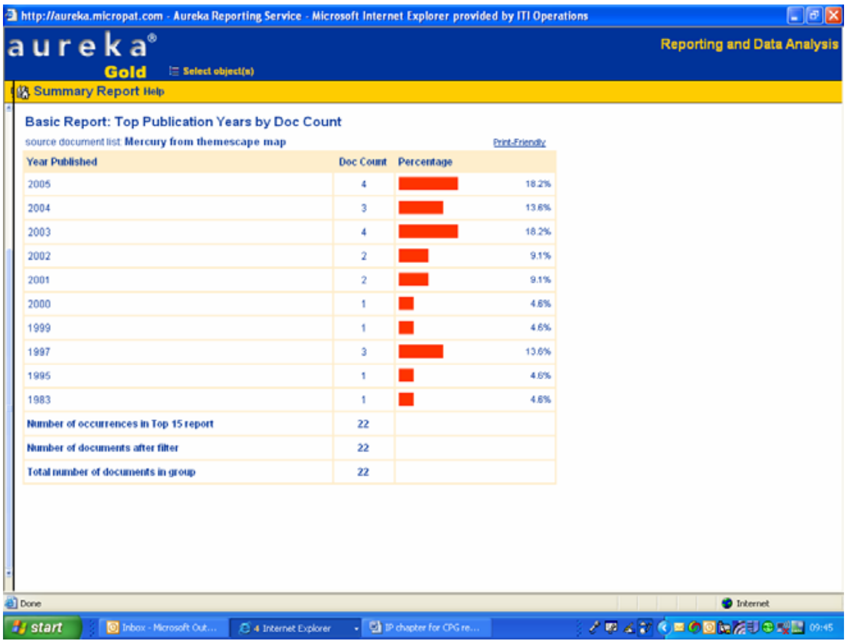
Groups ☑ Color Groups Combine Mode: Union

✓	Pub	Name	Type	# Docs	Modification Date
🟥		"carbon dioxide"		68	26/11/05 17:47
🟩		"flue gas"		132	26/11/05 17:47
🟨		membrane		24	26/11/05 17:46

Currently displaying 178 document(s) in union mode.

Figure 6.3: Aureka map for emission control patents with search strings “carbon dioxide”, “stack gases” and “membrane”
(Source: ITI Analysis on Aureka™)

Another useful Aureka™ tool is the Reporting function. This generates automated reports giving comparative information based on assignees, inventors, primary or complete IPC data, forward or backward citations or publication date, based on a defined patent list. The report for “mercury” in the above example shows document count per publication year. This can indicate any trends in patenting. In this case it can be seen there were significantly more patents published between 2001 and present, than for the period 1983-2001.



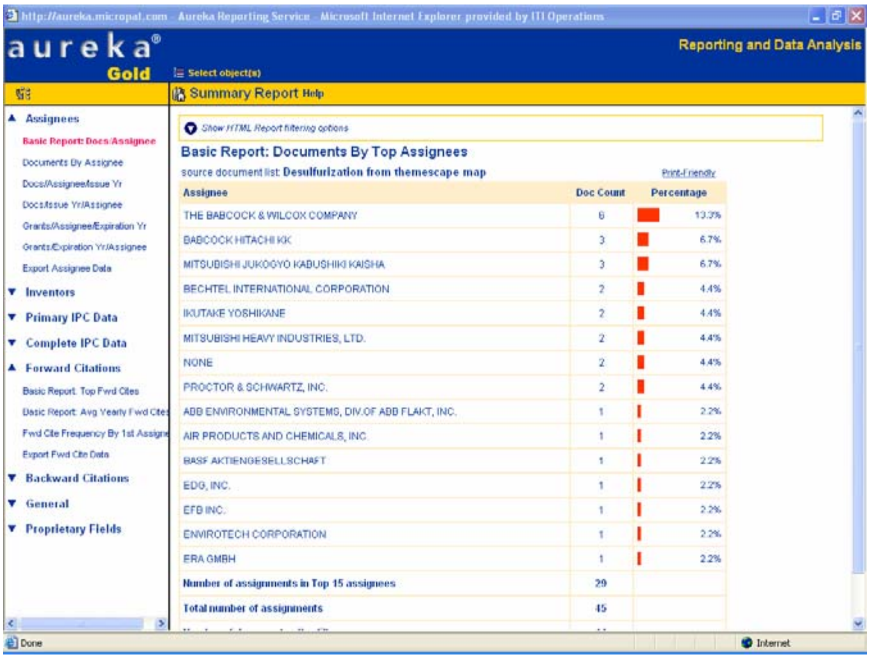
Basic Report: Top Publication Years by Doc Count

source document list: **Mercury from themescape map**

Year Published	Doc Count	Percentage
2005	4	18.2%
2004	3	13.6%
2003	4	18.2%
2002	2	9.1%
2001	2	9.1%
2000	1	4.6%
1999	1	4.6%
1997	3	13.6%
1995	1	4.6%
1983	1	4.6%
Number of occurrences in Top 15 report	22	
Number of documents after filter	22	
Total number of documents in group	22	

Figure 6.4: Aureka report example on "mercury"
(Source: ITI Analysis on Aureka™)

Another report shows the top 10 assignees in a given patent set. The relative numbers of patents to each of these can give an indication as to whether the market is made up of a few big players or not. An example of this is from a report created using a patent list comprising patents containing the keyword "desulphurisation" from the map. The report in Figure 6.5 shows that the Babcock & Walcox Company is the assignee with the greatest share of patents in the list.



Basic Report: Documents By Top Assignees

source document list: **Desulfurization from themescape map**

Assignee	Doc Count	Percentage
THE BABCOCK & WILCOX COMPANY	6	13.3%
BABCOCK HITACHI KK	3	6.7%
MITSUBISHI JUKOGYO KABUSHIKI KAISHA	3	6.7%
BECHTEL INTERNATIONAL CORPORATION	2	4.4%
IKUTAKE YOSHIKANE	2	4.4%
MITSUBISHI HEAVY INDUSTRIES, LTD.	2	4.4%
NONE	2	4.4%
PROCTOR & SCHWARTZ, INC.	2	4.4%
ABB ENVIRONMENTAL SYSTEMS, DIV.OF ABB FLAKT, INC.	1	2.2%
AIR PRODUCTS AND CHEMICALS, INC.	1	2.2%
BASF AKTIENGESELLSCHAFT	1	2.2%
EDG, INC.	1	2.2%
EFB INC.	1	2.2%
ENVIROTECH CORPORATION	1	2.2%
ERA GMBH	1	2.2%
Number of assignments in Top 15 assignees	29	
Total number of assignments	45	

Figure 6.5: Aureka report example on "desulpherisation" (Source: ITI Analysis on Aureka™)

6.4 IP Conclusions

This chapter does not intend to provide a comprehensive overview of the IP landscape for Conventional Power Generation. Instead it shows that a detailed analysis of the IP landscape for a specific technology area can provide very useful insights into the technical status quo, the 'hot' areas and the competitive situation.

When looking into specific CPG opportunities in more detail, ITI Energy has applied this analysis to improve its understanding of the commercial feasibility and risks related to the technology development.

7 INVESTMENT STRATEGY

ITI Energy must strive to optimise the impact of its investments on the Scottish economy. As such, we have analysed the market and technology developments and the commercialisation routes for conventional power generation technologies. Below are a number of considerations and our resulting conclusions.

- The core CPG technologies (gas turbines, reciprocating engines, steam turbines) have been around for many years and can now be classified as mature technologies. Further technical improvements are likely to be incremental rather than disruptive.
- On the other hand, however, a number of drivers (environmental, security of supply, DG, etc.) have created demand for a step improvement in technology to economically reduce emissions, provide alternatives to central gas-based generation, whilst continuing to generate power reliably and at acceptable cost.
- The industry is dominated by a relatively small group of large manufacturing companies, with their own R&D facilities, resources and budgets.
- However, there are also a large number of SMEs supplying into these manufacturers, who could benefit from R&D support.
- Globally, there are many sizeable R&D grants available (e.g. DTI, EU, USA) for energy generation technologies. These can be viewed as competition for ITI Energy, or as an opportunity to leverage ongoing research efforts.
- The immense generation capacity increases that are required, particularly in the Far East, have created a risk taking attitude locally towards testing and installing new technologies. This is in sharp contrast with the Western highly regulated and HSE-driven attitude.

As a result ITI Energy believes that it should not focus on technologies that simply offer incremental improvements to existing systems. Instead, focus should be given to enabling technologies that can be applied to create step-change efficiency and emissions improvements.

In collaborating with industry, ITI Energy will focus its efforts as indicated in Figure 7.1.

We will encourage universities, particularly Scottish ones, to come forward with novel ideas that are aligned with the opportunity areas outlined in this report. Furthermore, we will encourage collaborations with Scottish and other globally leading university departments.

Similarly, ITI Energy will look at other (private sector) Scottish R&D organisations to provide new ideas and we will look at globally leading capability to help.

Working with established manufacturers and other large corporates, collaboration efforts will be more aimed towards testing & demonstration and to build an efficient channel into the market.

Collaboration with Small and Medium Sized companies (SMEs) will be important in all aspects of product development and commercialisation. ITI Energy will aim to involve SMEs in its programmes.

Utilities are the ultimate buyers of the new CPG technologies and as such we aim our collaboration efforts with utilities in the early stages to test ideas and design concepts and to increase the utility involvement in the testing, demonstration and commercialisation phases.

Organisation	Generating new ideas	Resarch & Development	Testing and demonstration	First product customer
Universities	☻ ☻ ☻	☻ ☻ ☻		
Research organisations	☻ ☻ ☻	☻ ☻ ☻	☻ ☻	
Established manufacturers	☻	☻	☻ ☻ ☻	☻ ☻ ☻
SMEs	☻ ☻ ☻	☻ ☻ ☻	☻ ☻	☻
Utilities	☻	☻	☻ ☻	☻ ☻ ☻

Figure 7.1: Intended focus for collaboration
(Source: ITI Energy analysis)

8 CONCLUSIONS & RECOMMENDATIONS

This foresighting exercise has provided ITI Energy with many points of view on the applicability of, and need for new CPG technologies. To summarise briefly, the following arguments have driven ITI Energy to its recommendations:

- Power demand will continue to rise significantly over the next 25 years and most of this demand will be met by CPG technologies.
- The recent nuclear debates in some countries could result in a renaissance of nuclear power generation. This will require (new) solutions for inherently safe plants and for waste and decommissioning.
- Many countries are increasingly opting for higher levels of distributed generation and some of this capacity will be met by CPG technologies. DG technologies need to become more efficient in overall cost and in emission reductions.
- The core CPG technologies are mature technologies. Further technical improvements are likely to be incremental rather than disruptive.
- A step improvement in technology is required to economically reduce emissions and to provide alternatives to central gas-based generation
- The industry is made up of a relatively small group of large manufacturing companies, and a large number of SMEs supplying into these manufacturers.
- The risk averse attitude towards introduction of new technologies in the west is contrasted by a much higher acceptance of risk in China and other eastern countries.
- The ITI Energy budget available for investment in CPG technologies is limited when compared to the budgets that are required for some developments (e.g. new generation of gas turbines) or that are available by other means, such as EU grant schemes.

In drawing its conclusions, ITI Energy has taken into account information and analysis gathered from industry experts, events, other reports and background reading. During a second workshop that was attended by 12 industry experts, the original longlist of technology opportunities was further qualified and reduced to the 29 opportunities provided in Figure 8.1.

The ITI Energy team subsequently ranked these 29 opportunities by discussing them in turn and then giving them a rating High (H), Medium (M), or Low (L) for each of the criteria:

- **Market**: Size and ease of the available market and speed to adoption
- **Technology**: Feasibility of the technology
- **IP**: Strength of IP / potential barriers

The results of this rating exercise are also depicted in Figure 8.1.

Area	Technology Opportunity	Market	Techn	IP
Gas				
1	Hydrogen fired gas turbine	M	L	L
2	Dual-fuel multi-burner	M	L	L
Emissions				
3	Retrofit of amine scrubbing	M	L	M
4	Low cost Sorbents for amine scrubbing	H	M	M
5	Membranes for amine scrubbing, NG fuel, CO2 flue gas, pure O2 manufacturing	H	M/H	H
6	Materials that can withstand high stresses in Oxyfuel burners	L	L	L
7	Coatings to prevent oxidation at hight T for Oxyfuel burners	L	L	L
8	Combined emission scrubbing (other than CO2) for particulates and metals	H	M	H
9	Fuel pre-treatment (e.g. microbial)	H	?	L
10	Alternative process that optimises combined (CO2 and other) emission reduction	H	M	L
Co-firing				
11	Multi-burner (optimise the process, using feedback from the burner)	M	M/H	M
Coal				
12	Solid waste opportunities	L	L	M
13	Pulverised Coal at 700C – materials	H	M	H
14	Pulverised Coal at 700C – components	H	H	M
15	Pulverised Coal at 700C - plant design	L	L	L
Distributed Generation				
16	DG use of standard aerospace turbines	L	L	L
17	DG Emission - making it economic (for 'mini' generation (1-5MW) in medium term and 'micro' (<1 MW) in longer term)	M	H	H
18	DG Operations and Maintenance	H	M	H
Operations & Maintenance				
19	Ensure ramp rates and cycling are not detrimental to asset life - low cost instrumentation (sensors/comms)	H	M	M
20	Ensure ramp rates and cycling are not detrimental to asset life - data handling and interpretation	H	H	M
Enabling Technologies				
21	Smart coatings, e.g. that include sensors	M	M	H
22	Solutions that allow a better understanding of the material state at mulecular level (e.g. MRI alternative)	M	H	M
23	Low cost, high temperature sensors (wireless comms)	M	H	H
24	Alternatives to super alloys – coatings & pipelines	H	H	M/H

Area	Technology Opportunity	Market	Techn	IP
25	Corrosion prevention, particularly in small scale turbines	L	M	M
Nuclear				
26	Condition Based Monitoring for rotating plant and fuel conditions (radiation measurements)	M/H	M	L
27	Nuclear waste volume reduction	H	L	L
28	Monitoring of decommissioning (radiation)	M	L	L
29	SiC and/or GaNitrite for power electronics	M	H	L

Figure 8.1: Qualified and Reviewed List of Technology Opportunities, Prioritised by ITI Energy (Source: ITI Energy analysis)

In addition to the above ranking, we considered in how far Scottish capability could be created in the development of these new technologies and where ITI Energy could make a material difference. From this assessment, the technology opportunities have been categorised ‘A’, ‘B’, or ‘C’ as follows:

Category (A): The principal focus of ITI Energy effort and financial commitment in CPG technologies will be on opportunities in this category.

Category (B): Although opportunities in this category are of particular interest and ITI Energy may commission research and market assessments for opportunities in this category, this will not be a main focus for ITI Energy at this time.

Category (C): ITI Energy will respond to parties to bring forward specific project proposals.

		PROACTIVE		**REACTIVE**
		A) Pursue Specific Projects	**B) Explore Possibilities & seek 3rd Party Proposals**	**C) Respond to 3rd Party Proposals**
5	Membranes	🟦		
24	Alternatives to super alloys – coatings and pipelines	🟦		
8	Combined emission scrubbing		🟦	
11	Multi-burner for co-firing		🟦	
13	HT pulverised coal – materials		🟦	
14	HT pulverised coal – components		🟦	
17	DG emissions		🟦	
18	DG Operations and Maintenance		🟦	
20	Ramp rate and cycling management – data management		🟦	
23	Low cost HT sensors		🟦	
	Other 19 Technologies			🟦

This categorisation is based on a thorough analysis. It forms ITI Energy's judgment at this point in time. ITI Energy recognises that external forces may change and that new ideas will emerge, that may change the above prioritised list of opportunities. We therefore remain open to 3rd parties bringing forward proposals in areas outside the list of opportunities.

For further information on this study or ITI Energy, please contact Chris DeGoey, Acting Director, Technology & Markets on +44 (0)1224 701207 or email chris.degoey@itienergy.com.

APPENDIX 1 – KEY REFERENCES AND CONTRIBUTORS FOR THIS STUDY

REFERENCES

Reference materials used for this study include:

- IEA World Energy Outlook 2004, ISBN 92-64-10817-3 (2004)
- IEA World Energy Outlook 2005, ISBN 92-64-10949-8 (2005)
- TSR012, Flue Gas Desulphurisation Technologies, DTI Pub URN 00/652
- TSR013, CO2 Capture and Storage, DTI Pub URN 00/1081
- TSR018, Review and Status of Advanced Materials for Power Generation, DTI, Pub URN 03/692
- TSR020, Monitoring and Control of Trace Elements, DTI Pub URN 04/590
- The APGTF Carbon Abatement Strategy green paper: “A vision for clean fossil power generation”, 2004
- Scottish Enterprise: “Carbon Capture and Storage Market Opportunities, 2005”
- DTI Energy White Paper

WORKSHOP PARTICIPANTS

ITI Energy would like to acknowledge all companies and individuals that have contributed to this foresighting study. The following individuals have participated in the two workshops:

No	Name	Organisation
1	Gerhard Brandt	ABB
2	Colin McNaught	AEA Technology Future Energy Solutions
3	Keith Burnard	AEA Technology Future Energy Solutions
4	George Marsh	AEA Technology Future Energy Solutions
5	Jonathan Perks	AEA Technology Future Energy Solutions
6	Nick Otter	Alstom Power Technology
7	Allan Shuttleworth	Atkins Power
8	Jeremy Staines	BE – Nuclear
9	Paul Howarth	BNFL
10	Roderick Wilkie	Cadogan Consultants
11	Craig F Passe	CESI Power Generation
12	Makato Watanabe	Choyoda Corporation
13	John Oakey	Cranfield University
14	Rod Jones	Dundee University

No	Name	Organisation
15	Robin Irons	E.ON UK
16	Thierry Paturle	EDF
17	Pierre Dechamps	European Commission, Energy Production and Distribution Systems
18	Richard Kendal	Firth Rixon
19	Edward Angus	Fuel Cells
20	Gordon Lindsay	Fuel Cells
21	S.J. Finney	Heriot Watt University
22	Bert Dunwoody	Howden Power
23	Anne Bruce	Industrial & Power Association
24	Charles Shields	Industrial & Power Association
25	Dimitri Mignard	Institute for Energy Systems
26	Gareth Swales	IPA Energy Consulting
27	Giorgio Dodero	IPG Industrial Projects Group
28	Graham Wellford	Mitsui Babcock
29	Mike Farley	Mitsui Babcock
30	Richard Dennis	Mitsui Babcock
31	Stuart Mitchell	Mitsui Babcock
32	J.L. King	Mitsui Babcock
33	David Noonan	Mott MacDonald Ltd
34	John Cherrie	Mott MacDonald Ltd
35	Tony Box	Optimat Ltd
36	Robert Marshall	Robert Marshall & Associates
37	Brian Nixon	Scottish Enterprise
38	Stuart McKellar	Scottish Power
39	Rob Williams	SKF
40	Alberto Moioli	Tenaris Process & Power Plant Services
41	Keith Pinfield	TUV NEL Ltd
42	Leon Youngs	TUV NEL Ltd
43	Robert Holmes	TUV NEL Ltd
44	Paul Mitchell	University of Aberdeen
45	John Howell	University of Glasgow
46	Katherine Kirk	University of Paisley
47	John Irvine	University of St Andrews
48	John Spence	University of Strathclyde
49	Giancarlo Sioli	Wartsila

In addition the following companies provided information via their representatives at the PowerGen conference in Milan in June 2005:

- ABB Power Technologies
- Alstom Power
- Ansaldo Energia
- Babcock Power Espana
- E.ON
- Foster Wheeler Power Group
- GE Energy
- Hitachi Europe
- KEMA
- MAN Ferrostaal Power Industry
- Mitsubishi Heavy Industries
- Siemens Power
- USDOE
- Wartsila Finland