Advanced Technologies Applicable to Fossil Fuels: Cross-cutting Technologies and Carbon Capture/Storage

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1. The Technologies

Cross-Cutting Technologies

Ongoing Efficiency Improvements in Electricity Production

Increasing efficiency in the use of energy in electricity production, associated in large part with improvements in gas technologies (particularly combined-cycle gas turbines, where efficiencies could rise from the current state-of-the art 55% to 62% over the coming decades), and anticipated improvements in the efficiency of coal-fired power plants, up from the present 34% to more than 50% in the medium-to-long term (IPCC 1996)), the increasing importance of CHP technologies, and improved process control through the use of advanced sensors and electronics in energy production, will be an important energy-saver, along with further improvements in the efficiency of electricity transmission (innovation in power electronics) leading to fewer energy losses.

Combined Heat and Power

Combined heat and power (CHP) is one of the most promising technologies for the near-term reduction of greenhouse gas emissions. It involves the joint production of heat (steam) and electricity. Both the heat and the electricity can be used on site, or surplus electricity can be sold back to the grid and surplus heat can be used in district heating (DH) and community energy systems.

There are substantial thermodynamic advantages to the joint production of heat and power that could greatly reduce generation losses from traditional power production and would reduce carbon emissions system-wide. Little additional fuel is required for electricity production over that required for simple steam production, so overall efficiency is higher than with separate electricity generation and steam production. The most attractive use of CHP is where existing by-products and waste can be burned (for example, wood chips, paper mill wastes, refinery gas), substituting for purchased fuel.

Highly efficient lower-temperature CHP is well-developed technology for the commercial sector, but high-temperature CHP is still in its infancy. Industrial processes where direct heat is needed in the range of 200^{O}C to 800^{O}C, such as those in bakeries, ceramics manufacturing, brick making and dairies, can make use of high-temperature CHP, although using it on a retrofit basis would require major plant changes such as replacement of existing furnaces. Currently, industrial CHP is used particularly widely in countries with major energy-intensive industries and town centres with an extremely dense heating and cooling load, as in the United States and Japan. It is also used widely in Europe where the most technologically developed direct heat/CHP systems are to be found in the Nordic countries and Germany. In a number of European countries, the CHP share of direct heat production has increased markedly over the past 20 years, reaching 79 per cent in Sweden.

Recent advances in the efficiency and cost-effectiveness of electricity generating technologies have allowed for the development of new CHP configurations that reduce size yet increase output.

In a CHP or DH/CHP system, the overall conversion efficiency of fuel energy to useful heat or power can be as high as 85 to 92 per cent. It thus has the potential to reduce CO_2 emissions significantly compared with producing the heat and power separately from the same fuel. This is a technology that is widely seen as offering a major short-to-medium-term contribution to energy efficiency and thus CO_2 emissions, particularly in Western Europe, North America and Japan.

One of the largest barriers to CHP use is the difficulty of matching heat and electricity loads. In addition, the high initial costs of these systems could deter investment in the power-generation sector under deregulated markets as well as in industry. Operational problems, such as the effect of direct heating on product quality, could also deter industrial investment. Lack of experience with CHP in a given industrial sector could do the same. Depending on the locality, four additional barriers may be environmental permitting, which is often complex, time-consuming and uncertain; regulations that do not recognise CHP’s overall energy efficiency or credit emissions avoided from displaced electricity generation; discriminatory backup rates and interconnection fees charged by utilities; and unfavourable tax treatment and depreciation requirements (IEA 2000).

Advanced Gas Turbines

Advanced turbine systems (ATSs) are a promising, crosscutting technology for the near and longer terms. The turbines are high-efficiency, next-generation, gas-fired turbines that will produce less carbon per kWh than technologies used in conventional power markets. They are being developed in two size classes: industrial gas turbines (approximately 5 MW and 15 MW) and turbines for utility combined-cycle systems (approximately 400 MW). These ATSs are one of the major low-carbon technologies for the industrial sector between now and 2010 because of their high efficiencies (greater than 40 per cent) and their capability to cogenerate electricity and steam. These turbines are able to run on a variety of fuels and can be adapted for biomass and landfill gas fuels.

Advanced turbine systems are now commercially operating. Additional technology under development included ceramic materials and coatings, low emission technology, and alloys. ATSs have CO_2 emissions 21 to 61 per cent lower than conventional turbines (IEA 2000).

Sensors and Controls

Sensors and controls are a promising crosscutting technology for energy end-use and power generation applications. Sensors and controls do not themselves save energy, but they increase the efficiencies of equipment and processes, thus reducing energy use and related emissions. Sensors and controls have applications in industry, where precise industrial process control is often limited by the lack of advanced sensor technology. They are also used in fossil energy extraction systems, building energy systems, advanced vehicle engines and other systems.

Industrial process control and energy management are continuously evolving with new and improved sensors and advances in information processing technologies. Use of advanced sensing and signal processing capabilities allows a progressive transition from localised control of a production process to full factory floor automation. The speed of this transition has been sharply accelerating over the past five years, aided by significant advances in fibreoptic, semiconductor, microfabrication and microprocessor technologies. With new devices becoming more reliable and cost-effective, the use of ‘smart’ sensors in factory automation will become more widespread.

The use of sensors for industrial process control has already improved productivity substantially and has reduced energy consumption and CO_2 emissions. It is estimated that energy management systems using sensors and controls could save about 5 to 10 per cent of process energy use in industry. Combustion control through closed-loop feedback has improved passenger-vehicle efficiency by an estimated 15 per cent and fossil-fuel-burner efficiency by about 3 per cent, with commensurate reductions in CO_2 emissions.

The primary barrier to wide use of sensors and controls is technical: the lack of low-cost, robust and reliable sensors that are resistant to corrosive conditions and able to withstand high temperatures. The integration of sensors into control systems is also needed. High capital costs for new systems using sensors and controls is another barrier to wide use, as is the lack of readily available and accessible information on their potential economic and environmental benefits (IEA 2000)

Power Electronics

Power electronics serve to upgrade power from distributed and intermittent sources to grid quality and to iron out disturbances to the grid that could result from end-use electro-technologies such as variable speed drives. Power electronics are therefore important to renewables-based electricity generation, distributed generation and end-use electro-technologies. They themselves do not reduce CO_2 emissions but permit technologies to be used that can do so. For example, motors achieve variable speed capability, which results in increased efficiency, via power electronics. ‘Inverter’ circuitry converts power generated using a number of alternative technologies – such as photovoltaics, wind energy systems and fuel cells – into alternating-current (AC) power.

There are many commercial technologies, though improvements are still needed. Inverter technologies have recently been developed with improved efficiency, reliability and performance and reduced size and cost. A multi-level inverter has been developed that will allow 26 per cent more energy to be extracted from photovoltaic or other renewable-energy sources.

The use of improved electronics leads to reduced carbon emissions in virtually all electricity generating technologies and energy end-use technologies and can improve electricity grid operation and management.

Cost and technical barriers stand in the way of wider use of power electronics. Smaller, lighter, more efficient, lower-cost inverters are required, and reliability, cost and electromagnetic compatibility must be improved (IEA 2000).

Transmission and Distribution

Incremental improvements in energy efficiency can be realised as new improved transmission and distribution systems are introduced. More radical changes may occur in the long run. Advances are needed to better use existing systems. Advances are also needed in new systems and components, such as those required for distributed utility and generation concepts. R&D is needed on automated system control technologies and high-strength overhead line conductors to increase the capacity of existing systems. Developments in power electronics – including wide-band semiconductors for high-power switching devices and advanced converter designs – are needed to improve power management on existing systems and to enable high-voltage direct-current (DC) transmission for long-distance power transfers.

Technologies are now being developed in four areas that point the way to the smart grid of the future.

1. Utilities are experimenting with ways to measure the behaviour of the grid in real time.
2. They are looking for ways to use that information to control the flow of power fast enough to avoid blackouts.
3. They are upgrading their networks in order to pump more electricity through the grid safely.
4. They are looking for ways to produce and store power close to consumers, to reduce the need to send so much power down the transmitters in the first place (*The Economist* 2004).

The first practical superconducting power cables are now being installed. Superconductivity – the ability of a material to conduct electricity without losses due to resistance – is becoming feasible thanks to the discovery of materials that will do so above the boiling-point of nitrogen. These high-temperature superconductors are ceramics, usually brittle and difficult to draw into wires. But American Superconductor, a firm based in Massachusetts, has found a technology for producing wires long enough to be useful as superconducting cables.

Carbon Capture and Storage (CCS)

Greenhouse gas emissions could be reduced substantially by capturing and storing the CO_2 emitted from power generation and other energy-intensive industrial processes such as oil refineries, cement works, and iron and steel production, and the petrochemical industry. Other sources of CO_2 emissions, such as transport and domestic buildings, cannot be tackled in the same way because of the large number of small sources of carbon dioxide.

Carbon Capture

Capturing and storing carbon dioxide could slow down climate change and also allow fossil fuels to be a bridge to a clean hydrogen-based future. The efficient separation of CO_2 from flue gases is essential for any sequestration scheme.

The purpose of CO_2 capture is to produce a concentrated stream of CO_2 at high pressure that can readily be transported to storage site. In order to minimise energy and associated costs it is necessary to produce a nearly pure CO_2 stream for transport and storage (IPCC 2005).

Carbon capture technologies are not new; a number of proven methods exist to separate carbon dioxide from gas mixtures. For the past sixty years these technologies have been routinely used on a small scale by the oil, gas and chemical industries. While technically sound, none of today's commercial CO_2 capture technologies were developed for larger power plants and scaling them up is expensive and energy intensive (IEA 2005a).

Carbon dioxide capture is applicable to large flue gas streams in energy-intensive industries and in power generation. It is able to deliver deep reductions in emissions while enabling continued use of fossil fuels. It is primarily applicable to new plants, as replacing existing coal plants with renewable-based or more efficient fossil-based technology would be cheaper than retrofitting existing plants with CO_2 capture systems. In the case of coal plants, the obvious route to incorporating CO_2 capture into plant design is through coal gasification, which can be adapted to produce a pure CO_2 stream (IEA 2000).

There are currently three main CO_2 capture approaches. The most conventional approach is to capture the CO_2 from combustion products in power plant flue gas or industrial exhaust. This is known as post-combustion capture. Two other approaches to capturing CO_2 happen before fossil fuel combustion. In the oxy-fuel combustion approach, oxygen and recycled flue gas is used to increase CO_2 concentrations in flue gas for capture. In the hydrogen/syngas approach, coal is gasified or natural gas is reformed to produce syngas of carbon monoxide and hydrogen; a water/carbon monoxide shift then takes place to produce hydrogen and carbon dioxide for CO_2 capture. The capture step incurs most of the cost of carbon sequestration processes. Hence, the main challenges associated with capturing carbon dioxide are reducing costs and the amount of energy required for capture (IEA 2005a).

The cost of separating CO_2 is a major obstacle to the wide use of available methods for CO_2 capture, as it largely exceeds the cost of transporting it, even over long distances (IEA 2000). If capture is used to minimise CO_2 emissions from power plants (the capture of 90% of carbon dioxide is commonly assumed), fuel consumption per kWh using best current technology ranges from 24-40% for new supercritical PC plants, 11-22% for NGCC plants, and 14-25% for coal-based IGCC systems compared to similar plants without CCS. The increased fuel requirement results in an increase in most other environmental emissions per kWh generated relative to new state-of-the-art plants without CO_2 capture and, in the case of coal, proportionately larger amounts of solid wastes. However, advanced plant designs that further reduce

CCS energy requirements will also reduce overall environmental impacts as well as cost.

In addition, the generating efficiency would be reduced by 10 to 15 percentage points (e.g. from 55% to 45%) based on current technology. It is expected that widespread application of this technology would result in developments leading to a considerable improvement in its performance (IEA 2005b). CO_2 capture increases the cost of electricity production by 35-70% for an NGCC plant, 40-85% for a supercritical PC plant, and 20-55% for an IGCC plant. Over the next decade the cost of capture could be reduced by 20-30% and further cost reductions should be achievable by new technologies that are still in the research or demonstration phase,

The costs of retrofitting existing power plants with CO_2 capture have not been extensively studied. Limited studies suggest that a capture system retrofit should be combined with rebuilding the boiler and turbine to overcome the decrease in plant efficiency associated with the installation of the capture system (IPCC 2005).

What will be the best route forward in achieving the successful deployment of zero emissions technologies (ZETs)? In practice, no single system will be capable of meeting all future requirements, hence a portfolio of technologies will be necessary. By not concentrating on a single candidate technology, the associated technological risks can be minimised, and of equal importance, possible routes forward can be tailored to meet the different situations prevailing in different parts of the world. Some candidate ZETs will be based on PCC (pulverised coal combustion) and others on IGCC (integrated gasification combined cycle, IEA 2005c).

PCC

CO_2 capture from plant flue gases may be based on one of the technologies under development or currently in use within industry. Inevitably, CO_2 capture imposes additional costs and an energy penalty on plant, so the most likely candidates for future use will be those whose impact on plant economics and efficiency has been minimised.

In the shorter term, the most promising capture technology may be based on systems that scrub CO_2 from plant flue gases using amine solutions. Such systems are already used within some industrial sectors, although they were not developed specifically for treating the mix of gases that characterise the exhaust or flue gas from coal-fired power plants. However, the potential to retrofit such systems to the large number of existing coal-fired units justifies the significant development effort needed before this can be viewed as a viable option. Commercial developments, currently taking place, are aimed at increasing PCC plant efficiency above current, state-of-the-art levels, hence the impact of fitting a CO_2 capture system to a new plant would be less than retrofits to existing units.

In the medium term, alternative systems, such as those using membranes to separate CO_2 from flue gas, could be developed and deployed. The outcome of RD&D programs over the next few years will determine which options can be developed and refined to be most economic.

The other main possibility for ZETs-based PCC is where coal combustion takes place in an atmosphere comprising recycled flue gas mixed with oxygen (oxy-coal combustion). With conventional, PCC-based systems, the flue gas contains only a relatively low concentration of CO_2; however, with oxy-coal, a more concentrated stream of CO_2 is produced, easing its capture. Although the overall thermal efficiency could be higher than that of more conventional plants with CO_2 scrubbed from the flue gas, there would still be an efficiency penalty as production of the necessary oxygen consumes a considerable amount of energy. Further development of the technique is required and efforts are under way, notably in Canada, Australia and Europe (IEA 2005c).

IGCC

There are a number of different variants of the technology, some based on a dry feed and others on a wet feed of coal-water slurry. There are three generic types of gasifier that could be applied (entrained flow, moving bed and fixed bed) all of which have different operating characteristics. Such IGCC systems are acknowledged widely as having a lower environmental impact than combustion-based electricity generation technologies and this will influence future strategies formulated to ensure that coal-fired plant remains environmentally acceptable and commercially viable in the coming years.

Nevertheless there are far fewer IGCC plants operating today than PCC units, as the technology is perceived to be expensive, complex, and relatively unproven. By their very nature, some first-generation IGCC demonstration plants were costly and complex, although the next generation should see significant improvements in this respect. In fact, a number of IGCC plants are now operating with a high degree of reliability and experience gained with these will help provide a firm foundation for IGCC-based ZETs which offer a number of potential advantages.

1. CO_2 capture imposes a lower energy penalty than for the capture from PCC plant, since the CO_2 content of the pre-combustion, syngas stream is greater and hence more easily captured than from a flue gas.
2. The CO_2 can be captured at a pressure suitable for pipeline transport, hence reducing CO_2 compression costs.
3. A sequestration ready IGCC plant can be constructed today and CO_2 capture added at a later date, thus offering a valuable option to developers and investors faced with uncertain CO_2 emission costs.
4. Straightforward, chemical processing of the syngas, coupled with CO_2 capture, yields hydrogen suitable from combustion in gas turbines, direct conversion to electricity in fuel cells or other uses, such as transport.
5. Developments in gas turbine technology will boost efficiency levels and fuel cells offer the prospect of even higher efficiencies.

There are a number of developments that have the potential to increase the efficiency and attractiveness of IGCC providing they are supported under RD&D programs. These include the successful application of systems to remove particulates and other species from the syngas whilst still hot, and the deployment of a new, advanced method for generating oxygen (ion transport membrane technology. The latter has the potential to generate oxygen more cheaply than current processes, hence it could find application in a number of power generation cycles.

In a further development of IGCC systems, there may be a possibility of the simultaneous removal of CO_2 with the hydrogen sulphide (H_2S) present in syngas. These gases could then be co-disposed of in a single step. This technique is presently being carried out commercially in North America where so-called acid gas injection is being employed as an aid to recovering oil from mature fields. Such co-disposal offers the potential of lowering the costs of CO_2 capture.

Transport of CO_2

Except where plants are located directly above a geological storage site, captured CO_2 must be transported from the point of capture to a storage site.

Pipelines are the most common method for transporting carbon dioxide. Gaseous CO_2 is compressed to make it easier and less costly to transport. The first long-distance CO_2 pipeline came into operation in the early 1970s. In most pipelines the flow is driven by compressors at the upstream end, although some pipelines have intermediate (booster) compressor stations.

In some situations or locations, transport of CO_2 by ship may be economically more attractive, particularly when the CO_2 has to be moved over large distances or overseas. CO_2 can be transported by ship in much the same way as LPG, but this currently takes place only on a small scale because of limited demand.

The costs of CO_2 transport depend on the distance and the quantity transported. In the case of pipelines, the costs depend on whether the pipeline is onshore or offshore, whether the area is heavily congested, and whether there are mountains, large rivers, or frozen ground en route. All these factors could double the cost per unit length, with even larger increases for pipelines in populated areas. The typical cost of pipeline transport per tCO_2 ranges from $US1 at high mass flow rates up to $US8 at low mass flow rates. Steel accounts for a significant fraction of the cost of a pipeline, so fluctuation in such cost (such as the doubling in the years 2003 to 2005) could affect overall pipeline economics.

In ship transport, the tanker volume and the characteristics of the loading and unloading systems are some of the key factors determining the overall transport costs. If the marine option is available, it is typically cheaper than pipelines for distances greater than 1000km and for amounts smaller than a few million tonnes of CO_2 per year (IPCC 2005).

Geological Carbon Storage

Geological storage of CO_2 is the most promising sequestration technology for the near term. It involves capturing the gas and injecting it into subsurface repositories such as depleted oil and gas reservoirs; deep, confined saline aquifers, and deep coal beds. The technology for subsurface injection is readily available from the petroleum industry. That industry uses technologies for drilling and completion of injection wells, compression and long-distance transport of gases, and characterisation of subsurface reservoirs. It has experience with CO_2 injection for enhanced oil recovery. Natural gas is routinely transported and stored in subsurface reservoirs and aquifers.

Amine absorption, in combination with CO_2 storage in saline aquifers is used in the Sleipner Gas field, located in the Norwegian part of the North Sea. In this case, CO_2 is separated directly from the well stream before the gas is further processed and exported. Injection of CO_2 into partially depleted oil reservoirs is being used for enhanced oil recovery at about 70 sites worldwide. Injection into deep, unmineable coal beds to recover coal bed methane is under active investigation in a number of countries. A trial scheme for such technology is being undertaken in the United States.

Long-term storage in geological repositories will reduce greenhouse emissions by sequestering them from the atmosphere. Injection into depleted oil and gas reservoirs and deep coal beds could store CO_2 and also yield commercially valuable hydrocarbons. In a study carried out for the European Commission, underground aquifer storage capacity in the North Sea alone was estimated to be adequate to store up to 200 to 250 years of CO_2 emissions from OECD-Europe, at 1990 emissions rates (IEA 2000). IPCC estimates for geological storage capacities suggest a technical capacity of at least 2000 Gt of CO_2 which compares with annual emissions of 38 Gt of CO_2 by 2030 (IPCC 2005; IEA 2004a).

The costs of geological storage will vary due to site-specific features such as onshore versus offshore, reservoir depth and geological characteristics of the storage formation (such permeability and formation thickness). Representative estimates of the costs for storage in saline formations and depleted oil and gas fields are typically between 0.5-8US$/t$CO_2$ injected. Monitoring costs of 0.1-0.3 US$/t CO_2 are additional. The lowest costs are for onshore, shallow, high permeability reservoirs, and/or storage sites where wells and infrastructure from existing oil and gas fields may be re-used.

When carbon storage is combined with advanced oil recovery programs, the economic value of CO_2 can reduce the total cost of CCS. At the oil prices prior to 2003 (US$15-20 per barrel), enhanced oil production for onshore EOR with CO_2 storage could yield net benefits of US$/t$CO_2$, including the costs of geological storage. With oil prices maintained at current levels over the life of a CCS project, the economic value of CO_2 would be much higher (IPCC 2005).

Carbon storage systems may face risks due to leakage from storage. Global risks occur with the release of CO_2 into the atmosphere. Such leaks may also give rise to local hazards for humans, ecosystems and groundwater. The global risks can be estimated on the basis of analysing current carbon storage sites, natural systems, engineering systems and models. There is a probability of 90-99% that in appropriately selected and managed reservoirs the fraction of CO_2 retained would exceed 99% over 100 years and 99% or more over 1000 years.

Careful storage system design and siting, together with methods for early detection of leakage (preferably long before CO_2 reaches the land surface), are effective ways of reducing hazards associated with diffuse leakage. Once leakages are detected, some remediation techniques are available to stop or control them. Depending on the type of leakage, these techniques could involve standard well repair techniques, or the extraction of CO_2 by intercepting its leak into a shallow groundwater aquifer.

Experience will be needed to demonstrate the effectiveness, and ascertain the costs, of these techniques for use in CO_2 storage (IPCC 2005).

Monitoring is a very important part of the overall risk management strategy for geological storage projects. Standard procedures or protocols have not been developed yet. However, it is expected that some parameters such as injection rate and injection well pressure will be measured routinely. Repeated seismic surveys have been shown to be useful for tracking the underground migration of CO_2. Newer techniques such as gravity and electrical measurements may also be useful. The sampling of groundwater and the soil between the surface and water table may be useful for directly detecting CO_2 leakage. Surface-based techniques may also be used for detecting and quantifying surface releases.

Since all of these monitoring techniques have been adapted from other applications, they need to be tested and assessed with regard to reliability, resolution and sensitivity in the context of geological storage. All of the industrial-scale projects and pilot projects have programs to develop and test these and other monitoring techniques. Given the long-term nature of CO_2 storage, site monitoring may be required for very long periods.

It is important to match sources of captured CO_2 and storage sites, as much as possible, to reduce CO_2 transportation needs. Large point sources of CO_2 are concentrated in proximity to major industrial and urban areas. Many such sources are within 300 km of areas that potentially hold formations suitable for geological storage. However, a small proportion of large point sources is close to potential ocean storage locations.

Geological storage of CO_2 is ongoing in three industrial-scale projects: the Sleipner project in the North Sea, the Weyburn project in Canada and the In Salah project in Algeria. About 3-4 $MtCO_2$ that would otherwise be released to the atmosphere is captured and stored annually in geological formations.

In addition to the CCS projects in place, 30 $MtCO_2$ is injected annually for EOR, mostly in Texas, where EOR commenced in the early 1970s. Most of this CO_2 is obtained from natural CO_2 reservoirs found in the western regions of the United States, with some coming from anthropogenic sources such as natural gas processing. Much of the CO_2 injected for EOR is produced with the oil, from which it is separated and then reinjected. At the end of the oil recovery, the CO_2 can be retained for the purpose of climate change mitigation, rather than vented into the atmosphere. This is planned for the Weyburn project (IPCC 2005).

Other Carbon Storage Systems

Ocean Storage

A potential CO_2 storage option is to inject captured CO_2 directly into the deep ocean, where most of it would be isolated from the atmosphere for centuries. This can be achieved by transporting CO_2 via pipeline or ship to an ocean storage site, where it is injected into the water column of the ocean of sea floor. The dissolved and dispersed CO_2 would subsequently become part of the global carbon cycle. Ocean storage has not yet been deployed or demonstrated at a pilot scale, and is still in the research phase. However, there have been small-scale field experiments and 25 years of theoretical, laboratory and modelling studies of intentional ocean storage of CO_2.

Analysis of ocean observations and models both indicate that injected CO_2 will be isolated from the atmosphere for at least several hundreds of years, and that the fraction tends to be higher with deeper injection. The fraction retained could in theory be boosted by such techniques as forming solid CO_2 hydrates and/or liquid CO_2 lakes on the sea floor, dissolving alkaline minerals such as limestone to neutralise the acidic CO_2 and encouraging the growth of carbon-absorbing phytoplankton be enriching nutrient-poor regions of the ocean floor with iron or nitrogen. Dissolving mineral carbonates, if practical, could extend the storage time scale to roughly 10,000 years. However, large amounts of limestone and energy for materials handling would be required for this approach.

The injection of carbon dioxide into the ocean would produce a change in ocean chemistry in the region of injection and the injection of very large quantities would eventually produce measurable changes over the entire ocean volume. Experiments show that adding CO_2 can harm marine organisms. The implication for ecosystems over large ocean areas have not been studied.

Although there is no experience with ocean storage, some attempts have been made to estimate the costs of CO_2 storage projects that release CO_2 on the sea floor or in the deep ocean. The costs of carbon capture and storage to the shoreline are not included in the cost of ocean storage. However, the costs of offshore pipelines or shipping, pus any additional energy costs, are included in the ocean storage cost. For short distances, the fixed pipeline option would be cheaper (at 100 km offshore it is estimated at 6US$/t$CO_2$). For larger distances, either the moving ship or transport by ship to a platform with subsequent injection would be more attractive (at 500 km offshore it is estimated at 13-16US$/t$CO_2$, IPCC 2005).

Mineral Carbonation

Advanced *chemical and biological sequestration* is aimed at permanent stable sequestration and recycling of carbon into new fuels and chemical feedstocks. Emissions are reduced through converting CO_2 into an environmentally benign product while generating liquid fuels, generating hydrogen fuel and converting into organic compounds. Representative technologies include chemical sequestration as mineral carbonate, direct solar conversion of CO_2 to methanol, advanced conversion of coal to hydrogen and conversion of CO_2 into reusable biomass using microalgae.

Mineral carbonation refers to the fixation of CO_2 using alkaline and alkaline-earth oxides, such as magnesium oxide and calcium oxide, which are present in naturally occurring silicate rocks such as serpentine and olivine. Chemical reactions between these materials and CO_2 produces compounds such as magnesium carbonate and calcium carbonate (commonly known as limestone). The quantity of metal oxides in the silicate rocks that can be found in the earth's crust exceeds the amounts needed to fix all the CO_2 that would be produced by the combustion of all available fossil fuel reserves. These oxides are also present in small quantities in some industrial wastes, such as stainless steel slags and ashes.

Mineral carbonation produces silica and carbonates that are stable over long time scales and can therefore be disposed of in areas such as silicate mines, or re-used for construction purposes, although such re-use is likely to be small relative to the amounts produced. After carbonation, CO_2 would not be released to the atmosphere. As a consequence, there would be little need to monitor the disposal sites and the associated risks would be very low. The storage potential is difficult to estimate at this early phase of development. It would be limited by the fraction of silicate reserves that can be technically exploited, by environmental issues such as the volume of product disposal, and by legal and societal constraints oat the storage location.

A commercial process for mineral carbonation would require mining, crushing and milling mineral-bearing ores and transport to a processing plant receiving a concentrated CO_2 stream from a capture plant. The carbonation process energy required would be 30 to 50% of the capture plant output. Considering the additional energy requirements for the capture of CO_2, a CCS system with mineral carbonation would require 60 to 180% more energy input per kilowatt-hour than a reference electricity plant without capture or mineral carbonation. These energy requirements raise the cost per tonne of CO_2 avoided for the overall system significantly.

The best case studied so far is the wet carbonation of natural silicate olivine. The estimated cost of this process is approximately 50-100 US$/t$CO_2$ net mineralised (in addition to CO_2 capture and transport costs, but taking into account the additional energy requirements). The mineral carbonation process would require 1.6 to 3.7 tonnes of silicates to be disposed per tonne of CO_2 stored as carbonates. This would therefore be a large operation, with an environmental impact similar to that of current large-scale surface mining operations. Serpentine also often contains chrysolite, a natural form of asbestos. Its presence also demands monitoring and mitigation measures of the kind available in the mining industry. On the other hand, the products of mineral carbonation are chrysolite-free, since this is the most reactive component of the rock and therefore the first substance converted to carbonates.

A number of issues still need to be clarified before any estimates of the storage potential of mineral carbonation can be given. The issues include assessments of the technical feasibility and corresponding energy requirements at large scales, but also the fraction of silicate reserves that can be technically and economically exploited for CO_2 storage. The environmental impact of mining, waste disposal and product storage could also limit potential (IPCC 2005).

Industrial Uses

Industrial uses of CO_2 include chemical and industrial processes where CO_2 is a reactant, such as those used in the production of urea and methanol, as well as various technological applications that use CO_2 directly, for example in the horticulture industry, refrigeration, food packaging, welding, beverages, and fire extinguishers. Currently, CO_2 is used at a rate of approximately 120 MtCO_2 per year worldwide, excluding the use for EOR. Some two-thirds of this use is in the production of urea. Some of this CO_2 is extracted from natural wells, and some originates from industrial sources – mainly high-concentration sources such as ammonia and hydrogen production plants – that capture CO_2 as part of the production process.

As a measure for mitigating climate change, this option is meaningful only if the quantity and duration of CO_2 stored are significant, and if there is a real net reduction of CO_2 emissions. The typical lifetime of most of the CO_2 currently used by industrial processes has storage times of only days to months. The stored carbon is then degraded to CO_2 and again emitted to the atmosphere. Such short time scales do not contribute meaningfully to climate change mitigation. In addition, the total industrial use figure is small compared to emissions from major anthropogenic sources (120 $MtCO_2$/yr compared with 23579 $MtCO_2$/yr in 2002). Moreover, the total amount of long-term (century-scale) storage is presently in the order of 1 $MtCO_2$/yr or less, with no prospects for major increases.

Another important question is whether industrial uses of CO_2 can result in an overall net reduction of CO_2 emissions by substitution for other industrial processes or products. This can be evaluated correctly only by considering proper system boundaries for the energy and material balances of the CO_2 utilisation processes, and by carrying out a detailed life-cycle analysis of the proposed use of CO_2. In view of the low fraction of CO_2 retained, the small volumes used and the possibility that substitution may lead to increases in CO_2 emissions, it can be concluded that the contribution of industrial uses of captured CO_2 to climate change mitigation is expected to be small (IPCC 2005).

The Complete CCS System

There is relatively little experience in combining CO_2 capture, transport and storage into a fully integrated system. Complete CCS systems can be put together from existing technologies that are mature or economically feasible under specific conditions, although the state of the overall system may be less than some of its components. The use of CCS for large-scale power plants (the potential application of major interest) still remains to be implemented (IPCC 2005). Plans are being developed to establish trail commercial plants of a medium size. One example is the plant to be constructed by a range of partners in the FutureGen Industrial Alliance, comprising American and Australian coal producers and electricity generators, with support from the American government (Ball 2006).

Cost of CCS Systems

The future cost of capturing, transporting and storing CO_2 depends on which capture technologies are used, how they are applied, how far costs fall as a result of RD&D (innovation) and market uptake (learning-by-doing), and fuel prices. Since applying capture technologies requires more energy use and leads to production of more CO_2, the cost per tonne of CO_2 emission mitigation is higher than the per tonne cost of capturing and storing CO_2. The gap between the two narrows as capture energy efficiency increases.

Art this stage, the total cost of CCS could range from 50 to 100 US$ per tonne of CO_2. This could drop significantly in the future. In most cases it is projected that using CCS would cost 25-50 US$ per tonne of CO_2 by 2030, compared to the same process without.

The cost for CCS can be split into the cost of capture, transportation and storage. Current estimates for large-scale *capture* systems (including pressurisation of CO_2, excluding transportation and storage) are 25-50 US$ per tonne of CO_2 but are expected to improve as the technology is developed and deployed. If future efficiency gains are taken into account, costs could fall to 10-25 US$/t$CO_2$ for gas-fired plants over the next 25 years.

With CO_2 *transport*, pipeline costs depend strongly on the volumes being transported and, to a lesser extent, on the distances involved. Large-scale pipeline transportation costs range from 1-5 US$/t$CO_2$ per 100 km. If CO_2 is shipped over long distances rather than transported in pipelines, the cost falls to around 15-25 US$/t$CO_2$ for a distance of 5000km.

The cost of CO_2 *storage* depends on the site, its location and method of injection chosen. In general, at around 1-2 US$/t$CO_2$, storage costs are marginal compared to capture and transportation costs. Revenues from using CO_2 to enhance oil production (EOR) could be substantial (up to 55 US$/t$CO_2$), and enable the cost of CCS to be offset. However, such potential is highly site specific and would not apply to most CCS projects. Longer-term costs for monitoring and verification of storage sites are of secondary importance (IEA 2004b).

Comparisons With Other Emission-Reduction Options

CO_2 emission reduction options in the energy sector include lower carbon fossil fuels, renewables, nuclear, energy efficiency and CCS. Outside the energy sector there are options such as afforestation and land-use change, and reduction of non-CO_2 greenhouse gases. Each option is characterised by a (marginal) cost curve that allows for a certain emission reduction potential at a given CO_2 price. Therefore, different options co-exist in a cost-effective policy mix. The more ambitious the emission reduction targets, the more options will be needed, and the more effective and costly the options that will be needed. CCS can reduce emissions by 85 to 95% compared to the same processes without CCS but it is a relatively costly emission reduction strategy. Therefore the widespread use of CCS only makes sense in a scenario with significant emission reduction.

CO_2 capture and storage (CCS) could potentially allow for the continued use of fossil fuels while at the same time achieving significant reductions in CO_2 emissions. However, IEA analysis indicates that this would require significant policy action equivalent to a CO_2 penalty level of 50 US$/t$CO_2$. This scenario would halve emissions by 2050 compared to the scenario where no additional policy action was taken. CCS technologies contribute about half of the reductions achieved by 2050.

By 2050, 80% of the captured CO_2 would come from electricity production, particularly coal-fired generation. At a penalty level of 50 US$/t$CO_2$, power plants with CO_2 capture and storage would represent 22% of total global installed generation capacity by 2050 and produce 39% of all electricity. Within the electricity sector, coal-fired IGCCs fitted with CCS that co-generate hydrogen and other transportation fuels would play an important role. Capture from coal-fired processes would represent 65% of the total CO_2 captured by 2050, the remainder coming from gas, oil- and biomass-fired processes, and from cement kilns.

Up to 2025, CCS would mainly be applied in industrialised countries. By 2050, almost half of total capture activity could be rolled out in developing countries, mostly China and India. Technology transfer from industrialised countries (particularly pf efficient power-generation plants) could help to realise the full potential of CCS in developing countries. If CO_2 policies were limited to industrialised countries, the role of CCS would be significantly reduced (IEA 2004b).

The Environmental Benefits of CCS

The IEA constructed a number of scenarios in order to assess the environmental benefits of CCS. These scenarios suggest CCS potential are between 3 Gt and 7.6 Gt CO_2 in 2030, and between 5.5 Gt and 19.2 Gt CO_2 in 2050. This compares to 38.8 GT CO_2 emissions by 2030 under the WEO Reference Scenario.

Such results are sensitive to assumptions about future technology development, not only for CCS, but also for other mitigation options such as renewables, and nuclear. More optimistic assumptions for the future cost reduction of renewables and the potential for expanding nuclear would considerably reduce the future role of CCS.

One important finding of this analysis is that renewables, nuclear and CCs technologies can co-exist as part of a cost-effective portfolio of options for reducing CO_2 emissions from energy production. However, the relative role of each would vary from region to region (suitable carbon storage sites for CCS technologies are depleted oil and gas reservoirs; deep, confined saline aquifers; and deep coal beds; such storage sites will be available in some countries, but not others.) and also depend on policies and cost developments for all technologies, the extent to which promising technology options actually work, institutional and legal barriers, and public acceptance. Investing in CCS RD&D could be a worthy insurance policy for the future, hedging against the risk of technology failures (IEA 2004b).

The Consequences for the Fuel Market

CCS would result in a significant increase in the use of coal compared to the scenario where CCS is not considered, but the same CO_2 policies are applied. As coal is considered a more secure fuel than oil and gas, the fact that coal remains a viable energy option increases supply security. CCS would have a limited impact on the use of oil and natural gas since, by the time the technology becomes widely competitive, the availability and security of supplies of these fuels may begin to limit their use. CCS would result in a lower use of renewables and nuclear energy and increase clean fossil energy availability.

For regions with ample coal reserves, such as North America, China and India, CCS could result in lower imports and increased reliance on domestic energy sources. For a number of countries such as Australia, coal exports would be higher if global coal consumption were higher. This could have economic advantages that need to be analysed in more detail (IEA 2004b).

Geographic Implications

The relevance of CCS differs by region. Analysis from IEA modelling suggests that CCS can become an important option in North America, Australia and parts of

Europe. While the CCS potentials in China and India are important as well, the realisation of these potentials will depend on the extent of global efforts to reduce CO_2 emissions.

Given that long-range transportation of CO_2 seems an unlikely option given its high cost, for countries without sufficient storage potential close to their emission sources, it may be more cost-effective to consider alternative emission reduction strategies (IEA 2004b).

Fossil Fuel Technologies in the Long Term – The Energyplex

Ultimately, ultra high-efficiency, zero-carbon-emissions systems can be envisioned that would take advantage of synergies between energy generation, fuels production and chemicals production by integrating these processes into a single entity, an 'energyplex'. An energyplex would incorporate a series of modular plants capable of co-producing power and chemicals or fuels that can be integrated to use local sources of carbon (coal, biomass, municipal solid waste) as fuel and feedstocks. With the incorporation of modules for capture and sequestration of CO_2, energyplexes would have essentially no carbon emissions.

These complexes would optimise the entire cycle of carbon use by incorporating co-processing concepts, the integral capture of CO_2 and the incorporation of carbon into useful products or carbon sequestration. This is a long-term, futuristic concept that challenges the R&D community to make significant breakthroughs in areas such as novel industrial process configurations, novel power cycles and co-production of heat and power, with suitable energy-efficient reuse or storage options for carbon and CO_2. Representative technologies include IGCC systems, coal liquefaction, fuel cell/gas turbine bottoming cycle combinations with efficiencies of more than 70 per cent and integral capture of CO_2, power systems with alternative working fluids, high-temperature oxygen separation membranes, and advanced oxygen production techniques (IEA 2000).

The US Department of Energy has devised an R&D roadmap known as Vision 21: The 'Ultimate' Energy Complex. Vision 21 refers to a fleet of advanced, ultra-clean, highly efficient power plants capable of producing several energy products: electricity and steam, premium chemicals and feedstocks, and clean liquid fuels. Virtually every energy-using sector – residential, commercial, industrial, transportation – would benefit. These plants are called Energyplexes.

Several technologies now in the R&D pipeline are to be incorporated in Vision 21 Energyplexes. Advanced turbines, fuel cells, indirectly fired cycles, and integrated gasification combined-cycle (IGCC) systems form the nucleus of Vision 21. Each system emphasises high efficiency and low emissions.

There are five components in the operation of an EnergyPlex.

1. A gasifier burns fuel and sends the gas to one or more modules that use the gas for specific purposes.
2. One module would rid the gas of pollutants and particulate matter and then would channel it to a fuel cell module, which generates electricity.

3. Another module would capture CO_2 and pump it into the ground or store it for other uses;
4. Fuel cell exhaust would be used to drive a turbine that produces power.
5. A portion of the cleaned gas could be siphoned off and funnelled to a synthesis gas module that yields fuels and chemicals.

Because plant efficiencies in a Vision 21 configuration would reach and eventually exceed 60 per cent when coal is the feedstock (currently around 40 per cent with conventional technology) and 75 per cent when using natural gas (currently around 58 per cent), less fuel would be required. Combining high-energy efficiency with carbon sequestration, Vision 21 plants would effectively address climate change concerns while ensuing that fossil fuels, especially coal, remain an important part of the supply of energy. In addition, Vision 21 plants would be able to operate on several fuels – coal, natural gas, and, in time, combinations of fossil fuels with biomass or municipal solid waste.

Advanced turbines, gasifiers, high-temperature combustion systems, or fuel cells would be used in modular form to generate power. Early versions of these technologies are beginning to enter the commercial market. Because Energyplexes could be customised, they could better respond to specific needs of local markets. For example, an Energyplex could be equipped to produce electricity along with low cost fuels and chemicals near areas with several chemical-processing companies. Another Energyplex may be tailored to co-produce low priced feedstocks in regions where there is a market demand for them.

Timelines

Cross Cutting Technologies

The near-term cross-cutting technologies that are available to reduce GHG emissions from fossil fuels are:

1. Current state-of-the art high efficiency power plants.
2. Wider use of CHP systems.
3. Advanced sensors and controls in process control for power systems.
4. Power electronics to upgrade power from distributed and intermittent sources.
5. Improved electricity transmissions and distribution.

Longer term fossil- fuel cross-cutting technologies include:

1. Advanced high-temperature CHP systems.
2. Superconducting cables and other network improvements for transmission systems.

CCT

The current evidence suggests that, in the absence of measures for limiting CO_2 emissions, there are only small, niche opportunities for CCS technologies. These early opportunities involve CO_2 captured from a high-purity, low-cost source, the transport of CO_2 over distances of less than 50 km, coupled with CO_2 storage in a value-added application such as EOR. The potential of such applications is about 360MtCO_2 per year.

By 2050 emissions abatement policies are likely to become more stringent and CCS systems should become significant in terms of their contribution to emissions reduction. Nevertheless, the majority of CCS deployment is likely to occur in the second half of the century (IPCC 2005).

There is a window of opportunity for CCS to compete as a major technology option, starting from around 2020 and peaking in the second half of the 21st century. Beyond that, CO_2-free alternatives would make CCS redundant.

Energyplexes

Currently, energyplexes are in the first phase of pre-commercial development. Early versions could be commercially available with a decade. The total system, including CCS technology, may not be taking off until the 2030-2050 period. Widespread adoption of the energyplex is unlikely to occur until the very long term – beyond 2050.

2. A Fossil Fuel Technology System

The Diffusion of Emission-reducing Technologies

Inducements to Diffusion

Broad inducements to the diffusion of energy-efficient technologies are associated with higher prices for fossil fuels. Cross-cutting technologies and new gas and coal technologies are beneficiaries of higher prices for fossil fuels. It may also be the case that some firms in the energy industry are anticipating the introduction of such policies as carbon taxes and emissions trading.

A large number of new technologies are available on a commercial basis or diffusion through the energy sector. They include:

- combined-cycle gas turbines and advanced turbine systems;
- advanced energy-efficient coal technologies;
- CHP systems;
- improved process control in power generation;
- power electronics in energy applications; and
- transmission and distribution.

Constraints

There are two major constraints on the diffusion of emission-reducing technologies in the non-renewable energy sector. These are the following.

1. Uncertainty about future developments in energy markets, which places a premium on deferment of investment decisions.
2. The existence of a large stock of high-emitting power plants with years to go before they have to be replaced. While low capital stock turnover may be mitigated by retrofit, it is usually profitable only towards the end of the technical life of conventional power plants.

Induced Innovation in Specific Fields

Inducements

High prices for fossil fuels would encourage energy-efficiency improvements in cross-cutting technologies and new fossil fuel power technologies.

Technological opportunities for innovation exist in the following fields:

- advanced gas turbines (incorporating new materials technology);
- clean coal technologies, particularly ultrasupercritical boilers;
- advanced industrial process control applied to power plants;
- advanced applications of power electronics to power plants;
- advanced transmission and distribution technologies;
- carbon capture technologies;
- geological carbon storage; and
- enhanced oil recovery with carbon storage.

Constraints

The principal constraints on innovation in non-renewable energy systems are uncertainties about future trends in the energy market and in energy policies, and low capital stock turnover.

General Purpose Technologies and Complementary Innovations

General Purpose Technologies

There are three general purpose technologies in the non-renewable energy sector:

1. Information technology, which is used in process control for power generation, carbon capture, and the monitoring of stored carbon dioxide.
2. Advanced materials technology is deployed in high-technology gas turbines, and transmission systems.
3. Nanotechnology has applications in the following areas:
    - nanotechnology membranes in fuel processing;

- sensors and controls in power plants;
- power electronics; and
- transmission and distribution – new materials enabling superconductivity.

Inducements and Constraints

Inducements to deploy GPTs and undertake complementary innovations are:

- High fossil fuel prices and the introduction of carbon taxes and emission trading systems;
- Exogenous improvements in competitiveness of GPTs; and
- Widening range of energy-related uses in which GPTs can be utilised.

The principal constraints on broader-based innovation in non-renewable energy are:

- the high costs of technologies, limited applications and high costs of accompanying R&D (particualry in nanotechnology and advanced materials); and
- the level of adjustment costs.

Innovation in Business Processes

Innovation in business processes will be required with respect to process integration within electricity generation and production systems that are integrated across industries.

Process integration systems need to be further developed in power plants, CHP systems and carbon capture systems. Integrated production systems will be required to link CHP with carbon capture and storage and waste recovery. The proposed Energyplex goes beyond this level of integration by incorporating gasification at the beginning of the process with industrial production that utilises cleaned gas at the end of the process.

Public Research and Development

Carbon capture and storage technologies, advanced materials technology in relation to superconductivity, and high technology sensors are key topics for future public research and development. IEA (2005d) provides details of the chief research projects of international importance in this area. They include:

- the FutureGen integrated sequestration and hydrogen research initiative in the United States;
- the ENCAP and CASTOR projects in Europe; and
- the Coal21 project in Australia.

Taken together, all the planned CCS projects in the coming decade will barely reach 10 Mt per year in scale. If the full emission reduction potential of CCS is to be realised, RD&D activities need to be scaled up and accelerated significantly. The IEA argues for a fivefold increase in RD&D on CCS projects (IEA 2004b).

3. Climate Change Mitigation Policies and Fossil Fuel-based Energy

A key aspect of climate change mitigation policies is to encourage diversity in the range of RD&D on new emission-saving technologies. Diversity in new technologies provides a number of benefits:

- insurance against technological uncertainty that may emerge for time to time in specific areas;
- geographic limitations on the applications of some particular technologies; and
- greater substitution possibilities between different energy technologies which, in turn, will increase price-elasticities and hence the leverage exercised by economic instruments in influencing the direction of energy systems.

The Use of Specific Policy Instruments

Economic Instruments

The adoption of carbon taxes and international emissions trading would provide a clear system of incentives for the diffusion of new emissions-saving technologies, and for innovation in emission-saving technologies and related business processes. It would be add to the effectiveness of such policies if they were to be accompanied by announcements such as the quantitative goals for climate change policies and the type of technological outcomes expected from policies. Subsidies for the diffusion of pioneer technologies may be necessary for them to attain a critical mass for commercialisation.

Regulation

Regulation is an alternative policy instrument that can be used when the adoption of economic instruments are infeasible. Regulation can also be used to deal with slow capital stock turnover. Emissions standards can be applied to existing as well as old power plants. Attention needs also to be paid to regulatory impediments to energy investments in general.

A regulatory and legal framework for CO_2 storage projects must be developed to address issues arising in relation to liability, licensing and leakage, as well as landowner, royalty and citizens rights (IEA 2004b).

Science and Technology

The increased volume of R&D required on CCS technologies, in conjunction with the research demands of alternative energy, transportation, and other aspects of energy-related technologies, foreshadow increased demands on the science and technology infrastructure.

Education and Information

Information policies are particularly important in relation to the development and subsequent adoption of CCS technologies. The single most important hurdle that CCS must overcome is public acceptance of storing CO_2 underground. Unless it can be proven that CO_2 can be permanently and safely stored over the long term, the option will be untenable, whatever its additional benefits. Processes which consult, review, comment, and address stakeholder concerns should be built into all pilot projects. Procedures for independently verifying and monitoring storage and related activities should also be established (IEA 2004b).

Two important aspects of education and training policies will be of major importance:

- the provision of the skills needed to accomplish the evolution of the non-renewable power sector towards a system based on the utilisation of CCS technology; and
- the provision of the skills needed for increased RD&D in CSS technologies.

International Cooperation

The future role of CCS depends critically on sufficiently ambitious CO_2 policies in non-OECD countries. Therefore, outreach programs to developing countries and transition economies and international commitment to reduce CO_2 emissions are a prerequisite. The maturation of a global emissions-trading scheme, a meaningful price for CO_2 and a predictable return on investment are important factors that could stimulate the timely deployment of CCS (IEA 2004b).

4. Overview

Conclusions

Table 1 examines the trend in CO_2 emissions from electricity and heat production in the context of sources of CO_2 emissions from other parts of the energy sector.

For the world as a whole, it is noteworthy that the growth in CO_2 emissions from electricity and heat production are expected to outstrip the growth in other sources of emissions from the energy sector. This highlights the need to accelerate innovation and diffusion of new emissions-saving technologies in the electricity sector as outlined in this paper and Paper 7.

Table 1. CO_2 Emissions From the Energy Sector, 2002 to 2030 (Mt)

	2000	2010	2020	2030	2030/2000
World					
Power generation and heat plants	9417	11494	14258	16771	78.1
Other energy production	1220	1405	1648	1865	52.9
Total final energy consumption	12479	14447	16837	19063	52.8
Total energy emissions	**23579**	**27817**	**33226**	**38214**	**62.1**
OECD					
Power generation and heat plants	4793	5389	6023	6191	29.2
Other energy production	635	689	713	743	17.0
Total final energy consumption	7018	7735	8416	8900	26.8
Total energy emissions	**12446**	**13813**	**15151**	**15833**	**27.2**
Developing economies					
Power generation and heat plants	3354	4684	6676	8941	166.6
Other energy production	491	597	798	969	97.4
Total final energy consumption	4381	5445	6919	8455	93.0
Total energy emissions	**8226**	**10726**	**14392**	**18365**	**123.3**

Source: Derived from the Reference Scenario of the IEA (2004a). Other energy production comprises petroleum refining and the transformation of coal and gas.

While CO_2 emissions from electricity and heat production in the OECD are projected to rise at around 30% between 2002 and 2030, the central problem for emissions from the electricity sector is found in the developing economies. The problem arises from a combination of rapid growth in several very large developing economies, electrification of the economies, and relatively high rates of emissions-intensity in electricity production that are expected to persist through the projection period. This makes international cooperation to achieve major changes in the technology of electricity production and distribution a priority in climate change mitigation policies.

Finally, it is worth reiterating a theme that underlies the analysis of the last two chapters. The strategy for controlling and reducing emissions from the electricity sector should focus on encouraging a diversity of technological advances. Three broad streams of technology would be most important – renewable energy, nuclear energy, and CCS technologies. Within these three fields, and in the cross-cutting technologies that are common to all of them, there are opportunities for many possible directions in new technologies. Encouragement of a broad range of prospective technologies has the advantage of:

- providing a wide field of choice that facilitates selection of the most appropriate technologies for the varying needs of the future;
- giving insurance against the delays (or, perhaps, major long-run impediments) in resolving unforeseen technological or political obstacles arising in relation to specific technologies;
- providing a broad menu of technologies that can be adapted to the wide variation in the geographical, resource and social circumstances of individual countries or regions; and
- facilitating increased efficiency in economic instruments as an instrument of climate change policy be ensuring a wide range of alternatives in future energy

technology choices (hence the trade-off between sustainable energy pricing and sacrifices to economic growth would be improved as lower carbon taxes would secure given reductions in emissions).

Non CO_2 Emissions

The analysis of energy markets conducted so far has concentrated on just one form of greenhouse gas emissions – that of CO_2. Table 2 provides some data on other forms of greenhouse gas emissions from the energy sector in the advanced economies.

Table 2. Non-CO_2 Emissions From the Energy Sector in the Advanced Economies, 1990-2010 (Mt CO_2-e)

	1990	2000	2010	2010/2000 (a)
Energy				
Methane	55	50	54	0.8
NO_x electricity	29	32	37	1.5
NO_x other stationary energy	64	66	74	1.2
NO_x transport	82	122	148	2.0
SF_6 electricity	50	26	28	0.7
Total non-CO_2 energy sector	**280**	**296**	**341**	**1.4**
Fugitive emissions				
Methane coal mining	303	216	216	0.0
Methane oil & gas	663	678	696	0.3
HFC-23	80	66	56	-1.6
Fugitive emissions	1046	960	968	0.1
Total non-CO_2 emissions	**1326**	**1256**	**1309**	**0.4**

Source: US EPA (2001).
Note: (a) Average annual rate of growth.

Direct non-CO_2 emissions from the energy sector in the advanced economies are mainly comprised of methane, nitrous oxide (NO_x) and sulphur hexafluoride (SF_6). Nitrous oxide is the most important source of these emissions. Emissions of NO_x from road vehicles have grown rapidly over recent times as a result of anti-pollution technologies being applied to vehicles. The level of such emissions is expected to stabilise at some future date. Non-CO_2 emissions are likely to comprise 2.4% of direct greenhouse gas emissions from the energy sector in the advanced economies, a proportion which has been stable in the recent past but is likely to decrease in the medium-term future.

Fugitive emissions arise from the exploration, development, production and distribution of fossil fuels (coal, oil and gas). Methane is the main gas emitted. The shift towards open cut mining of coal has led to a decline in methane emitted form coal mining. Apart from this, fugitive emissions are roughly stable. If we include fugitive emissions in total greenhouse gas emissions from energy in the advanced economies, they comprise 6.4% of total emissions, a proportion which has been falling. Total non-CO_2 emissions from the energy sector in the advanced economies are likely to be 8.7% of all greenhouse gas energy-related emissions for the advanced economies.

For the developing economies, data on non-CO_2 energy-related emissions is available only for fugitive emissions. Such emissions are estimated by Scheehle (2002) to have risen from 552 $MtCO_2$-e in 1990 to 632 $MtCO_2$-e in 2000 and may reach 941 $MtCO_2$-e by 2010. By that period they would comprise 8.1% of all greenhouse gas emissions form energy in the developing countries. This would compare with 6.4% in the advanced economies. In contrast to the latter group of countries, fugitive emissions are expected to be an increasing percentage of all greenhouse gas emissions for the developing countries in the immediate period ahead.

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