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Contents

EXECUTIVE SUMMARY

The existing global energy system is no longer capable of supporting economic activity, providing security of supply, and maintaining human well-being within an acceptable resource budget, without imposing significant impacts on the environment.

For more than a century governments and industries have developed technologies, built environments and infrastructure with the assumption that supplies of energy will remain abundant and cheap. Provision of useful energy services has depended on a complex energy system encompassing natural resources, their extraction, energy carriers, conversion plants, refineries, distribution networks and a wide range of consumer technologies and appliances. In OECD countries and economies in transition, the system has been developed over several generations to provide heating, cooling, electricity and mobility for businesses and communities. In many developing countries provision of affordable energy services has been less successful and, to reduce energy poverty levels, will require major investment in infrastructure and conversion technologies, particularly in rural areas.

For many nations the energy system is on the brink of evolving from its historic dependence on surplus resources to one of constrained supplies, and thereby necessitating the wiser use of energy. Extraction and consumption will need to be replaced by environmental stewardship. This evolution will require long term vision and leadership based on sound science to support technical, social and cultural change. Sustainable energy systems will need to emerge as a result of government, business and private interactions.

This chapter on energy supply aims to provide a clear and focused analysis of the problems, constraints, and opportunities relating to current and future energy services in both developed and developing countries. Extraction of global fossil fuel sources, production of energy carriers, and technically mature processing and conversion systems together constitute the main energy supply chain. These are all well understood and have underpinned the growth and development of many economies during the past century. Sustainable development of other nations, as outlined by the goals of the United Nations Millennium Declaration (UN, 2000), will largely depend on the provision of adequate, affordable and reliable energy supplies.

Current global energy demands are met largely by fossil fuels which results in the release of around 6.8 GtC per year giving an annual increase in atmospheric greenhouse gas concentrations of around 3 parts per million (ppm). It is well understood that the global dependence on fossil fuels has led to the release of over 350 GtC into the atmosphere since 1850. It is also clear that to continue to extract and combust the world’s rich endowment of oil, coal and natural gas in this manner is no longer environmentally acceptable – even though hydrocarbon reserves remain in abundance. In spite of this most scenarios point to continued growth of world population and GDP by 2050 supported by a significant energy demand increase and with a doubling of carbon emissions. Those relatively few scenarios that have shown a reduction in carbon emissions by 2050 have assumed drastic measures have been needed as well as reductions in world GDP.

Carbon dioxide emissions from the energy sector directly relate to:

GDP x energy intensity x carbon intensity of the energy mix.

If any of these parameters increase then so will the total carbon emissions. Energy intensity can be reduced by energy efficiency measures and carbon intensity can be reduced by fuel switching (from coal to gas to renewables and nuclear) and carbon capture and storage.

The necessary transition to a future secure and decarbonised world will involve continued development of a wide range of technologies and their greater uptake, especially low emitting renewable energy systems, biofuels, advanced nuclear power, carbon capture and storage methods, hydrogen and distributed energy. Many of these technologies are at an early stage of development and require greater public and private investment in research, development and demonstration if rapid deployment and diffusion are to result. Research investment has varied greatly from country to country but overall remains significantly less per year than the levels achieved as a result of the oil shocks during the 1970s.

The potential to mitigate for carbon dioxide emissions from the energy sector by the uptake of new and emerging technologies and switching between energy sources is difficult to determine as it relies on many unpredictable variables and future government policies. Abundant sources of primary energy sources from both finite fossil fuels and renewable energy fluxes remain available to meet global energy demand for centuries. However the rate of transition to a decarbonised world is also uncertain. So the potential emission reductions from the energy supply sector costing less than $100 /tC avoided remain at between 350-700 MtC by 2020 as identified in the TAR.

A wide range of policies are already in place, mainly in OECD countries, to encourage the deployment of low emitting technologies. However the use of cheaper fossil fuels, often heavily subsidized by governments, will remain dominant in all regions to meet ever increasing energy demands unless the full benefits of environmental and health issues from their use are properly valued. Renewable energy systems in particular have proven benefits linked with energy access, health, equity and sustainable development.

In summary:

- It is vitally important to meet the future needs of all people by providing basic and affordable energy services (such as comfort and mobility) using all available energy resources with innovative conversion technologies while minimizing GHGs and other environmental damages. To accomplish this will require collaboration of governments and the global energy industry.
- There is a critical need to improve the overall delivery of energy services and to minimize disruptions to the climate systems by integrating the provision of heating, cooling, electricity and transport fuels and increasing energy supply system efficiency. This can be accomplished within the primary energy, energy management, agriculture, forest, water, waste, communication and environment sectors. The optimum method and scale of integration will vary with region, rate of growth of energy demand, existing infrastructure and identified co-benefits.
- Near-term government intervention and coordination in terms of appropriate policies and measures is critical to provide strategic direction for energy investment decisions if carbon emissions are to be abated. In addition much more and sustained public and private research investment is essential if we are to better understand our energy resources and develop cost effective and efficient low or zero carbon emitting technologies.
- These actions will determine future:
    - security of energy supplies;
    - deployment of energy carriers and conversion technologies;
    - accessibility, availability and affordability of desired energy services;

  - attainment of sustainable development;
  - quantities of GHGs emitted for most of this century; and
  - thus achievement of Article 2 of the UNFCCC objectives.

4.1 Introduction

Secure and sustainable energy is vital to future prosperity. For all people to have adequate food, water, processed materials, comfort and mobility, health and social well-being, longer life expectancy skilled employment and generally higher standards of living, supplies of energy a need to be secure and reliable, affordable and with minimal adverse environmental impact. A vibrant energy industry is vital for the global economy to be able to support the lifestyle expectations of everyone without which economic depression and social deprivation will continue.

Globally, demand for all forms of energy has continued to rise to meet the demand of a growing population and expanding economies. This demand will continue to drive the global energy technology industry to provide new and improved infrastructure as well as energy carrier and conversion systems which will require a total investment of $US17.5 trillion (or around 1% of global GDP) by 2030 (IEA, 2004). Total annual capital investment by the global energy industry is around US$280 with energy R&D investment of around $US8.1 billion by governments (IEA Statistics, 2005) and perhaps half to a third of this again by industry.

Energy technology solutions will continue to emerge from private and public investment and international collaboration in basic and applied research, development and demonstrations. Market deployment will result at a rate related to the level of investment.

The economic, social and environmental risks of being unprepared for major future supply constraints are immense. The social obligation should be to ensure that energy security is achieved so as to not compromise the ability of future generations to meet their own well-being and needs for energy services.

The United Nations has set goals to eradicate poverty, raise living standards and encourage sustainable, economic and social development in its Millennium Declaration, (UN 2000). To succeed everyone will require improved access to modern energy. At present the 1 billion people living in developed (OECD) countries consume around half of the 490 EJ annual global primary energy demand whereas 1 billion of the poorest people only consume around 4%, mainly in the form of traditional biomass used for cooking and heating. As the global population increases and developing countries attempt to alleviate poverty by expanding their economies, primary energy demand could double before 2050. Technological development, improved energy efficiency, diversity of energy supply systems and provision of affordable energy services are imperatives to meet this growing demand.

A transition in global energy supplies away from traditional fossil fuel use to low or zero carbon emitting energy systems is necessary as a part solution to greenhouse gas emission reduction. It is yet to be determined which technologies will help drive this transition, which policies will provide appropriate impetus for their uptake, and which countries will become sustainable energy developers. A mix of options to lower the carbon intensity of energy supply systems (chapter 4) and to encourage the more efficient use of energy (chapters 5, 6, 7 and 8) will be needed to achieve a truly sustainable energy future in a decarbonised world.

Implementing any major energy transition takes time. The rate of new technology uptake depends on the expected lifetime of capital stock and equipment, the relative costs and any new proposition value. It took over 50 years for computers to reach their current level of use and decades to provide large scale electricity and natural gas infrastructures now common in many countries. Power stations, gas and electricity distribution networks and buildings are usually replaced only at the end of their useful life, which can, in an increasing number of examples, be over 50 years. Delaying the start of the transition process by building "more of the same" will therefore make it more difficult to meet future targets for stabilizing atmospheric greenhouse gas concentrations.

Emerging energy technologies will only diffuse rapidly once they can compete economically with existing alternatives or are seen to provide a new value proposition (for example if appropriate government policy incentives such as emission trading systems are made available to help them compete). For energy supply systems there has often been a lag between a technology reaching maturity in OECD countries and its widespread adoption in developing regions. Investment in state of the art technologies in developing countries without embedded infrastructure may be possible by "leap-frogging" rather than following a similar historic course of development to that of the west, An analogy is the deployment of cellular mobile phone systems overcoming the cost barrier to developing costly landline telephone infrastructures.

In all regions of the world energy demand has grown in recent years (Fig 4.1.1). A 60% global increase in primary energy demand is anticipated by 2030 under business as usual (IEA, 2004). This will require investment of around $550 billion / yr in energy supply systems, mainly for the electricity sector to provide an additional 3500GW of large scale generation plant and transmission networks. Over half the total investment will be needed in developing countries and as a result energy related carbon emissions will rise from 6.42 GtC in 2002 to 10.4 GtC in 2030, assuming business as usual with respect to technology choice. (Note that 1ppm increase in atmospheric carbon dioxide concentration results from 2.1 GtC being released). Any means of reducing carbon emissions is therefore desired in order to slow down the rate of increase of atmospheric concentrations (WBCSD, 2004). Even if carbon capture and storage were widely utilized by 2030 and nuclear and renewable energy generation built instead of coal and gas-fired plants, allowing for the long lifetimes of existing and planned energy plant stock, annual carbon emissions would only be reduced at best, rather than avoided altogether.

INSERT Figure 4.1.1 Global annual primary energy demand from 1990 to 2004 by region (BP, 2005).

Since reduced economic growth is generally unacceptable, a continued decoupling between increasing energy consumption (especially from fossil fuels) and an improved standard of living is needed, particularly in developing countries. This is not yet apparent with respect to electricity supplies in S E Asian countries, though in OECD countries the historical record shows a decrease in the amount of energy needed per capita per unit of GDP to provide increasing energy services.

The current status and possible future of the energy supply sector is outlined in this chapter which links with other sector chapters (Fig 4.1.2). Greenhouse gas emission trends are analysed; developments in the primary and secondary energy sectors evaluated including supply chains; mitigation options, their interaction and vulnerability to adaptation are discussed; linkages to sustainable development and the various risks involved are identified; current policies and instruments are described that may affect future energy use; and investments in research, development and demonstrations to encourage deployment and to support future sustainable energy supply is considered.

INSERT Figure 4.1.2 Primary and secondary energy supplies to meet societal needs for energy services. The Energy supply chapter (yellow box) links with the sector chapters on industry, transport, buildings and wastes.

As global populations increase over time, energy demand will also increase. A projection of global population (Fig 4.1.3) showed the bulk of population growth will be in developing countries (DCs) more than in developed (OECD) states or the former Soviet Union (FSU) (IIASA, 1998). Around two billion people now live without access to basic energy services and have standards of living (life expectancy, infant mortality, environmental conditions, and economies) far below even the least developed country (BIREC, 2005). Without access to electricity and its related energy services, and more modern heating, cooking and transport technologies, these conditions cannot be improved. Since there will likely be around 80% of total population living in the developing world, an unchanged situation in these countries will present an international security issue (at the very least uncontrolled migration, and at the worst international terrorism and potential regional or global conflict).

INSERT **Figure 4.1.3 Estimated and projected world population from 1950 to 2050 (UN, 2002)**

How energy supply will ultimately meet the growing demand for energy services provided to all in developing countries is open to debate. A robust mix of energy sources (fossil, renewable, and nuclear) will probably be required to accomplish this goal. For medicine, agricultural production, food processing, environmental protection, safety, as well as for energy supply, it will be necessary to transfer the most appropriate technologies. How best to meet future energy demand varies as shown by three possible scenarios, two of them at the extremes (WEC, 2004 adapted from IIASA/WEC, 1998):

- high growth, with very large productivity increases and wealth being both technologically and resource intensive and technological changes yielding rapid stock turnover with consequent substantial improvements in energy intensity (energy / unit of GDP) and efficiency;
- business-as-usual, being a more cautious approach to economic growth, rate of technological change and energy availability, hence having a higher probability of occurrence; and
- reduced energy consumption, with a goal to reduce carbon emissions to 2 GtC/yr by 2100. This is technologically very challenging and assumes unprecedented progressive international cooperation focused explicitly on environmental cooperation, international equality, and aggressive changes in lifestyle in terms of resource conservation and dematerialization.

At present about one third of final energy currently reaches consumers in solid form as coal and biomass (which are the primary cause of many local, regional, and indoor air-pollution problems associated with traditional energy uses); one third is in liquid form, (consisting primarily of oil products used in transportation); and one third is through distribution grids in the form of electricity and gas (mostly natural gas methane) (Fig. 4.1.4). Over the next few decades, and across all three scenarios, the delivery of solid fuels will decline as they will be increasingly converted to the energy carriers of electricity, gases and liquids, thereby leading to a reduction of adverse environmental and health impacts. The share of energy liquids will remain but with a gradual transition toward synfuels, such as methanol from coal and ethanol from biomass. The share of grid-oriented energy carriers will probably increase to about one half of all consumer energy by 2100. New energy carriers such as hydrogen will only become more prevalent towards the end of the century whereas the development of smaller scale distributed energy systems and micro-grids could occur much sooner (Datta *et al.*, 2002; IEA, 2004d).

INSERT **Figure 4.1.4. Final energy across three scenarios (A,B,C) showing a gradual shift toward gird-oriented energy carriers and away from the direct use of solids, which are instead converted to synfuels, electricity, and energy gases (WEC, 2004).**

4 Mitigation options

Several options to reduce net carbon dioxide emissions to the atmosphere have been identified and categorised (IPCC 2000a; IPCC, 2001),

Reduce energy consumption by both demand and supply side efficiency gains during energy conversion and/or utilisation. On the supply side technological advancements for the generation of electricity have increased energy conversion efficiencies for conventional steam and gas turbines. Combining heating, cooling and electric power generation systems also substantially reduces emissions. On the demand side the energy consumption of vehicles, lighting and many appliances has been reduced by factors of 2 to 4 since 1970 with further improvements and wider applications expected to continue into the future.

Dematerialisation of processes leading to less energy intensive production and hence lower greenhouse gas emissions per unit of production.

Switch to less carbon intensive fuels, for example substituting coal with biomass or natural gas which can be cost-effective where suitable fuel supplies are available. Typical emission reduction is around 100-115g C/kWh electricity when changing from coal to gas or even greater if using co- or tri-generation.

Increase the use of renewable energy sources which emit little or no net CO_2 emissions. There are a wide variety of renewable energy supplies potentially available, including wind, solar, biomass, hydro and ocean energy, the resource varying with geographic location. They could make significant contributions to electricity generation, vehicle fuels and heating or cooling, thereby displacing fossil fuels.

Provide more nuclear power with zero stack emissions from power plants and low emissions from the front-end fuel cycle. The speed at which its use might be increased will be determined by the sector's ability to achieve a broader social acceptance than it presently enjoys in many countries regarding economic competitiveness, safety, long term management and disposal of high-level nuclear wastes, proliferation and terrorism. Its future role is more likely to be determined by the political process and public opinion rather than by technical factors.

Sequester CO_2 through the enhancement of natural, biological sinks such as forests and soils enhanced to take up carbon from the atmosphere (IPCC, 2005). Natural sinks already play a significant role in determining the concentrations of CO_2 in the atmosphere. Agricultural and forestry practices could significantly enhance their carbon storage capacity though this may be limited by land-use practice, and social and environmental factors. Carbon stored biologically (as in plantation forests) may not always be secure (being re-emitted to the atmosphere as a result of forest fires).

Capture and sequester CO_2 from fossil and biomass fuel combustion, industrial processes and fermentation using physical or chemical storage in geological sites or in the ocean. Where this option is applicable, it should be able to make deep reductions in emissions from central electric power plants, industrial facilities and other major centralized sources, (but not in oil based transportation which currently uses around 36% of global energy). The issues of concern for this option such as the cost relative to other mitigation options, the uncertain period that carbon dioxide will remain stored stably and avoid the risks of abrupt or slow release, transportation to disposal sites, and the political acceptability of this approach have been elaborated on in a special report (IPCC, 2005).

Reduce leakage of methane emissions during natural gas production, processing, transmission and distribution.

Technologies either exists or are being developed to reduce the addition of anthropogenic carbon into the atmosphere (BP, 2005b). Pacala & Socolow (2004) introduced the concept of a “wedge” to identify an activity beginning now to gradually reduce the rate of carbon buildup in the atmosphere such that 1 billion tC /yr would not otherwise be added in 2054 (Fig 4.1.5). One wedge is the equivalent of replacing about 50 EJ of primary energy in 2050 (average 25 EJ/yr over the period) from the mix of fossil fuels used in the world today. Renewable electricity and transport fuels were assigned one of the seven wedges. Potential parts of other wedges include more efficient vehicles and buildings; mass transit systems; efficient coal power; switch to natural gas; solar PV and wind energy replacing coal for power production; carbon capture and storage in fossil based systems; nuclear power; biomass replacing fossil fuel for power and for making liquid fuels; reforestation and soil tillage.

INSERT Figure 4.1.5. Technologies (wedges) that could conceivably each avoid releasing 1GtC/yr from fossil fuels by 2054 (Pacala & Socolow, 2004).

Each of the options can potentially play a role in reducing CO_2 atmospheric concentrations. The extent to which each option will be utilised will depend on many factors including costs, potential capacity, the extent to which emissions must be reduced, environmental impacts, rates at which the technology can be introduced and social factors such as public acceptance.

4.1.2 Summary of Third Assessment Report (TAR)

The TAR identified reductions in greenhouse gas emissions that occur both through the introduction of lower emitting replacement technologies and by improved efficiency of existing ones. Low emission technological innovations by industry and from government supported research and development are introduced into the market because of multiple drivers including economic profit or productivity gains, non-energy related benefits from the technology, tax incentives and environmental, efficiency and other regulations. Except when low emission technologies are encouraged by specific tax or other incentives, or are mandated by policies, low emissions are seldom a factor in their adoption. The drivers for choosing lower emission technologies differ among industrial nations, economies in transition and developing countries. Foreign Direct Investment and Official Development Assistance each provide unique opportunities to bring low emission technologies to developing countries if there are deliberate policies to do so. The problem of technological lock-in by existing technologies and the economic and political and social systems that support them was seen as a major barrier to the introduction of low emission technologies in all types of economies.

The TAR examined estimates of fossil fuel consumption relative to resources and known reserves of fossil fuels. It estimated that 296 GtC were released from fossil fuel combustion between 1860 and 1998, and annual releases were approximately 6.5 GtC/yr. Known reserves were equivalent to 1549 GtC, with a conventional resource base estimated at 4,959 GtC. Methane clathrates contain an estimated additional 12,000 GtC. Hence there is at least 5 times as much carbon in proven conventional reserves of oil, gas and coal as has been burned during the entire industrial revolution. Fossil-fuel scarcity, at least at the global level, is therefore not a significant factor in considering climate change mitigation. More than two thirds of the carbon in the reserves is as coal. Hence there is an abundance of fossil fuels that if burned without carbon sequestration, will contribute to atmospheric CO_2 concentrations in the future. Debate continues over whether petroleum production from conventional oil is likely to peak soon (section 4.3.1.1.3).

Electric power sector emissions of 2.1 GtC/yr (37.5% of total C emissions) were projected to rise to 4.0 GtC by 2020 because of the expansion of coal power plants in many countries including India and China. In 1995, coal was the leading source of electrical power (38%) followed by hydropower (18%), nuclear (17%), natural gas (15%), oil (10%) and other renewables (2% but fastest growing with wind increasing 21% and solar 30% per year). Natural gas was projected to grow the most to be used in very efficient combined cycle gas turbines, while nuclear production was expected to decline slightly between 2010 and 2020. Hence it was anticipated that the electric power sector will receive major attention for greenhouse gas mitigation.

Chapter 3 of the TAR included an extensive table (3.36) of energy supply and end use efficiency options that were especially promising for reducing CO_2 emissions from the industrial and electric power sectors. The section on energy sources indicated that there are many alternative technologies to reduce GHG emissions, including more efficient electrical power generation from fossil fuels, greater use of renewable technologies and nuclear power, utilization of biofuels, biological carbon sequestration and the physical capture and storage of CO_2. It was estimated that a cost effective reduction of 350-700 MtC is possible in the electric power sector (Table 3.37) with opportunities divided nearly equally between developed and developing countries. Improved end-use efficiency held the greatest potential for reductions during the period up to 2020.

Opportunities to reduce emissions of methane were identified including extracting it from coal-mines and utilizing it as a low carbon fuel; reducing its release during production of oil and gas; and lowering losses during transport and use of natural gas. In addition, the effectiveness of distributed generation and combined heat and power in lowering CO_2 emissions during electrical power production using fossil fuels, renewables and fuel cells especially by industry and for district heating of buildings was recognized.

Barriers to implementing the technologies and measures identified included a lack of human and institutional capacity, imperfect capital markets that discourage investment in small decentralized systems, uncertain rates of return on investment, high trade tariffs on emissions lowering technologies, lack of market information, and issues of intellectual property rights for mitigation technologies. For renewable energy, high investment costs, lack of access to capital, policy impediments to distributed and combined heat and power systems and subsidies for fossil fuels constrained their adoption. Altering agricultural practices could substantially expand the use of biomass in many sectors including for power production and transport fuels. Appropriate national and international policies will help to overcome these barriers.

4.2 Status of the sector

Energy services need to be provided from a range of energy sources to meet society’s demands, but in so doing impacts on the environment and social issues can be significant. Recent liberalisation of energy markets in many countries has led to energy supply security and affordability of energy services taking priority over resulting environmental impacts.

Primary energy sources (Fig. 4.2.1) come from the natural endowment of finite and non-renewable fossil fuel, geothermal heat and radioactive mineral supplies produced during the Earth’s geological and biological evolution; gravitational and rotational forces from the moon and sun; and the solar flux, being a renewable energy source in human time scales. The solar flux supplies both short term intermittent energy forms including wind, waves, and sunlight, and more predictable energy (with seasonal variations) when the solar energy is stored in biomass, ocean thermal gradients and potential hydrologic water supplies. In order to obtain desirable energy services, sources and carriers of energy are required.

Figure 4.2.1 Global energy flows and carriers from primary energy through secondary energy conversions to end uses.

Notes:

1) The current capacity of energy carriers is shown by the width of the lines.
2) Further energy conversion steps may take place in the end-use sectors, such as the conversion of natural gas into heat and/or electricity on-site at the individual consumer level.
3) Sources: IEA, 2004; IEA Highlights (2004 Edition).
4) Building and other sectors include residential, commercial and public services and agriculture.
5) Peat is included with coal.
6) Waste is included with biomass.

Consumer energy can be derived directly from a natural primary source (e.g. fuelwood, natural gas or coal) or from a secondary energy carrier using conversion technologies (e.g. electricity, diesel fuel, hydrogen, bioethanol). Primary energy sources must be extracted, collected, concentrated, transformed, transported, distributed, and stored (if necessary) using technologies which at every step of the supply chain consume some energy (Fig 4.2.2). The conversion efficiency of the system represents the cost, in both monetary and energy terms, of delivering useful energy services to the consumer.

INSERT Figure 4.2.2. To obtain 1 energy unit of useful light requires 320 units of primary energy combusted in a thermal, steam turbine, power station to overcome the supply chain losses. Improving the generation plant conversion efficiency from 35% to 50% using a combined cycle gas turbine plant (CCGT) would reduce this to 224 energy units but using a compact fluorescent light bulb instead of a standard light bulb would only require 45 units to be generated. (Cleland, 2005)

Energy services to enable appliances to be used to improve quality of life, provide comfort and mobility, and remove drudgery are the main goal of all transformations. Value is obtained when energy sources are employed to increase economic growth, aid development and keep societies functioning, but often with adverse environmental consequences.

Energy supply analysis must be integrated with energy demand since both these aspects of energy use are inextricably and reciprocally dependent. Energy efficiency improvements can occur in conversion of primary energy resources into energy carriers (e.g., mining, refining); conversion of primary energy sources and carriers into electricity and/or heat; transmission of electricity and heat; and within the sectors (transport, buildings, industry – see chapters 5, 6 and 7).

Reducing energy intensity during recent decades has largely focused on improving the efficiency of technical appliances and devices along with demand side management, as well as improving the efficiency of conversion processes. Non–technical solutions to energy demand reduction relate to behaviour, culture, habits and social lifestyles. Reducing energy demand by the consumer using more efficient appliances also reduces energy losses and carbon emissions along the supply chain and is usually cheaper and more efficient than increasing the supply quantity (Fig 4.2.2). Reduced energy demand however has been largely offset by the ever increasing numbers of appliances and vehicles.

Total global energy demand reduction in developed countries is imperative if mankind is to support the socio-economic development of the 2 billion people who at present have limited or no access to electricity and other commercial energy carriers necessary for education, sanitation and health services, employment, entertainment and other human rights. Increasing the implementation of renewable energy will aid this sustainable development goal (Renewables, 2004). For sustainable development to succeed, per capita energy demand will need to increase for those living in the developing world (BIREC, 2005).

The uptake of local energy sources such as landfill gas or coalbed methane may assist isolated communities in poverty without increasing GHG emissions to the same degree as coal to provide the same energy services. Introducing new approaches to provide energy services by employing renewable and non-carbon producing energy sources and more efficient and modern net carbon-free technologies that require less primary energy will help stabilize GHG atmospheric concentrations (Jochem *et al*., 2002; Duchin *et al*., 1994). China, for example, has legislated for 10% renewable electricity by 2010 and has a goal of 15% of its primary energy from renewables by 2020 (Martinot, 2005). Most of this will be installed as a way to reach the poor in isolated areas not easily accessible by an electric grid or pipeline. With the annual growth in 2003 and 2004 of power generation plant capacity around 55-60 GW$_e$ (equivalent to the total capacity of the UK) mainly coming from coal plants (Zheng, 2005), this will be no easy achievement.

4.2.1 Energy access and energy security

Energy access is the availability of adequate and affordable energy supplies and associated energy services essential to support the global economy. Lack of access frustrates the aspirations of developing countries with over one-third of their population without access to modern energy carriers crucial to their economic and social evolution. In the absence of improved energy access for all it is unlikely that the United Nations' Millennium Development Goals of halving the proportion of people living on less than a dollar a day by 2015 will be met. Achieving this target implies a need for increased access to electricity and expansion of modern cooking and heating fuels for 600 million people in developing countries mainly in South Asia and sub-Saharan Africa (IEA, 2004). By 2030 around 2,400GW of new power plant capacity will be needed in developing countries which, together with the necessary infrastructure, will require around $5 trillion investment.

To achieve the same percentage of developing country populations having access to electricity that is presently the case in developed countries by year 2020, over 100 million people per annum will need to gain access to electricity which will be difficult to achieve. To meet this target present efforts will need to be greatly exceeded based on the historic electricity access rate of 40 million people per annum in the 1980s and 30 million in the 1990s. Access to modern and new technologies which employ renewable energy efficiently is the key to sustainable development in the long term because these sources will last indefinitely by human scales.

Security of existing energy supplies is a major challenge facing developed and developing economies alike since prolonged disruptions will cause major economic dislocation. Major global consumers of petroleum and natural gas resources, including OECD countries, China and India, depend to varying but significant degrees on fuels imported from distant, often politically-unstable regions of the world. For example, currently 26 million barrels of oil are shipped daily through the Straits of Hormuz in the Persian Gulf and the Straits of Malacca in Asia. A disruption in supply at either of these points could have a severe impact on global oil markets. In the foreseeable future international trade in oil and gas will expand and so the risks of supply disruption will increase (IEA, 2004).

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The term "security of supply" also relates to the capacity of an electricity infrastructure system meeting growing load demand as well as the threat of terrorist or revolutionary attacks on power plants, transmission & distribution lines, gas pipelines etc. Overall energy security is therefore more than just security of existing supplies but includes diversity and increased domestic supply capacity.

4.2.2 Effects of price fluctuations

Price uncertainties are involved with every energy source. Oil and gas price fluctuations impact on world economies, particularly those from developing countries. The poorest economies suffer most because they cannot afford short-term price spikes without reducing the investment budget necessary for modernizing their energy infrastructure. Nuclear power price uncertainties also exist due to surplus uranium supplies lowering costs, financial markets being unwilling to invest, and increasing environmental concerns raising the costs of obtaining resource consents. Renewable energy systems also face uncertainty in terms of dry years for hydro, poor crop yields for biomass, increased cloud cover for solar radiation and changes in mean annual wind speeds. Varying energy prices will also affect the carbon trading price.

4.2.3 Development trends in the energy sector (production and consumption)

Global primary energy consumption almost doubled from 238 EJ in 1972 to 426 EJ in 2002. The average annual growth was 1.4% /yr during the period 1990-2002 which was lower than the rate of 2.4% /yr for the period 1972-1990 due to the dramatic decrease in primary energy consumption in the former Soviet Union (FSU) (Fig 4.2.3) and to energy conservation and efficiency improvements in OECD countries. The highest growth rate in the last 12 years was for Asian developing countries (3.2% /yr) and North America (1.5% /yr). There is a large discrepancy between the primary energy consumption per capita ranging from 336 GJ /yr in 2002 for a North American to around 26 GJ /yr for an African (Enerdata, 2004), (although there is high uncertainty in energy use data, especially from developing countries). The region with the lowest per capita consumption has changed from Asia developing countries in 1972 to African countries today.

INSERT Figure 4.2.3. Trends in primary energy consumptions in world regions (BP, 2005)

Primary energy consumption data of the major energy sources since 1972 shows that oil and coal are still the most important with coal increasing its share since 2000 (Fig. 4.2.4). The total share of fossil fuels dropped from 86% in 1972 to 80% in 2003 mainly due to the increase of the share of nuclear energy (BP, 2005). Biomass contributed 11% of primary energy consumption in 2002 (Table 4.2.1) with more than 80% used as household fuel for cooking and heating in developing countries.

INSERT Figure 4.2.4. World primary energy consumption by fuel type (Enerdata, 2004).

INSERT Table 4.2.1. Total global primary energy consumption mix in 2002 (Enerdata, 2004).
Note: Hydro is sometimes quoted in hypothetical thermal equivalents when its share would be closer to 6% (see www.iea.org/textbase/stats/questionnaire/faq.asp)

4.2.3.1 Electricity

Since 1995 global electricity generation has had an average growth rate of 2.8% /yr (IEA, 2004) and is expected to continue growing at a rate between 2.5 - 3.1% /yr until 2030 depending on assumptions made for the IEA "reference" and "alternative" scenarios (Table 4.2.2). Coal and natural gas fired power generation are expected to retain their dominance, but with non-hydro renewables increasing to 5% share in the reference scenario and 8% in the alternative scenario in 2030.

INSERT Table 4.2.2. Global electricity generation by energy type (Enerdata, 2004; IEA, 2004). Note: Biomass includes all combustible renewables and wastes though a portion is not truly 'renewable'.

In 2002 coal plus lignite fuels provided 32% of world electricity production with natural gas providing 19%, nuclear 17%, hydro 16%, and oil 7% (Enerdata, 2004). Non-hydro renewable energy power plants have expanded substantially in the past decade with wind turbine and photovoltaic installations growing by 30% annually and 10% for solar heating. However they still supply only 1.8% of the electricity market (Table 4.2.2).

The average electrification rates in the Middle East, North Africa, East Asia/China and Latin America have resulted in grid connection for over 85% of their populations whereas sub-Saharan Africa is 23% (but only 8% in rural regions) and South Asia is 41% (30% in rural regions) (IEA, 2002). Therefore it appears that socio-economic development of the least developed countries relates to the lowest electrification rate.

4.2.4 Emission trends -all gases

4.2.4.1 Carbon dioxide emissions

Global CO_2 emission stabilized after the two oil crises in 1973 and 1979 and then growth continued (Fig. 4.2.5) averaging 1.9% /yr during the period 1990-2003. The European Union's carbon emissions almost stabilized in this period mainly due to reductions by Germany, Sweden and UK offsetting increases by other members of the EU-15 (BP, 2004). The total had risen 6.5% by 2003 but with higher emissions anticipated in future due to switching back to coal from gas and increased transport. Other OECD countries including North America increased by 25% during the same period, Brazil by 49% and Asia and Pacific countries by 33%.

INSERT Figure 4.2.5 Global CO_2 emission trends by region from 1972 to 2002 (Enerdata, 2004)

Carbon emissions need to be placed in the context of energy intensity and GDP growth to be meaningful (Chapter 1). Asia had the highest annual economic growth in the 1990 -2003 period (4.2% /yr). Carbon emissions from Central and Eastern Europe and the former Soviet Union dropped by 38% between 1989 and 1999 due to the economic transitions and have since started to increase.

From 1990 to 2000 China's carbon dioxide emissions increased from 666 MtC to 881MtC to become 13.7% of global emissions (IEE, 2004) but at relatively low per capita levels. Continuous technical progress towards energy efficiency however has led to a decline in carbon dioxide emissions per unit of GDP (Wang, 2004).

4.2.4.2 Methane emissions

Coalbed methane (CBM) is naturally contained in coal seams and adjacent rock strata. Unless it is intentionally drained and captured from the coal and rock the process of coal extraction will liberate methane into the atmosphere. Around 10% of total anthropgenic methane emissions in the USA are from this source (US EPA, 2003). The 13 major coal-producing countries together produce 85% of worldwide CBM estimated to be 237 $MtCO_2$-eq in 2000. China was the largest emitter (102 $MtCO_2$-eq) followed by the US (36 $MtCO_2$-eq), and Ukraine (30 $MtCO_2$-eq). Total CBM emissions are expected to increase to 308 $MtCO_2$-eq in 2020 (US EPA, 2003) unless mitigation projects are implemented.

Several CDM projects are being developed in China to reduce CBM emissions (UNFCC, 2005). Methane (around 1% by volume) is extracted from the ventilation airflow at the coal mine and concentrated to a gas with about 60% CH_4 content then used to fuel reciprocating engines used to power generators. Income from the sales of emission reduction credits of around US$5/t CO_2 result in the cost of electricity production being below the average Chinese wholesale price of US$35/MWh.

Methane emissions from natural gas production, transmission and distribution are uncertain (UNFCCC, 2004). According to default emission factors, 0.3-1.6% of natural gas consumed is emitted to the atmosphere (IPPC, 1997). Most of the emissions reported to the UNFCCC in 2002 were in this range. An average calorific value of 39MJ/m^3 of CH_4 and a density of 716.8 g/m^3 implies a global emission of 5-26 Mt CH_4 in 2002, lower than the 25-50Mt CH_4 estimated by Weubbles & Hayboe (2002). Modern leak detection and repair equipment can reduce the emissions from compressor stations and gate stations in natural gas transmission pipelines.

For more than a decade, flaring and venting of the gas associated with oil extraction has remained stable at a level of about 300 Mt CO_2-eq. Developing countries account for more than 85% of this emission (GGFR, 2004). The large amount of methane presently being vented and flared in Nigeria will, from 2008, be collected and transported to Benin, Togo, and Ghana in a 617 km long pipeline.

4.2.4.3 Nitrous oxides

During combustion of fossil fuels and biomass, nitrous oxides as well as methane are produced (Global Emission Report, USEPA, 2005).

4.2.5 Regional trends

The Asia-Pacific region has almost 30 % of proven coal resources but is highly dependent on imported energy, particularly oil, now the largest source of primary commercial energy consumption in the region (Table 4.2.3). In 2003 82 % of imported oil came from the Middle East and the region will continue to depend on OPEC countries.

INSERT Table 4.2.3 The Asia-Pacific region's share of global proven fossil fuel reserves, and regional annual production and consumption in 2003

A continuation of China’s rapid annual economic growth of 4.5 % from 1990 to 2003 will result in continued new energy demand, the primary energy consumption having increased steadily since 1980s. Energy consumption in 2003 reached 1,178 Mtoe which became double that of Japan (BP, 2004). High air pollution in China is directly related to energy consumption particularly from coal combustion which produces 70% of particulate emissions, 90% sulphur dioxide, 67% nitrogen oxide and 70% carbon dioxide.

Chinese coal reserves are probably sufficient to last at least another hundred years at present extraction rates but the government is aiming to decrease the share of coal in the primary energy mix due to stricter emission standards, transport issues and safety in the coal mines. There are constraints for expansion of oil production, both in reserves and economics. Daquig, the biggest oil field in China, has already peaked in its production and since 1993, China became one of the major oil importing countries. Clean-burning natural gas and the emergence of new technologies (including renewable energy) will play an increasingly important role in the market due to heightened environmental awareness.

Recent years have seen a stronger movement toward increased use of natural gas throughout the Asian region, although its share of 12% of primary energy remains lower than the 26% and 23% shares in the United States and Europe respectively (BP, 2004). Gas resources in the Asia-Pacific region are usually located far from the largest centres of demand, which has contributed to the slow development of a regional market. A liquefied natural gas (LNG) market has emerged in the region with about 75% of worldwide trade.

Nuclear and hydropower play an important role in electricity generation in some countries of the Asia-Pacific to offset rising electricity demand. Nuclear power currently provides nearly a third of Japan's electricity but plans for the construction of new reactors has been scaled down from thirteen to four with a target to expand the current 45 GW to 50GW in 2010 (IEA, 2004).

Primary energy consumption in the Asia-Pacific region due to continued overall economic growth is estimated to increase by 1.0 % annually over the period 2002-2030 in OECD Asia, 2.6% in China, 2.1% in India, and 2.7% in Indonesia and will then account for 42% of the increase in world primary energy demand (IEA, 2004). The economic growth rate of each country, except Japan, is between 3-4 %. The region will be faced with both overall energy resource shortages and geographically problematic trade in the coming decades. Energy security risks will likely increase and stricter environmental restrictions on fossil fuel consumption may be imposed.

Transition to a market economy, for all its long-term rewards, has not been an easy process for economies in transition (EIT) from the FSU and its client states. The transition period from a centrally planned to free market economy was accompanied by an economic decline and the total primary energy consumption of Central and Eastern Europe as well as the former Soviet Union in 2000 was only 70% of the 1990 level (Enerdata, 2004). A sharp downturn in GHG emissions resulted and although increasing slightly in the 2000-2002 period, emissions remain some 30% below 1990 levels (IEA, 2003a).

Over the past four years, EIT have generally made significant progress in their economic and political transformation. Market reforms have been accompanied with the opening of these economies, leading to their further integration into the European and global economies. This transition and integration process has advanced at different speeds across various countries, 20 out of the 27 countries having not reached their pre-transition real GDP level by 2002 (UN, 2004).

On 1 May 2004 eight Central and East European countries became full members of the European Union which was a major recognition of their achievements in economic transformation and reintegration into the European economy. As a result the total primary energy consumption of EIT increased by 2% /yr since 2000. Energy demand is expected to continue to increase steadily over the next couple of decades as income levels and economic output expand unless energy efficiency manages to stabilise demand. Growth is likely to accelerate even faster in those countries that have achieved EU membership (IEA, 2003b).

Energy systems in EIT countries are characterised by over capacity in electricity production, high dependency on fossil fuel imports and inefficient use (IEA, 2003b). Renewable energy and energy efficiency can play a role in future energy supply by reducing import dependence and improving the environment.

New concepts of energy policy combining future economic, energy and environmental issues for developing countries will help achieve sustainable development as will international cooperation in energy resource development projects and industry productivity improvement strategies. Combining energy supply security and environmental impacts with the free market economy will help encourage market efficiency, energy conservation, common oil storage, investment in resource exploration and carbon emission trading.

4.2.6 Implications of development

Energy supply is intimately tied in with development in the broad sense, including economic development and increase in the quality of life in all of its aspects such as standard of living, human health, life expectancy, and environmental pollution. Abundant and affordable energy, as well as access to that energy is the basis for the overall quality of life (Chapter 3 and section 4.9). How energy is used will determine how many humans achieve a decent standard of living in the future.

Scenarios often assume an annual increase in global world product (GWP) between 1 and 3% whereas it has in fact been increasing at a rate of about 4% /yr for the past 50 years. However, higher rates of economic growth are generally associated with lower rates of population growth and higher rates of capital turnover leading to lower energy intensity (WEC, 2004). The World Energy Council projected 2000 data out to 2050 for three selected scenarios with varying population estimates. Implications of development were that primary energy demands are likely to be between 600 and 1040 EJ, a 40 to 150% increase. This presents difficulties for the energy supply side to meet energy resource growth requiring technological progress and capital provision, and also provides challenges for minimizing the environmental consequences and sustainability of the dynamic system. Electricity is expected to grow even more rapidly than primary energy use by between 110 and 260% and presents even more challenges in needing to build power production facilities.

Ecological implications of energy supply also result from coal mining, oil extraction, oil transport, de-forestation erosion and riverflow disturbance. Certain synergetic effects can be reached between renewable energy generation and ecological values such as re-forestation and landscape structural improvements but are relatively minor.

INSERT Table 4.2.4. Scenarios for 2050 from WEC, 2004 (A and C cases) and IEA (2005).

4.3 Primary energy sources, supply chain and conversion technologies

The oil crises in the 1970s urged the diversification of energy supply away from oil. Natural gas and nuclear power increased market share especially for electricity generation in developed countries which played a role in lowering greenhouse gas emissions. Renewable energy and hydropower (mainly in developing countries) also contributed to the carbon intensity of primary energy declining from 20 gC/MJ in 1973 (Rotty, 1984) to 17 gC/MJ in 2000 (BP, 2005).

4.3.1 Energy resource potentials and technology status

Energy flows stem from primary sources through energy carriers to provide energy services for the end user (Fig. 4.2.1). The status of various forms of energy is reviewed here along with their estimated available resource potential and current usage rates, conversion technologies, current costs, and issues of environmental impacts. For each resource, future contributions, potentials and technological developments to meet the world's growing energy needs and reduce atmospheric greenhouse gas emissions are covered.

World population rose nearly four-fold during the twentieth century, from 1.6 billion in 1900 to approximately 6.1 billion in 2000 (Fig. 4.1.3). However, world primary energy use increased at a much faster rate, rising more than 10-fold between 1900 and 2000 (Bradley, 1999). Most energy forecasts predict considerable growth in demand in the coming decades and attribute it to increasing growth rates in both developed and developing countries, most notably Asia, especially China and India. Assessments of global energy reserves, resources and fluxes, together with cost ranges and sustainability issues, are summarized in Table 4.3.1. More detailed information on each source appear in subsequent sub-sections.

INSERT Table 4.3.1 Approximate global energy resources (including reserves), annual rate of use, cost ranges for good locations and comments on associated environmental impacts. (Data from BP, 2005; WEC, 2004; IEA, 2004; IAEA, 2004 USGS, 2004; Johansson, 2004)

4.3.1.1 Fossil Energy

Fossil fuels supplied 79.8 % of the world primary energy supply in 2002 (IEA, 2005). Excluding traditional biomass this share approaches 90% and is expected to grow over the next 20-30 years. Oil was the largest constituent at 42%, coal 31%, and gas 27% (BP, 2005). Oil accounted for 95% of the road, water and air transport sector demand (IEA, 2005a) which is projected to grow (IEA, 2003c) as there is no evidence of saturation in the market for transportation services (WEC, 2004). World oil consumption increased 3.4% in the year to 2004, gas by 3.3%, and coal by 6.3%. The remaining reserves of oil and gas are enough to last for many decades and in the case of coal, centuries (Table. 4.3.1). Undiscovered resources extend these projections even further. Oil and gas will continue to dominate world energy supply until at least 2030 if current energy policies remain in place and do not change. IEA (2005b) projected that oil demand will grow by more than 50 % between 2002 and 2030 and gas demand will almost double.

All of this fossil energy use is responsible for about 87% of the anthropogenic CO_2 emissions produced annually (IEA, 2003d). This impact is so substantial (being 87% of the current 7.9 GtC/yr global emissions) that if GHGs are to be reduced significantly, either current uses of fossil energy will have to shift to non-carbon sources, or technologies will have to be adopted that capture and sequester CO_2. Transportation fuels must then be manufactured without GHG release as capture is neigh impossible at the point of use in numerous vehicles. Making these changes calls for major investments in the development of new technologies.

Fossil energy resources remain abundant but contain significant amounts of carbon that are released during combustion. Stabilizing the carbon content of the atmosphere therefore requires decreasing the amount of fossil fuel resources utilized in the future, improving conversion efficiencies, or finding technologies that can separate the carbon and permanently sequester it at reasonable costs.

Total resources available for coal, gas and oil should last for decades under current and anticipated future consumption rates (Fig. 4.3.1). The width of the columns indicates the current consumption level of each resource including uranium, section 4.3.2) and the area represents the reserves size in terms of primary energy.

INSERT Figure 4.3.1. Sufficiency of conventional fossil fuel and uranium resources at current consumption levels.

4.3.1.1.1 Coal and peat

Resources

Coal is one of the world's most abundant fossil fuels which continues to be a vital fuel resource in many countries. Coal consumption accounted for 26% in 2002 of total world energy consumption, primarily in the electricity and industrial sectors, (US EIA, 2005; Enerdata, 2004). In addition to carbon, hydrogen and oxygen, most coals contain sulphur, nitrogen, minerals, and chlorine which on combustion are released to the environment in harmful forms inducing acid rain, smog, forest die off, eutrophication of lakes, and global warming.

Global proven recoverable reserves of coal are about 22,000 EJ (BP, 2004; World Energy Council, 2004) with another 11,000 EJ of probable reserves and an estimated additional possible resource of 140,000 EJ. Although coal deposits are widely distributed, 57 percent of the world's recoverable reserves are located the United States (27%), Russia (17%), and China (13%). India, Australia, South Africa, Ukraine, Kazakhstan, and Yugoslavia account for an additional 33% (US DOE, 2005). Two-thirds of the proven reserves are hard coal (anthracite and bituminous) and the remainder are sub-bituminous and lignite. Together these resources represent almost 3500 Gt of stored carbon. Consumption is currently around 100 EJ/yr which introduces approximately 2.5 GtC/yr into the atmosphere. Assuming an annual growth rate of 4% for coal, the proven reserves would last for another 60 years but total resources would obviously last for hundreds of years under this assumed growth rate.

Peat has been used as a fuel for thousands of years, particularly in Northern Europe. In Finland it provides 7% of electricity and 19% of district heating and in Sweden, Ireland Belarus, Russia and Baltic countries, it is also a significant source of energy. Peatlands are found in all parts of the world except deserts and arctic regions on about 400 Mha (4.5% of total land area) (www.peatmoss.com). Carbon emissions from combustion are realtively high due to low heating values (around 8 MJ/kg), high moisture content and low energy density. When co-combusted with wood fuels, the ashes bind roughly one third of the sulphur dioxide from the peat (Orjala, 2001).

The implementation of modern high-efficiency and clean utilization coal technologies are key to the development of economies, to minimize effects on society and environment (section 4.7.4). The demand for coal is expected to more than double by 2030 and the IEA has estimated that more than 4500 GW of new power plants will be required in this period (IEA, 2004). Major economic projections propose that coal will remain the dominant fuel resource for power generation providing about 40% of total energy sources but releasing about 70% of carbon from coal supplies (www.uic.com.au/nip83.htm). Carbon capture and storage technologies aim to reduce these emissions (section 4.3.1.2)

"Clean coal" technologies are available to virtually eliminate local and regional pollutants of SO_x and NO_x from new coal-fired power plants, but electricity generation costs have increased as a result. In addition since some heat energy is diverted back into the plant by the SO_x and NO_x clean-up technologies, less total power is generated and net CO_2 emissions per kWh are increased.

Exploration, extraction, refining and, transport

Improved geophysical exploration methods such as electromagnetic and seismic techniques, minimise the environmental impacts and improved mining technologies aim to maximise extraction efficiencies while minimising energy usage. The method of coal mining is largely determined by the geology of the coal deposit. Underground mining currently accounts for about 60% of world coal production, although in several important coal producing countries, open cast, surface mining is more common. Surface mining recovers a higher proportion of the coal deposit than underground as all coal seams are exploited so that 90% or more of all the coal present can be recovered.

The coal industry has made substantial progress in recovering and using coal bed methane through drainage systems. Methane capture and utilization can reduce emissions into the atmosphere and provide an alternative energy source. Most of the recovered methane is pipeline-quality gas. Technologies under development, including ultra-lean-burn turbines and methane concentration systems, could expand the options available for recovery and use (Harvey, 2003).

Coal preparation and washing can produce a better quality coal with reduced fines resulting in reduced air emissions and less ash formation during combustion. It is standard practice in many countries, however, substantial quantities of lignites and brown coals are used worldwide without pretreatment, drying or upgrading. This means that there is scope for efficiency improvements by improving the quality of the coal prior to use. Upgrading to supply a more consistent, lower ash content fuel, could increase the average thermal efficiency by at least 2-3% on existing pulverised coal boilers and possibly by as much as 4-5% (IEA, 2002). Simply by washing coal and, in so doing, removing waste material can yield up to a 5% reduction in CO_2 emissions for the same heat output (Wicks, 2005).

Coal can be produced in various forms as alternatives to the traditional dry coal forms which are difficult to transport. Coal-oil slurries prepared by adding heavy oil to coal, or coal-water mixtures can be distributed, stored and handled in a similar manner to oil and burnt in plants designed for coal, oil or gas. Capsules involve compressing coal into water to produce wear-resistant logs or cylinders that are suspended in water and transported in a pipeline. The benefits of this transport system include reduced costs per tonne-mile and significantly less energy requirements compared to other transport methods. The technology saves up to 70% of water used in slurry pipelines while transporting the same amount of material (US DOE, 2002).

A CSIRO (2005) project is being undertaken to investigate the production of ultra-clean coal (UCC) which reduces ash below 0.25% and sulphur to very low levels. This means that pulverised coal might be able to be fed directly into gas turbines and combusted at higher thermal efficiencies. The use of UCC with combined cycle direct-fired turbines for power generation can reduce greenhouse gas emissions by 24% per kWh of electricity compared with conventional coal power stations and reduce greenhouse gas emissions by up to 10% .

Generation

Efficiency improvement is an important option for reducing GHG from coal-fired power plants. The average thermal efficiency for pulverized coal power plants is about 30% worldwide but up to 36% in advanced plant designs in OECD countries (www.ieagreen.org.uk). An improvement in efficiency of 1% reduces the CO_2 emission /MWh by about 2.5% since the same volume of coal produces around 2.5% more electricity.

Continued developments of integrated gasification combined cycle (IGCC) systems and new supercritical combustion technologies are expected to further reduce conventional coal combustion emissions (section 4.4.1.1.2). Fuel to electricity conversion efficiencies have increased from around 35% in typical steam plants to higher than 55% in the best integrated gasification combined cycle (IGCC) designs but for a greater cost of power generated (Equitech, 2001). This has significantly reduced the amount of waste heat and carbon that would otherwise have been emitted per unit of electricity generation (Sims *et al.*, 2003; NEA/IEA 2005). IGCC plants for the production of electricity or, in the future, hydrogen, may involve the capture and separation of CO_2.

The development of new materials will allow higher steam temperatures and pressures to be used in "supercritical" plant designs. The best plants currently commercially available operate at up to 600 ºC and have efficiencies of 48.5% (IPCC, 2001; Danish Energy Authority, 2004). It was assumed that such advanced pulverised coal plants could have wet gypsum desulphurisation (96%) and de-NO_x equipment installed to give <0.04 kgNO_x/GJ, but for an investment cost of approximately €1.1M/MW_e. With further developments requiring steam at 700 ºC and the use of nickel-based alloys, conversion efficiencies could reach 53% by 2015 and 55% by 2025.

One of the most promising advanced coal based cycles with "zero emissions" is DOE's Vision 21 Cycle (US DOE/NETL, 2002) where the efficiency could reach 60% using several advanced concepts. For example high-pressure compressor exhaust is introduced into integrated gasification fuel cells. The fuel cell exhaust is used in a gas turbine to produce additional power without the addition of fuel. The gas turbine exhaust can then be used in a steam turbine to produce additional power. DOE estimates that 63% efficiency is achievable by 2010.

Cogeneration

The amount of GHG emissions produced from thermal electricity generation depends on the type of fuel being used, the efficiency of the power plant, and electricity transmission and distribution losses. A well-designed and operated cogeneration scheme (section 4.4.1.1.3) will always provide better energy efficiency than conventional plant, leading to both energy and cost savings (Fig. 4.3.2; UNEP, 2004; EDUCOGEN, 2001).

INSERT Figure 4.3.2. Carbon emissions and conversion efficiencies of selected coal and gas-fired power generation and cogeneration plant technologies: A) traditional coal-fired steam turbine; B) new clean coal-fired steam turbine; C) coal gasification/ gas turbine; D) new combined cycle gas turbine (CCGT); E) coal-fired cogeneration; F) gas-fired cogeneration. (Source: Minett, 2003).

4.3.1.1.2 Methane fuels

Conventional natural gas

The proven reserves of natural gas remaining are estimated at 179.5 trillion cubic metres (161.6 billion ton of oil equivalent or about 10,000 EJ) (BP, 2005, WEC, 2004, USGS, 2004). Almost three-quarters of the world's natural gas reserves are located in two regions: the Middle East and the transitional economies of the EE/FSU. Russia. Iran, and Qatar combined account for about 56 percent of the world's natural gas reserves. Reserves in the rest of the world are fairly evenly distributed on a regional basis(BP,2005).

The amount of reserve growth in discovered fields and undiscovered resources is not well known, but is considerably significant. According to the probabilistic estimates reported by U.S. Geological Survey, worldwide reserve growth and undiscovered resources expected to be added over the next 25 years account for 66.4 trillion cubic metres (2,510 EJ) and 121.7 trillion cubic metres (4,600EJ), respectively (USGS, 2005). More than one-half of the undiscovered natural gas estimate is concentrated in three regions, the FSU, the Middle East, and North Africa.

Natural gas normally has little or no sulphur and little or no particulates except nitrogen oxides produced during the combustion process, and is the most advantageous as a low-CO_2 energy source among fossil fuels. Natural gas consumption accounts for 23.7% of global energy consumption. Present consumption of natural gas is 2.69 trillion cubic metres or 165 EJ (BP Statistical review, 2005) contributing about 1.55GtC annually to the atmosphere. Use of natural gas is produces 14.3 gC/MJ versus 25.1 and 20.8 gC/MJ for coal and oil use respectively.

Unconventional natural gas

Unconventional natural gas is even more abundant than conventional gas (Table 4.3.2), but much of it is not likely to be developed in the next few decades. Unconventional natural gas is natural gas stored in a variety of geologically complex, unconventional reservoirs, such as tight gas sands, fractured shale gas, coal bed methane, and methane hydrates. Worldwide development and distribution of unconventional gas resources are still limited, concentrated mainly on coal bed methane and selected tight gas sands in the U.S.

Coal bed methane gas trapped on the internal surfaces of coal represents 6 or 7 times as much gas as a conventional natural gas reservoir of equal rock volume. Utilization of coal bed methane reduces the amount of methane released to the atmosphere during the mining process. The coal bed methane resources of the Unites States alone are estimated to be almost 800 EJ but less than 110 EJ are believed to be recoverable economically today (USGSb, 2004). Worldwide resources may be larger than 8,000 EJ but a scarcity of basic information on the gas content of coal resources makes this number highly speculative.

Large quantities of natural gas resources are known to exist in geologically complex formations with low permeability. The tight gas resource is ubiquitous. Most of the exploration and production of tight sand gas has been in the U.S. Estimates of the total gas-in-place in the U.S. vary from 26.2 trillion cubic metres (NPC, 1980) to 425 trillion cubic feet (Surdam, 1995). However, only a small percentage is economically viable with existing technology. Current U.S. production has stabilized between 70 and 100 billion cubic metres per year.

INSERT Table 4.3.2 Unconventional natural gas resources (Encyclopaedia of Energy, 2004)

Methane gas hydrates, also known as clathrate compounds, are crystalline solids composed of methane and water molecules. They occur abundantly in nature and are stable as deep marine sediments on the ocean floor at depths greater than 300 m and in polar permafrost regions (Kvenvolden 1988, 1993, 1998; Satoh, 1996). The amount of carbon bound in global gas hydrates is not well understood, but is estimated to be twice as large as in all other known fossil fuels (USGSa, 2004). Hydrates may provide an enormous resource (60,000 EJ (USGSa, 2004) but recovering the methane is difficult and represents a significant environmental problem if the methane were to be unintentionally released to the atmosphere during extraction. Safe and economic extraction technology still needs to be developed (USGSa, 2004). Technologies such as injection of hot water or depressurizing are being evaluated. Governments of USA, Canada, Russia, India, and Japan are encouraging research to utilize this promising source of energy (Encyclopaedia of Energy, 2004)

Extraction, processing, transportation, distribution

Over the past two decades, the natural gas industry and others have tried to reduce the methane emissions lost to the atmosphere during extraction, processing, transportation, storage, and distribution of natural gas. Among the numerous studies to estimate methane emission during the whole process, the most commonly cited leakage rates range from 1-4 percent of the gross natural gas produced (Kirchgessner *et al*., 1997). Transportation and storage account for the largest portion of the total methane emissions at 37% followed by extraction at 27%, distribution at 24%, and processing contributing the least at 12% according to the study of the US EPA (Harrison *et al*., 1997).

The worldwide trade and utilization of gas highly depend on the availability and economies of gas transportation and distribution facilities. Pipeline transportation is the oldest and most common technology and widely utilized worldwide for transportation of natural gas. The worldwide extent of natural gas pipelines is estimated at 868,400 km in length and 47% of the total length is located in the U.S. (The World Fact book, 2005).

Liquefied natural gas can be more conveniently, safety, and economically transported in large quantities than can gases. At present, LNG trade accounts for about 6% of world natural gas consumption and about 26% of total international natural gas trade in 2002. The Pacific Basin is the largest LNG producing region in the world, supplying 49% of all global exports in 2002 (Annual Energy Outlook, 2005). LNG transportation is expected to increase substantially and play a prominent role in the future. According to US-EIA's Annual Energy Outlook 2005), the share of total U.S. natural gas consumption met by net imports of LNG is expected to grow from about 1 percent in 2002 to 15% (0.12 trillion cubic metres) in 2015 and 21% (0.18 trillion cubic metres) in 2025. Energy loss on LNG liquefaction process is estimated at 7 to 13% of withdrawn natural gas, larger loss than the around 5% typical of pipeline transportation loss over 2,000 km with consequent effects on the amount and potency of greenhouse gases released to the atmosphere.

Production, consumption, generation

Natural gas production has been increasing at an annual growth rate of 2.6% in the past decade (1994-2004). Since the 1980s natural gas production in the Middle East and the Asia-Oceania has been gradually increasing. 30% of the world's natural gas in 2004 was produced in the Middle East, while Europe and Eurasia produced 22%, and North America 17% (BP Statistical review, 2005).

According to the forecast of the U.S. EIA (International Energy Outlook, 2005), natural gas is projected to be the fastest growing primary energy source worldwide, maintaining average growth of 2.3% annually over the 2002 to 2025 period. Total world natural gas consumption is projected to rise from 2.65 to 4.4 trillion cubic metres (165 to 270 EJ) in 2025. The power generation sector and industrial sector remain important end-use consumers for natural gas worldwide. The electric power sector accounts for nearly 50% of the increase in global natural gas demand over the 2002 to 2025 period, and the industrial sector accounts for another 36%.

Natural-gas-fired power generation has grown rapidly since 1980s. It is seen as a desirable option for electric power in many parts of the world because it is relatively superior to other technologies in environmental benefits, fuel efficiency, operating flexibility, rapid deployment, and lower installation costs. Natural gas is expected to remain an important supply source for new electric power generation in the future. Its share of total energy used to generate electricity worldwide is projected to increase from 18% in 2002 to 24% in 2025 (DOE/IEA, 2005).

Combined-cycle gas turbine (CCGT) plants produce less carbon dioxide per unit energy output than other fossil technologies because of the high hydrogen-carbon ratio of methane and the relatively high thermal efficiency of the technology (see also section 4.4). A large number of CCGT plants currently operating, being built, or planned are generally in the 10-500 MW size range. An existing single cycle gas turbine in the medium range would normally have an efficiency of 32%. The efficiency for a medium sized 10-100 MW CCGT plant is currently about 50%. Advanced gas turbines currently under development, such as so-called "G" designs, will have efficiencies approaching 60% through the use of high combustion temperatures, steam-cooled turbine blades, and more complex steam cycles.

CCGT with high thermal efficiency also contributes to increase the efficiency of cooling and heating heat supplied by heat pump in the demand side. Electric heat pump (EHP) makes remarkable progress in coefficient of performance(COP), which is 3 to 4 available in general commercial use(Kiho *et al.*, 2004) and 6.4 as maximum COP of turbo refrigerator (www.mhi.co.jp/aircon/). Fuel cell cogeneration system combined with absorbed heat pump (AHP) can supply energy with total efficiency of 67% consisting of 35% for electricity and 32% for cooling heat of air conditioning. If the same amount of heat and electricity demand is supplied by electric heat pump and grid electricity which is generated by advanced CCGT, the system consumes 75.5% of the amount of natural gas required for phosphoric acid fuel cell (PAFC) cogeneration system (Fig. 4.3.3). A system consisting of a heat pump combined with CCGT can achieve higher system efficiency and produce less carbon dioxide than cogeneration system fuelled by natural gas.

INSERT Figure 4.3.3 Comparison of system efficiency between cogeneration and heat pump when using a CCGT plant.

4.3.1.1.3 Petroleum

The world's current energy systems have been built primarily around the convenience and logisitical advantages of relatively cheap and transportable fossil fuels, particularly oil. Economic systems are overwhelmingly dependent upon it. Moreover, oil resources have been concentrated by natural processes with the major concentrations in relatively few countries (Hallock, 2004). Two-thirds of the world's proven crude oil reserves are located in the Middle East and North Africa (Fig. 4.3.4)

INSERT Figure 4.3.4 Crude oil production by region and refining of crude oil.

Conventional oil

Conventional oil refers to crude oil produced from well bores by primary, secondary or tertiary methods. Oil alone represented about 40% of total world non-solar consumption of energy in 2001 (Hall, 2003). It is produced by 42 countries, exported by 35 and used by 220 (Hallock *et al.*, 2004). Assessing the amount used, the amount remaining for extraction and whether or not the "peak oil" tipping point is imminent have been very controversial due to a lack of reliable data and "game playing" by the industry. The uncertainties are poorly understood and the problems for modern industrial society will be unprecedented. Poorer developing countries could be affected the most in terms of socio-economic disruption. A report to the US Administration (Hirsch, 2005a) concluded that peak oil will happen; be abrupt and revolutionary; avoiding economic upheaval will require timely fuel efficiency and substitute fuels; such mitigation efforts will need a lead time of more than a decade; attention to supply, demand and risk management is warranted; and government intervention will be required.

Reserves and resources are defined as having been discovered but with the original oil still in place. Reserves are considered proven and resources probable based on historical experience in geologic basins combined with geologic history. The world reserves of oil have been estimated by The US Geological Survey's World Assessment Summary (USGS, 2000), the World Petroleum Congress and the IFP have estimated that approximately 800 Gbbl have already been consumed and 1000

Gbbl of proven reserves remain. Detailed analysis by Bentley (2002) concluded 850 Gbbl had been consumed by 1998 reaching 1100 Gbbl by 2008. The USGS also estimated there are 724 Gbbls of probable undiscovered oil. Thus the total reserves calculation should be based on proven reserves plus probable resources giving around 1800 Gbbls, which is about 70 years supply at the present rates of consumption. However consumption rates will likely rise and 40 years is therefore a more reasonable estimate.

Both BP (2005) and World Energy Council (2004) claimed consumption to be about 25.7 billion bbl/year, or 70 million bbls/day whereas Hirsch *et al.* (2005a) quoted just under 80Mbbl/day in 2003. By mid 2005 the demand had reached 81 Mbbl/day of which OPEC countries provided around 51 Mbbl/day (Shibab-Eldin, 2005). Over 3 GtC/yr are emitted to the atmosphere as a result (IEA, 2004). At this consumption rate the proven reserves would last for a few decades but once peak oil is reached the rate of extraction will decline, the world oil price will increase, and the range of unconventional oil supplies will become more competitive. Natural gas condensate liquids add another 2.5% to the total reserves, providing slightly less than 5 EJ of current annual consumption, and adding about another 100 Mt C/yr to the atmosphere (WEC, 2004a).

Estimates of the ultimate extractable resource (proven + probable + possible reserves) with which the world was endowed have varied from <1000 to 6000 Gbbl, though the most recent predictions have all ranged between 2000 – 3000 Gbbl (Fig. 4.3.5).

INSERT Figure 4.3.5 Estimates of the ultimate extractable conventional oil resource from evaluations (Based on Bentley, 2002a; Andrews and Udal, 2003)

Various studies and models are used to forecast future oil production. Geological models take into consideration the volume and quality of hydrocarbons but they do not include economic effect on price which in turn has a direct effect on supply and the overall rate of recovery. Mathematical models generally use the historical as well as the observed patterns of production to estimate a peak (or several peaks) when half the reserves are consumed. Global conventional reserves and resources of recoverable crude oil and natural gas liquid condensates using current technology are in the order of 10,000 EJ. Approximately 60% of this total are proven reserves, the remainder unproven resources (BP, 2004; WEC, 2004a). At the current rate of use the reserves plus the unproven resources will last for several decades, although there is considerable uncertainty as to when the tipping point of "peak oil" production will actually occur.

Different measures are used to determine the life of oil resources such as the ratio of global reserves/production (R/P) and the oil peaking model. The simplest method of global R/P ratio expresses the number of remaining years. Historical records have shown this to vary from 150 years in the 1950s down to around 30 to 40 years in the last 40 years (WEC, 2004a). Oil production peaking is defined as the reservoir maximum production rate which typically occurs after roughly half of the recoverable oil in the reservoir has been produced (Hirsch *et al.*, 2005). Several experts reported that peaking may occur between 2006 and 2010 (Bakhtiari, 2004; Simmons, 2003; Skrebowski, 2004; Deffeyes, 2003; Goodstein, 2004; Campbell, 2003). Others projected peaking to happen between 2010 and 2016 (Laherrere, 2003; WEC, 2004a and US DOE EIA, 2005). A few reports have predicted peaking to be after 2020 (Jackson *et al.*, 2004; Shell, 2005) or not visible (Lynch, 2003).

Improved technologies for recovering more conventional oil are advancing and include seismic exploration, drilling, and production. Continued discovery of new reserves and the application of increasingly-advanced exploration procedures in addition to emerging technologies in energy conservation and efficiency improvement are expected to extend the life of this resource. On the other hand increased economic growth in the oil producing countries as well as other non-producing developing countries may dramatically change present consumption patterns leading to faster depletion of this resource. How fast that depletion will be is hard to determine.

Energy Efficiency in Refining

Petroleum industry operations consume up to 15-20% of the energy in crude oil, with refineries consuming most of that energy (Eidt, 2004). In response, the industry has had long-standing energy efficiency programmes for refineries and the chemical plants with which they are often integrated. Major components of these programs include use of co-generation, flare reduction, fuel switching, combustion optimization, use of efficient electrical devices, and improved heat integration. (BP, 2005; Chevron, 2005; Eidt, 2004; Shell, 2005). These efforts have yielded significant results. Exxon Mobil reported over 35% reduction in energy use in its refineries and chemical plants from 1974-1999, and in 2000 instituted a program whose goal was a further 15% reduction, which would reduce emissions by an addition 12 $MtCO_2$/yr. (Eidt, 2004). Chevron reported a 24% reduction in its index of energy use between 1992 and 2004 (Chevron, 2005). Shell has shown energy efficiency improvements of 3-7% at its refineries and chemical plants. However care must be taken when comparing refinery energy use. Simple measures (e.g. energy consumed/barrel refined) do not account for refinery complexity so many refiners use a proprietary index developed by HSB Solomon Associates, LLC which takes this into account to compare energy efficiency (Barats, 2005).

Unconventional oil

Oil which requires extra processing such as from oil shales, heavy oils and tar sands is classed as unconventional. As the price of conventional oil increases these resources will become more viable. The most promising of these fuels is orimulsion, a tar like substance that can be burned to generate electricity or refined into light petroleum products. Venezuela has reserves of more than 1.2 trillion barrels of oil-equivalent. Extra heavy oil represents a resource of 1500 EJ with current production of 1.2 EJ/yr, mostly in Venezuela's Orinoco delta where most of the resource lies (World Energy Council, 2004). Oil shales (kerogen that has not completed the conversion to oil due to insufficient heat and pressure), represent a potential resource of 20,000 EJ with a current production of just 0.024 EJ/yr, mostly in Brazil, China and Estonia. The largest resource of 16,000EJ lies in the Western United States. Tar sands represent a known resource of 15,000 EJ almost all in Alberta, Canada, with a current oil production of 1.6 EJ/yr. These resources represent at least 400 Gt of stored C and will probably be added to as more are discovered assuming the technology is available to extract the hydrocarbons and natural gas and/or water (steam) are available at a reasonable cost. Technologies for recovering these resources include open cast mining where the deposits are shallow enough, or injection of steam to reduce the viscosity of the oil prior to extraction. In both cases cleaning and upgrading is necessary to produce feedstock suitable for refining. Tar sands require large amounts of heat for extraction whereas oil shales require a lot of water.

4.3.1.2 Carbon capture and storage

Carbon dioxide capture from large point sources followed by storage in deep geological reservoirs appears to be feasible. IPCC (2005) published a Special Report on CCS to assess the potential of this technology for global warming mitigation. The report defined CCS as the separation of CO_2 from anthropogenic sources, transport to a storage location, and isolation from the atmosphere. It found that under appropriate circumstances, CCS would be one option in the portfolio of actions for stabilization of greenhouse gas concentrations that would allow for the continued use of fossil fuels. Capture of CO_2 can best be applied to large point sources including large fossil fuel or biomass electric power generation or cogeneration facilities, major energy-using industries, synthetic fuel plants, natural gas fields and CO_2 producing chemical facilities for hydrogen, ammonia, cement and coke. Physical storage could take place in geological formations, the ocean, and in mineral inorganic carbonates (Fig. 4.3.6). Geological and ocean storage have the largest potential along with biological sequestration in forests and soils (see www.accstrategy.org). Forming inorganic carbonates is scientifically possible, but has yet to be demonstrated on a large scale. Using CO_2 in industrial processes captures only a small amount to storage as chemicals.

INSERT Figure 4.3.6 Sources of carbon dioxide for which CCS might be relevant and transport and storage options (IPCC, 2005).

The dynamic nature of ocean storage and biological sequestration requires consideration in terms of carbon stocks and flows into reservoirs and releases from them (Fig 4.3.7). The stock in the atmosphere depends upon the difference between the rates at which CO_2 reaches it and at which it is removed. Flows to the atmosphere may be slowed by a combination of mitigation options, such as improving energy efficiency, using alternatives to fossil fuels, enhancing biological storage in forests and soils, or by CCS.

Figure 4.3.7. Stocks and flows of CO_2 with net flows of captured CO_2 to each reservoir (CCS) excluding residual emissions associated with the process of capture and storage which can be considered as additional sources.
R = the rates of emissions from each of the storage reservoirs.

The *amount* in storage at a particular time is determined by the capacity of the reservoir and the past history of additions to and releases from the reservoir. The *change* in stocks of CO_2 in a particular storage reservoir over a specified time is determined by the current stock and the relative rates at which the gas is being added and released. In the case of ocean storage, the level of CO_2 in the atmosphere will also influence the net rate of release. As long as the *input* storage rate equals or exceeds the *release* rate, CO_2 will accumulate in the reservoir, and some amount will be stored away from the atmosphere.

Capture

The purpose of CO_2 capture is to produce a concentrated stream which can readily be transported to a CO_2 storage site. While large-scale power plants are the major source of CO_2 emissions, there are at present no full-scale applications of CCS at such plants and the cost of separation technology is high. Depending on the process or power plant application, there are three main approaches to CO_2 capture:

- post-combustion systems, which separate CO_2 from the flue gases produced by the combustion in air of a primary fossil fuel (coal, natural gas or oil) or biomass fuel;
- pre-combustion systems, which process the primary fuel in a reactor in the presence of steam or oxygen to produce separate streams of hydrogen used as an energy carrier and CO and then CO_2 for storage; and
- oxyfuel combustion systems, which use oxygen instead of air for combustion to produce a flue gas that is mainly water and CO_2 which is subsequently removed for storage.
-

Whereas the former two options are commercially proven, the third is currently in the demonstration phase. (IPCC, 2005; Gonschorek *et al.,* 2005)

Transport

Transportation by pipelines is mature and costs are known with greater accuracy than any other part of the CCS system. The major barrier is likely to be local opposition to additional pipelines of any kind being constructed in some areas. Transportation by truck and by ship may also be used in some applications, and experience with the more challenging liquefied natural gas (LNG) provides a good guide for estimating costs and technologies for handling cryogenic fluids such as liquid, supercritical CO_2.

Storage

Storage of CO_2 in geological formations can be achieved in oil fields, gas fields, saline formations or unmineable coal formations. In order to geologically store CO_2, it must first be compressed, usually to a dense supercritical state. Depending on the geothermal gradient, the normal hydrostatic pressure at depths of >800 m will then keep the injected CO_2 in a stable dense supercritical state. Enhanced oil recovery (EOR) through CO_2 flooding has captured attention because of the potential economic gain from incremental oil production. The CO_2 resulting from burning the extra oil produced will, however, exceed the amount stored in most cases. Most of the 30 Mt CO_2 injected annually for EOR is in West Texas, USA where it commenced in the early 1970s. The CO_2 is obtained from natural reservoirs found in western regions of the US, with some coming from anthropogenic sources such as natural gas processing. While technology for drilling and injection is mature and monitoring methods have largely been developed in the oil and gas industry, there is further need to develop technology for computer simulation of long-term storage reservoir dynamics (IPCC, 2005).

Ocean storage can be achieved by injecting CO_2 into the water column (typically below 1,000 m) via a fixed pipeline or a moving ship, or by depositing it via a fixed pipeline or offshore platform on the sea floor at depths below 3,000 m at which CO_2 is denser than water and forms a “lake” that would delay dissolution of CO_2 into the surrounding environment. Ocean storage is still in the research phase (IPCC, 2005).

4.3.1.2.1 Risks of CCS

The risks of CO_2 capture and storage are local and global risks arising from the release of stored CO_2 to the atmosphere. For existing CO_2 pipelines mostly in areas of low population density, accident numbers reported per km of pipeline are very low and comparable to those for hydrocarbon pipelines. Impacts would probably not be more severe than those with natural gas accidents. If a sudden and brief large release of CO_2 happened, the local impacts on animal health could be significant since a local concentration of greater than 7-10% in the air would cause immediate danger to life.

Risks posed by geological storage would depend on the criteria and available subsurface information used for site selection, the design of the monitoring program to detect problems, the regulatory system, and the appropriate use of remediation methods to stop or control CO_2 releases if they arise. Leakage could be abrupt, due to injection well failure or escape up an abandoned well, or more gradual, through undetected faults and fractures in pipes or wells. Impacts of elevated CO_2 concentrations in the shallow subsurface could lead to local high CO_2 concentrations in the air that could harm animals or people. Pressure build-up caused by CO_2 injection could trigger small seismic events. While there is limited experience with geological storage, closely related industrial experience and scientific knowledge could serve as a basis for appropriate risk management, the effectiveness of which still needs to be demonstrated.

The chronic effects of direct CO_2 injection into the ocean on ecosystems over large ocean areas and long time scales are unclear. In contrast, adding CO_2 to the ocean or forming pools of liquid CO_2 on the ocean floor at industrial scales will alter the local chemical environment to an extent that has been shown in laboratory studies to cause mortality of ocean organisms.

Among the major issues concerning carbon dioxide storage is how long it will remain out of the atmosphere. IPCC (2005) considered ways in which this issue has been addressed economically and physically and concluded that any release rate that did not allow atmospheric concentrations of CO_2 to exceed policy goals might be considered useful. For example if no significant releases occur until after the end of the fossil fuel era, and release rates do not exceed absorption rates into oceans and biosphere, this might be judged an adequate storage period by policy makers. Other factors to be considered beside storage residence time are the size of the reservoir, its economic cost and political acceptability. How much CO_2 abatement is done through CCS will depend on the relative cost of other mitigation options such as energy efficiency, alternative zero emission technologies, enhanced biological sequestration, their relative social and political acceptability and the balance determined by policy goals. For example, the introduction of technologies and measures that reduced CO_2 emissions absolutely would lower the need for CCS and vice versa.

Continuous release of small quantities of CO_2 over a long time frame could offset the benefits of CCS for mitigating climate change and, depending on the storage option and the selection process, leaks could become a disperse emission source which would be difficult to control. For well-selected, designed and managed geological storage sites, the vast majority of the CO_2 will gradually be immobilized by various chemical processes and will therefore be retained for up to millions of years. Observations from engineered and natural analogues as well as models suggest that the fraction retained in appropriately selected and managed geological reservoirs is very likely to exceed 99 % over 1,000 years. Release of CO_2 from the oceans would be gradual. Ocean tracer data and model calculations indicate that, in case of ocean storage, depending on the depth of injection and the location, the fraction retained is 65 to 100% after 100 years, and 30-85% after 500 years (lower number for injection at 1,000 m depth, higher number at 3,000 m) (IPCC, 2005).

4.3.1.2.2 Technology RD and deployment

New or improved methods of CO_2 capture, combined with advanced power systems and industrial process designs, could reduce CO_2 capture costs and energy requirements. Although there is considerable uncertainty about the magnitude and timing of future cost reductions, it is expected that improvements to commercial technologies can reduce CO_2 capture costs by at least 20-30% over approximately the next decade, while new technologies under development could achieve more substantial cost reductions. Future cost reductions will depend on deployment and adoption of commercial technologies in the marketplace as well as sustained R&D (IPCC, 2005). As an example the US government sponsored a US$1billion, 10-year research project “FutureGen” in 2003 to build the world's first coal-fired plant to produce electricity and hydrogen with zero emissions. The 275 MW prototype plant will serve as a large scale engineering laboratory for testing new clean power, carbon capture, and coal-to-hydrogen technologies. (US DOE, 2004). BP have also announced plans to produce hydrogen from natural gas to fuel a demonstration 350MWe power plant in the North Sea and capture and sequester 1.3 MtC / year (BP, 2005a).

Geological CO_2 storage has reached the commercial stage, except for storage in unmineable coal seams. EOR using CO_2 is a mature market technology but with the exception of the Weyburn field in Canada, EOR activities up until now have been for oil production, not for isolating CO_2 from the atmosphere. The Weyburn project is expected to inject 19 Mt CO_2 and extend the life of the oil field by 25 years. The fate of the injected CO_2 will be closely monitored by the IEA (Moberg *et al*., 2003; IPCC, 2005).

Storage in saline aquifers is commercially proven as demonstrated in the Sleipner project in the North Sea (about 250 km off the coast of Norway). It was the first commercial-scale project dedicated to geological storage of CO_2. Annually, approximately 1 Mt CO_2 is removed from the natural gas produced from the Sleipner field and injected underground into the aquifer. Over the lifetime of the project, a total of 20 Mt CO_2 is expected to be stored. The saline Utsira formation into which the CO_2 is injected is about 800 to 1,000 m below the sea floor. Total storage capacity is in the order of 1,000 Mt CO_2 (270 MtC). Storage in gas fields has also been implemented in the In Salah project in Algeria (IPCC, 2005) and pilot-scale demonstration projects have also been conducted such as the Nagaoka project in Japan which is evaluating the geophysical monitoring of CO_2 injection in an onshore saline aquifer. The project injected 10,400 t CO_2 (2800 tC) from July 2003 to January 2005 and provided improved understanding of CO_2 behaviour in a porous sandstone reservoir. Post-injection monitoring is planned to continue (Kikuta *et al*, 2004). The Frio Brine project in Texas, U.S.A., involves injection and storage of 1,900 tCO_2 (510tC) in a highly permeable formation with a regionally extensive shale cap rock (Hovorka *et al*., 2004).

Storage in unmineable coal seams and the associated enhanced methane production is technically feasible, and has been demonstrated at a pilot scale in the northern San Juan Basin of northcentral New Mexico, U.S.A. and at Yubari in central Hokkaido, Japan. Commercially viable projects will depend on the permeability of the coal (IPCC, 2005).

4.3.1.2.3 International collaboration

International collaborations already exist, such as the IEA Weyburn monitoring and storage project and the Carbon Sequestration Leadership Forum which is an international climate change initiative that is focused on development of improved cost-effective CCS, to make related technologies broadly available internationally; and to identify and address wider issues. The first ministerial-level meeting in Virginia, U.S.A. in June 2003, was attended by delegations from 13 countries and the European Commission. By the end of 2004 17 members included Annex I and Non-Annex I countries.

CO2GeoNet is another research partnership for the geological storage of CO_2 funded by EC, and 13 institutes participate in the network. Its main aim is to integrate, strengthen, and build upon the momentum of previous and existing European R&D of CO_2 underground storage research. Research activities comprise the development of predictive numerical tools, rock and fluid dynamic experimental facilities, enhanced hydrocarbon recovery methods and tools, monitoring techniques, and risk and uncertainty assessment methods and tools including ecosystem, health and safety and long-term impacts.

4.3.1.2.4 Legal and regulatory framework

Onshore storage is subject almost exclusively to national legal frameworks, but offshore storage is also relevant to the international legal framework (OECD/IEA, 2005). International frameworks include UNFCCC, Kyoto Protocol, UNCLOS London Convention 1972 and its 1996 Protocol and the OSPAR Convention. How to combine these frameworks in the face of technological change and of growing knowledge about climate change is one of the main challenges to the development of an enabling international legal framework for CCS activities.

The main legal and regulatory issues relating to definition and policy include:

- balancing the various objectives of the international community;

- defining CO_2 as a waste;
- deciding how to treat the inevitable contaminants such as H_2S and hydrocarbons;
- storage site selection and ownership;
- monitoring requirements;
- long term liability;
- use of the precautionary approach in principle; and
- CCS as a climate mitigation technology.

In addition two issues relate to the process. Gaining additional empirical information is one of the key priorities for moving forward in establishing a legal and regulatory framework for CCS. How best to build this framework depends on the diversity of countries' institutional structures and policy processes. This prevents the adoption of a single recommended framework and options for consideration include existing versus new, national versus international and demonstration versus general or activity specific approach.

4.3.2 Nuclear energy

In 2005 440 nuclear power plants were in operation with a total installed capacity of about 366 GW_e (IAEA PRIS, 2005). In 2004 2620 TWh of electricity (16% of the world total) was generated by nuclear power requiring about 68,000 tons of natural uranium (BP, 2005).

All energy sources require attention to issues of economics, safety and environmental impacts but the nuclear option also requires processing of materials and overcoming public concerns over the proliferation of nuclear weapons. In order to meet sustainable development goals, nuclear energy will have to achieve a higher level of social acceptance than it has in many countries today. The general public will have to put economic, social, ethical and political issues relating to nuclear energy into perspective with alternatives in order to create conditions for decision-making processes consistent with the goals of sustainable development (NEA, 2005).

Total life-cycle GHG emissions from nuclear power per unit of electricity produced at only around 1-11 gC_{eq}/kWh are at a similar level to renewable energy sources (Fig. 4.4.4). Hence it is an effective GHG mitigation option, especially by way of investment in the lifetime extension through retro-fitting of existing plants.

The emissions originate mostly from the front-end of the fuel cycle (extraction/leaching, isotope enrichment, and fabrication of fuel). The technologies employed in enrichment (gaseous diffusion or centrifuge) have different energy input needs and thus have significant variations in emissions. Energy use in the mining stage correlates with the costs of mineral recovery. Even in the case of exploiting low-grade ore deposits with 0.03-0.06% uranium content the energy used in extraction/ leaching phase is still low and the CO_2 emissions brought about by mining are only about 1 gCO_2/kWh generated.

Global power from nuclear energy currently avoids approximately 0.7 GtC/yr (World Nuclear Association, 2003) if that power were instead produced from coal without sequestration of the carbon or 0.4 GtC/yr if using the world average carbon dioxide emissions of electricity production in 2000 of 150 gC/kWh) (WEC, 2001). In spite of the various cost and environmental limitations regarding nuclear power, China and India, with large populations to provide energy services for, are both planning significant expansions in their nuclear industry. China alone has announced plans for two new power plants per year over the next 15 years (New York Times, 2005).

Nuclear energy technologies will have an increasing role in the development of carbon-free or low-carbon energy technologies with the introduction of more sustainable closed fuel-cycle systems and more efficient use of uranium and thorium resources. The introduction of breeder reactors and P&T-technologies will minimize the amounts and toxicity of wastes for geological disposal.

Exploration, extraction, refining

In the long-term the potential of nuclear power is dependent on the uranium resources available. Reserve estimates of the uranium resource vary with assumptions on its use (Fig. 4.3.8). If used in thermal reactors with a “once-through” utilization of the uranium fuel, only a small percentage of the natural uranium is consumed and the U-235 is present as less than 1%. Where breeder reactors are utilized, a “closed” fuel cycle occurs, the uranium is recycled, the plutonium produced is extracted and reserves of natural uranium resources will therefore be extended to tens of thousand years at the present consumption level. Furthermore around 4Mt of thorium resources (OECD, 2001) add considerably to the fuel resources available.

Used in typical light water reactors (LWR) the proven conventional resources of 4.6 Mt uranium at prices up to USD130/kg correspond to about 2300 EJ of primary energy and will be sufficient for close to hundred years (OECD, 2004a). The total proven and probable resources including reasonably assured, estimated, additional and yet undiscovered uranium resources are sufficient for several hundred years of usage being around 14.4 Mt uranium (7200 EJ).

Fig. 4.3.8 Estimated years of uranium resource availability for various nuclear technologies (OECD 2004; Red Book, 2003).

Conventional proven resources of uranium will have been earmarked once the installed total plant capacity triples to about 1300 GW_e. In addition, there are non-conventional uranium resources such as about 22 Mt contained in phosphate minerals recoverable for between USD 60-100/kg) and about 4000 Mt present in the oceans, but due to the high cost of extraction requiring large energy requirements it is uneconomic to exploit these resources for use in thermal reactors.

The more efficient use of uranium in breeder reactors would exploit the other much more abundant uranium isotope (U-238). Where breeder reactors are assumed to utilize depleted uranium and only plutonium is recycled (OECD, 2001), the resource efficiency is increased by a factor of 30. If breeder reactors are designed to utilize both recycled plutonium and uranium the resource utilization efficiency increases up to 180-fold compared to once-through thermal LWR reactors (OECD, 2002). Hence the share of nuclear power could be increased considerably, maintaining it as a sustainable source of energy in the very long-term.

Nuclear power production could also be based on thorium, which is three times as abundant as uranium in the earth's crust. Since thorium is converted in the reactor to U-233, another fissile uranium isotope, all of the mined thorium is potentially useable without the need for breeder reactors. However, the thorium fuel cycle still requires major technological development to be commercially viable.

Nuclear waste management and disposal

Deep geological repositories are the most extensively studied technical option for safe and long-term disposal of high-level radioactive waste with greater societal acceptance of the siting of these repositories. For example in 2001 the Finnish Parliament ratified the previous decision of principle concerning the siting of a spent fuel repository in the vicinity of the Olkiluoto nuclear power plant. After detailed rock characterisation studies the construction will start in early 2010s and plant operation around 2020. Similarly, in Sweden a repository siting process is now concentrating on the comparison of site alternatives close to the Oskarshamn and Forsmark power plant sites. In the USA the Yucca Mountain area has been chosen as the preferred site for a repository of LWR fuel and extensive site characterisation and design studies are underway, although not without significant local opposition. Repositories are already in operation for the disposal of low- and medium level radioactive wastes in several countries.

High level waste volumes can be further reduced if the spent nuclear fuel is reprocessed so that most of the plutonium and unutilized uranium is extracted for reuse. The remaining high-level waste is then compacted and “vitrified” (melted with other ingredients to form a glass) and placed into canisters that are appropriate for long-term disposal. Alternatively in some countries priority is given to the development of reprocessing and advanced separation techniques as well as transmutation in advanced fast reactors or sub-critical systems (e.g., accelerators) to decrease the heat output and the toxicity of remaining wastes. As a result it is appropriate to postpone the detailed development of geological disposal systems and the site selection of repositories because their safety requirements are then less stringent.

Proliferation aspects

The enrichment of uranium, reprocessing of spent fuel and the separation of plutonium are often viewed as the critical steps in the nuclear fuel cycle in terms of potential nuclear weapons proliferation. Therefore, comprehensive safeguard activities have been established. The Treaty on Non-Proliferation of Nuclear Weapons (NPT) is at the centre of the international regime. In addition to various international control actions, one of the key objectives in the development of next generation nuclear reactors and their fuel cycle is the improvement of their proliferation resistance. An important aspect of the once-through system is that stocks of plutonium, a desirable nuclear weapons material, are continuously built up in spent fuel. Recycling through breeder reactors on the other hand allows most of this material to be burned up in a reactor to make power, although there are vulnerabilities in the reprocessing step.

Development of future nuclear power systems

There is no internationally accepted definition of reactor technology nomenclature. Generations I and II are terms presently used and Generation III are advanced reactors for which construction decisions have recently been made and aim to be in operation before 2010 or shortly thereafter (GIF, 2002) (Fig. 4.3.9). Generation III+ includes evolutionary reactor designs likely to be operational well after 2010. An example of a Generation III reactors is the European pressurized water reactor (EPR) one being scheduled to be in operation in Finland on the Olkiluoto site in 2009. The design includes evolutionary features concerning the management of severe accidents (such as a core catcher). France has made a preliminary decision to build such a plant at the Flamanville site.

Fig. 4.3.9 Evolution of nuclear power systems from Generation I commercial reactors in 1950s up to the future Generation III+ systems which could be operational after about 2030 (GIF, 2002).

Generation IV reactor designs are being developed by comprehensive international co-operation efforts. The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) is coordinated by the IAEA and aims to seek effectively unlimited fuel resources; exclude severe accidents; provide environmentally safe energy production without disturbing the natural radiation balance; reach economic competitiveness; and blocking nuclear weapons proliferation. The Generation

Four International Forum (GIF, a group of ten nations plus the European Union co-ordinated by US Department of Energy), has developed a framework to plan and conduct international cooperative research on advanced nuclear energy systems including the INPRO aims plus reducing waste generation and evaluating new applications for the process heat (GIF Roadmap). INPRO and GIF intend to work co-operatively following the IAEA Board meeting of September 2005.

Three variations of fast breeder reactor (FBR) are included in the GIF concept: sodium-cooled (SFR), gas-cooled (GFR) and lead-cooled (LFR), as well as high temperature reactors (VHTR). Reactor concepts capable of producing high temperature nuclear heat are intended to be employed also for hydrogen generation either by electrolysis or directly by special thermo-chemical water splitting processes. In addition, there is an ongoing development project by the South African utility ESKOM for an innovative high temperature, pebble bed modular reactor (PBMR). The specific features of that concept include its smaller unit size, modularity, improved (intrinsic) safety, lower power production costs and the direct gas cycle design utilizing the Brayton cycle (Koster *et al*, 2003; NER, 2004). The supercritical light water reactor (SCWR) is also one of the GIF concepts intended to be operated under supercritical pressure and temperature conditions.

4.3.2.1 Nuclear fusion

Energy from the fusion of heavy hydrogen fuel (deuterium, tritium) is actively being pursued as a long-term almost inexhaustible supply of energy. A major international effort is underway (ITER) to demonstrate the magnetic containment of a sustained, self-heated plasma under fusion temperatures. There are also efforts in several countries to demonstrate sustained inertial containment of plasmas (http://www.itercad.org). While potentially availing the world with a vast energy resource, it awaits technical breakthroughs to achieve commercial status. Even then a long period of penetration into the market place will be needed. Deuterium can be found in abundance in the oceans and tritium can be produced by a nuclear breeding reaction from lithium atoms. Many scientific and technical challenges remain and it will be some time even after these challenges are met before fusion could become a dominant power supply.

4.3.3 Renewable Energy

Renewable energy accounted for approximately 13.3% of world primary energy supply in 2003 (IEA, 2005) mainly as traditional biomass (11%) and large hydro electricity (2.2%). Wind at <0.7% of total renewable energy has grown by an annual rate of 23.9% of installed capacity per year since 1990. Modern biomass, geothermal and solar have each also significantly exceeded the annual primary world energy demand growth of 1.6%. Even so, under a business-as-usual case of continued growing energy demand, renewables start from a low base and are not expected to greatly increase their market share during the next 3 or 4 decades without major intervention. Due to slow growth in the mature hydro and geothermal technologies, their share may even decline. In OECD countries for example, renewable energy sources fuelled 24% of electricity generation in 1970 but this had fallen to only 15% by 2001 due to increased fossil fuel and nuclear supply (IEA, 2004). Concerns at these trends going against the long term vision that many hold for renewable energy making a significant contribution to the world primary energy supply within a few decades, have led to renewed support from many governments.

Renewable energy systems can contribute to the security of energy supply and protecting the environment. The benefits of renewable energy systems were clearly defined in a political declaration agreed to by government representatives of 154 nations at the international “Renewables2004” conference held in Bonn, June 2004 (Renewables, 2004) which was a follow-up to the 2002 World

Summit on Sustainable Development, Johannesburg. Benefits outlined included energy supply security, equity and development, improved health, overcoming peak oil price fluctuations, provision of clean water, close association with energy efficiency measures, climate change mitigation, and “there will be no need for war over solar energy”.

Renewable energy technologies can be broadly classified into

- mature with high market penetration (large hydro, woody biomass combustion, geothermal, landfill gas, solar water heating and on-shore wind);
- commercially developed but relatively low market penetration (crystalline silicon PV, municipal solid waste-to-energy, anaerobic digestion, biodiesel, bioethanol from sugars and starch, co-firing of biomass, concentrated solar dishes and troughs, small and mini-hydro; tidal range and off-shore wind); and
- under development and possibly near to market (thin film PV, organic nano-solar cells, concentrating PV, ocean energy from waves and current, biomass gasification, biomass pyrolysis, bioethanol from ligno-cellulose, bio-refineries, solar thermal towers, wave power, ocean thermal and saline gradients and ocean currents.
-

The main mature technologies (hydro, biomass combustion and geothermal) have mostly been left to compete in today’s energy markets without policy support. In the best locations newer renewables including landfill gas, solar water heating, wind farms and biofuels can compete on an average cost basis with conventional energy sources due to mass production, project experience gained (Fig 4.3.10) and use of waste biomass materials requiring disposal. In regions where deployment is slow due to resource, market and social barriers these technologies still need government supporte. The less mature technologies are usually not competitive and supportive policies are therefore needed for both their continued technological development and future market deployment.

INSERT **Figure 4.3.10. Investment costs and penetration rates for PV, wind and ethanol systems showing cost reductions of 20% due to technological development and learning experience for every doubling of capacity (Johansson *et al.*, 2004).**

A wide range of policies and measures exist to enhance the deployment of renewable energy (IEA, 2004 and section 4.7). Over 40 nations (including Brazil, China, Egypt India, S. Korea, Malaysia, Mali, Mexico, South Africa and Thailand) and numerous individual states of the USA, Canada and Australia have set renewable energy targets (Renewables, 2004). The IEA has established a new implementing agreement in September 2005 to encourage collaboration on “Renewable energy technology deployment” by member countries and to provide support for developing countries. Many of these targets also include heat and biofuels for which Brazil, Canada, China, India, Netherlands, New Zealand, Thailand and USA have mandates in place for blending bioethanol and biodiesel with petroleum fuels.

Renewable energy sources originate mainly from the sun’s radiant energy (geothermal and tides being the exceptions). They are ubiquitous, long-lived, and essentially free of carbon emissions. They are however intermittent over various time frames (Fig 4.3.11) and energy storage technologies may be needed, particularly for wind and solar, though stored hydro reserves, geothermal and biomass fuels can all be used as back-up sources.

INSERT **Figure 4.3.11. Renewable energy technologies are intermittent over various time frames and need to be managed accordingly if to provide reliable energy supply system (Based on Gul & Stenzel, 2005).**

Since the TAR large industry corporate companies such as General Electric, Siemens, Shell and BP have invested in the renewable energy market and other investments have come from a wide range of public and private sources. Many commercial banks such as Fortis, ANZ Bank, Royal Bank of Canada are financing a growing number of projects; investment firms including Goldman Sachs and Morgan Stanley are acquiring renewable energy companies; traditional utilities are developing more of their own renewable energy projects; commercial reinsurance companies such as Swiss Re and Munich Re are offering new insurance products targeting renewable energy; and venture capital investors are taking note of future market projections for wind and photovoltaics (PV). The OECD has also improved the terms for Export Credit Arrangements for renewable energy by extending repayment terms. (Martinot, 2005).

There has also been increasing support for renewable energy deployment in developing countrie;, not only from the usual international development and aid agencies which have increased their support, but also from large and small local financiers with support from donor governments and market facilitators to reduce their risks. Total public funding commitments in the “Renewables2004 Action Programme” amounted to around $US50 billion (Renewables, 2004).

Numerous detailed and comprehensive reports, web sites and conference proceedings have been produced since the TAR on renewable energy resources, conversion technologies, industry trends and government support policies (see for example Renewables, 2004; BIREC, 2005; Martinot, 2005; IEA, 2004; IEA, 2005a; IEA 2006?; WEC, 2004; ISES, 2005; WREC, 2006; WREA, 2005). The following sections therefore address only the major key points relating to recent broad trends for each major technology.

4.3.3.1 Hydroelectricity

Large (>10MW) hydroelectricity systems account for 25 EJ/yr of global energy (BP, 2004). They provide 17 % of global electricity and avoid releasing 0.6 GtC/yr of carbon into the atmosphere if from a similar amount of coal-fired power generation. Hydro projects under construction will increase the share of electricity by about 4.5 % (World Energy Council, 2004).
Questions have arisen over the environmental impacts of large hydropower schemes and sustainable guidelines have been produced (Rowe, 2005; Hydro Tasmania, 2005). Gross carbon dioxide and methane emissions were measured in several Brazilian hydro-reservoirs and compared with combined cycle natural gas turbine (CCGT) plants with 50% efficiency (dos Santos *et al.*, 2004). GHG emissions from the flooded reservoirs tended to be less per kWh generated than those produced from thermal power plants. Large hydro-power complexes with greater power density (W capacity/m^2 area flooded) had the best environmental performance. Lower power density systems produced similar or more GHG than the CCGT plants.

Where sites for natural reservoirs are limited and peak power demands are problematic, pumped water storage has good potential. Power from a thermal generation facility or wind farm is used to pump water up to a reservoir in off-peak hours, to later be converted into electricity during periods of peak demand by the pump acting as a turbine.

Expansion of hydropower capacity requires continuous technology improvements to maximize the use of existing plants, development of new projects that meet sustainability guidelines and further R&D investment on low head, in-stream systems (IEA, 2006?). Hybrid wind-hydro and hydro-hydrogen systems for small plants also need evaluation.

4.3.3.2 Wind

The global wind energy resource is several times higher than the current total global electricity demand. However only a little over 0.5 EJ/yr of wind energy was captured in 2003 (World Energy Council, 2004). Wind power has increased from an installed capacity of 2.3 GW in 1991 to 39 GW at the end of 2003 generating 67 TWh in that year. New wind installation capacity is currently growing at an average of 25 % /yr (IEA, 2006?) due to improved technology development, lower costs and government support from feed-in tariff and renewable energy certificate policies (section 4.7). Off-shore wind capacity now exceeds 500MW with the expectation that it will soon grow rapidly due to higher mean annual wind speeds experienced offshore in some regions and reduced public objections due to perceived negative visual impacts.

Wind energy can not yet be considered to be a global market as the main investment has been in only 10 countries, mostly in Europe. The European Wind Energy Association set a target of 75 GW (168 TWh) for EU-15 countries in 2010 and 180 GW (425 TWh) in 2020 (EWEA, 2004). Other regions including Australasia and the USA have similar stretch targets, mainly to meet the increasing demand for power rather than to displace retired nuclear or fossil fuel plants. Rapid growth in Russia, China, Mexico, Brazil and India is also expected where private investment interest is increasing (Martinot, 2005).

The average size of wind turbines has increased in the last 25 years from less than 50 kW to the largest now approaching 5 MW with a rotor diameter exceeding 125 m. The average turbine size being sold currently is around 1.6 - 2 MW but there is also a market for small turbines <100kW. Current capital costs for land-based wind turbine turbines are below US$900 /kW with 25% for the tower and 75% the rotor and nacelle. Generation costs continue to decline (Fig. 4.3.12), based on a learning rate experience of 15% cost reduction per doubling of installed capacity as seen in Denmark since 1985.

INSERT **Figure 4.3.12. The development of wind turbine economics based on Danish experience since 1985 with variations due to land surface and terrain variations (Morthorst, 2004).**

New developments include improved wind forecasting, larger turbines, the use of carbon fibre technology in wind turbine blades replacing glass-reinforced polymer, noise reduction, and optimized designs to maximize energy capture for lower wind-speed sites.
The trend is to replace older and smaller wind turbines by more efficient, quieter and reliable designs giving higher power outputs from the same site but at a lower density of turbines per hectare.

Due to the fluctuating and somewhat unpredictable nature of wind energy, it is not considered practical to supply more than 20% of total electricity demand with wind energy without storage. Integration with a district heating and cooling system is possible if the wind-energy component of a local power system is sized to provide more electricity than needed at times. The excess power can be used with heat pumps to supply hot or chilled water or to charge thermal storage reservoirs. This allows the wind system to be sized to meet a larger fraction of total electricity demand with less wastage of excess wind energy.

4.3.3.3 Biomass and bioenergy

Biomass is a major renewable energy resource. Its multi-uses, for not only bioenergy but also for biochemicals and biomaterials, will become key components for transitioning to a renewable energy future. Along with other co-benefits such as promoting global sustainable development and supporting local economies, it is the target for ambitious, near term policy objectives in many countries (IEA, 2004).

In spite of large potentials, biomass should not be viewed as a panacea since there are often practical difficulties when implementing bioenergy projects. These result particularly from its dirty and low technology image by the public; the challenge to secure biomass fuel supplies; its relative low energy density compared with fossil fuels; the high demand for water and nutrients by some energy crops; and the difficulties in achieving economies of scale for conversion plants using widespread feedstocks, negotiating financing and contractual arrangements, and obtaining resource and planning consents. Climate change effects in some regions may also impact on the future biomass production potential.

Biomass sources include forest, agricultural and livestock residues, short rotation forest plantations, specialist energy crops, the organic component of municipal solid waste (MSW), and other organic waste streams. These are used as feedstocks to produce energy carriers in the form of solid fuels (chips, pellets, briquettes, logs), liquid fuels (methanol, ethanol, diesel), gaseous fuels (synthesis gas, biogas, hydrogen) and heat (Fig 4.3.13). This section of Chapter 4 concentrates on the conversion technologies of biomass resources to provide heat, electricity and transport fuels to the competitive energy market.

INSERT **Figure 4.3.13. Biomass supplies originate from a wide range of sources and, after conversion in many designs of plants, from domestic to industrial scales, are converted to useful forms of bioenergy. Chapters containing sections on specific biomass resources and the use of bioenergy carriers and biomaterials are shown.**

Globally, biomass currently provides around 46 EJ of bioenergy in the form of combustible biomass and wastes, liquid biofuels, renewable MSW, solid biomass/charcoal, and gaseous fuels (Fig. 4.3.14). This share is estimated to be 13.4% of global primary energy supply (IEA Statistics, 2004) mainly from “traditional biomass” in the form of 32EJ in 2002 of mainly non-commercial firewood, charcoal and dung (WEO, 2004) used for cooking and heating in developing countries (IEA, 2004). Such low-grade biomass provides around 35% of primary energy in many developing countries but more than 70% in Africa (Sims *et al.,* 2003). The existence of many forms of biomass and ways of using it have caused the UN Food and Agricultural Organization (FAO), in association with the IEA, to better define the terminology to be used for energy and forestry statistics as well as for future international standards required as biomass trade develops (FAO, 2001). In addition a FAO woody biomass database has been compiled for 215 countries from 1961 to 2003 with projections out to 2030 (FAO, 2004).

Residues from industrialised farming, plantation forests and food and fibre processing operations that are currently collected worldwide and used in modern bioenergy conversion plants contain approximately 9 EJ /yr of energy. Current combustion of over 130 Mt of MSW annually provides a further 6 EJ/yr (though this includes plastics etc). Much more organic waste is deposited in landfills, which in turn create large volumes of GHGs, mainly methane which when collected as landfill gas contributes 3EJ/yr. If the 46 EJ of total energy from biomass were to be provided by a mix of fossil fuels at around 75tCO_2/TJ and 20-40% efficiency instead, atmospheric carbon emissions would be greater by about 0.5 -1Gt/yr.

INSERT **Figure 4.3.14 World biomass energy flows and their thermochemical and biochemical conversion routes to produce heat, electricity and biofuels.**

Bioenergy projects depend on securing a reliable supply of sustainable biomass. They can create employment opportunities, though high labour content can be a cost disadvantage. Increasing bioenergy demand in future will depend to a greater degree on the active production of biomass crops from either surplus productive or marginal lands. Improved quality of degraded soils can result and if grown as riparian strips, the quality of waterways and lakes can be improved by reducing nutrient loadings. Low production costs give significant potential for biomass production in the former USSR, Oceania, East and Western Africa and East Asia. Biochemical technologies can convert cellulose to sugars and glycerides that, in turn, can be converted to bioethanol, biodiesel, hydrogen and chemical intermediates in bio-refineries. However the energy input/output ratios can be marginal.

Organic residues and wastes are often cost effective feedstocks for current bioenergy conversion plants which have resulted in niche markets for forest, food processing and other industries. Industry use of biomass in 2002 in OECD countries equated to 5.6 EJ (IEA, 2004) mainly in the form of black liquor in pulp mills, biogas in food processing plants, and bark, sawdust, rice husks etc. in process heat boilers. Net carbon emissions from generation of a unit of bioenergy are 10 to 20 times lower than emissions from fossil fuel-based generation (Mann & Spath, 2000; Matthews & Mortimer, 2000).

Traditional use of biomass (mainly fuelwood and charcoal for cooking and brick making) is still common in many developing countries. African and Asian countries consume more than 75% of the total global use of fuelwood. In some biomass provides 90% or more of their primary energy supply (Sims *et al.* 2003). Traditional biomass conversion is based on inefficient combustion, often combined with significant local and indoor air pollution and unsustainable use of biomass resources such as native vegetation. In India for example, domestic biomass combustion is the largest source of black carbon particulate emissions (Venkataraman *et al*. 2004). These absorb sunlight, cause changes to the monsoon system, and also impact on the global climate by decreasing the Earth’s surface temperature and increasing the temperature in the upper atmosphere.

There are synergies between the greater uptake of modern biomass and sustainable development (section 4.7.4), at least until increased competition for fertile land results, but in many countries this is unlikely till the longer term. The widespread uptake of cleaner and more efficient cooking stove designs could provide more energy services from the same biomass resource and in addition, reduce health risks particularly to women, and produce a significant climate change mitigation option. Even though efficiency improvements to conversion devices and use of cleaner fuels reduce unsustainable biomass use, they are currently not eligible under the CDM (Schlamadinger & Jürgens, 2004). However, work is under way by the CDM Executive Board in this direction (let’s keep this placeholder, as this may be resolved until the report comes out).

4.3.3.3.1 Conversion technologies

A wide range of conversion technologies to produce bioenergy carriers and useful energy (Fig. 4.3.15) are under continuous development both for small and large scale applications. The use of biomass for cogeneration (combined heat and power) and industrial, domestic and district heating continues to expand (Martinot, 2005). Combustion of biomass for heat and steam generation remains the state of the art, but advanced technologies including second generation biofuels, biomass integrated gasification combined cycle (BIGCC) systems, co-firing (with coal or gas), and pyrolysis, are awaiting further technical breakthroughs and demonstrations to bring down the costs of heat and power production from biomass.

Figure 4.3.15 Thermochemical and biochemical conversions from a range of biomass feedstocks to energy carriers and then to useful bioenergy.

Biomass tends to have low energy density compared with equivalent fossil fuels which makes transportation, storage and handling more costly per unit of energy (Sims, 2002). These costs will be minimized if biomass can be sourced from a location where it is already concentrated, such as a sawmill or sugar mill, and converted nearby (IEA, Bioenergy, 2005). The reason bioenergy projects using forest and crop residues are often not competitive at present lies in the resource being dispersed over large areas leading to high collection costs.

Bioenergy carriers range from a simple firewood log to a highly refined transport fuel. Different biomass products suit different situations and specific objectives for using biomass are affected by the quantity, quality and cost of feedstock available, location of the consumers, type and value of energy services required, and whether there are any co-products or benefits (IEA, 2005).

Combustion and co-firing

Combustion is by far the most commonly applied conversion route for biomass. Improved insight into fundamental aspects relating to combustion performance and ash behaviour could lead to further increases in plant reliability and efficiency. Emission levels and specific investment costs will be reduced and better understanding of the combustion of challenging fuels such as straw is needed (IEA, 2002). Cogeneration through combustion to generate useful heat and power is increasing.

Biomass pellet and briquette heating systems for domestic and small industrial heat supply are experiencing growing demand in OECD countries since the TAR due to their convenience. They also provide good potential for developing countries to export their surplus biomass as pellets are portable, flowable, have consistent quality with a low moisture content, good energy density, and can be made from a range of feedstocks.

Biomass can easily be combined with fossil fuel technologies by co-firing solid biomass particles with coal; mixing synthesis gas, landfill gas or biogas with natural gas prior to combustion; blending diesel with biodiesel and gasoline with bioethanol; and using flexible fuel engines in vehicles. There has been rapid progress since the TAR in the development of the co-utilisation of biomass materials in coal-fired boiler plants. Worldwide more than 150 coal-fired power plants in the range 50-700 MWe have operational experience of co-firing with woody biomass or wastes, at least on a trial basis (IEA, 2004a). Commercially significant lignites, bituminous and sub-bituminous coals, anthracites, and petroleum coke have all been co-fired up to 15% by energy content with a very wide range of biomass material, including herbaceous and woody materials, wet and dry agricultural residues and energy crops. This experience has shown how the technical risks associated with co-firing in different types of coal-fired power plants can be reduced to an acceptable level through proper selection of biomass type and co-firing technology. It is a relatively low cost and low risk means of adding biomass capacity, particularly in developing countries where old coal-fired plants are prevalent.

Gasification of biomass

Gasification of biomass is generally easier than for coal (section 4.3.1.1.1). It has a higher conversion efficiency (40-50%) than combustion, can generate electricity through a gas turbine or the synthesis gas produced can be used as feedstock for a range of liquid biofuels. Development of efficient BIGCC systems is nearing commercial realization but the challenges of gas clean up remain. Several pilot and demonstration projects have been evaluated with varying degrees of success (IEA, 2006). A life cycle assessment of the production of electricity in a BIGCC plant showed 95% of carbon delivered was recycled (Mann & Spath, 1997). From the energy ratio analysis, one unit of fossil fuel input produced approximately 16 units of carbon neutral electricity exported to the grid.

Biogas

Recovery of methane from anaerobic digestion plants has increased since the TAR. More than 4,500 installations (including landfill gas recovery plants) in Europe, corresponding to 3.3 Mt methane or 92 PJ / year, were operating in 2002 with a total potential estimated to be 770 PJ (28 Mt methane) in year 2020 (Jönsson and Persson, 2003; Jönsson, 2004).

Biofuels for transport

Global biofuel consumption in 2002 was between 0.35 EJ (IEA, 2004) and 0.50 EJ (UNDP, 2004). Biochemical and thermochemical conversion technologies can convert CO2 neutral biomass feedstocks into carbon containing fuels such as biodiesel, di-methyl esters and Fischer-Tropsch liquids as well as to hydrogen. The primary feedstock for ethanol production worldwide remains sugar or starch from agricultural crops, and its primary use is as an oxygenate within gasoline at 5%-22% blends. Reacting ethanol with butylene produces ETBE also used as an 8-10% blend with gasoline. Fermentation techniques are commercially undertaken in a number of jurisdictions, including Brazil from sugar cane at over 300 distilleries (Moreira & Goldemberg, 1999; Martinot, 2005), the USA, Spain and France from maize and other cereal crops (Jeanroy, 2000), and more recently in Canada and Sweden from ligno-cellulosic sources (Lawford & Rousseau, 2003). The bioethanol market is likely to continue to expand as the processing of ligno-cellulose to sugars and glycerides matures. These carriers can be converted to ethanol, diesel, hydrogen and chemical intermediates to displace petro-chemicals (Sims, 2004). Process demonstration units have been installed in several locations including the National Renewable Energy Laboratory, USA (Nguyen et al. 1996), University of British Columbia, Canada (Boussaid *et al*., 2000), and northern Sweden (Wingren *et al*., 2004). Commercial ventures for ligno-cellulosic-based ethanol include Iogen (Canada) and Abengoa (Spain and USA). Anaerobic digestion and Fischer-Tropsch processes can also be used for producing gaseous and liquid fuels at the small scale (Larson and Jin, 1999).

Overall performance and impacts of bioenergy

If no policies are in place for supporting sustainable biomass production schemes or for incentivizing advanced bioenergy technologies, then the global share of bioenergy may decrease in the next few decades, as other energy sources increase faster than bioenergy. Criteria need to be recognised to avoid serious negative impacts in terms of water use, biodiversity, and socio-economic issues.

Long-term analyses using integrated assessment models (Read & Lermit, 2005) indicated that a combination of biomass technologies together with carbon capture and storage, will have an important bearing on the attainability and costs of low stabilization levels (below 450 ppmv). Where biomass is used as a feedstock for combustion, gasification or hydrogen production at a large scale plant, it would be physically possible to capture, transport and sequester the CO_2. For solid biomass gasification projects at a smaller, more dispersed scale, the incorporation of the resulting charcoal into the soil to enhance crop growth, soil water holding capacity, and increase in soil carbon content could be feasible (Okimori *et al.,* 2003; Day, 2005). The potential to reduce atmospheric CO_2 concentrations relatively rapidly is the reason these options are being espoused as a possible solution to abrupt climate change.

Fossil energy is usually consumed in producing bioenergy carriers, but usually this energy input is a small fraction of the total energy output. Typical energy ratios for bioenergy forestry and agriculture systems are 1:25 to 1:50 units (Matthews, 2001). While energy output / input ratios are often quoted they should be used with care. Biomass can be produced and converted independent of external fossil energy by using its own product. However, this means that less of the product can be sold to markets to displace fossil fuels. Also energy ratios do not indicate any GHG mitigation potential since this depends on the fossil fuel reference system. Thus, in some cases it might be preferable to transport biomass over longer distances if this means that a more carbon intensive and less efficient fossil fuel system can be replaced. Overall, careful choice of system boundaries is necessary when analyzing the GHG impacts of bioenergy systems and full life cycle analyses are essential. (Schlamadinger *et al*, 2005).

Which measure to use when assessing the GHG mitigation of bioenergy partly depends on the limiting resource. Where the volume of residues available is restricted, the GHG mitigation per tonne of biomass used should be maximized. This suggests finding uses for biomass where carbon intensive fossil fuels can be replaced. When extra land is used to produce biomass for energy, then the GHG mitigation potential per unit of land area is of interest. When subsidies, tax exemptions, feed-in tariffs or similar measures are in place, then the GHG mitigation per unit of monetary support is relevant, taking into account co-benefits that may help to justify this support (Table 4.3.3 and section 4.7).

Table 4.3.3 The multi-benefits of biomass uptake can be social, environmental as well as economic (based on IEA, 2005)

Overall bioenergy is envisaged to maintain its position as the highest contributor to global renewable energy in the short to medium term (Faaij, 2005; IEA, 2006). Costs vary widely due to the complex characteristics of the resource, their site specificity, national policies, labour costs and efficiency of the conversion technologies used but they are expected to continue to decline over time. The social and environmental co-benefits, including carbon sequestration opportunities, will be drivers to future bioenergy project uptake. De-coupling of agricultural subsidies from food and feed production could be another driver, especially for agricultural and short-rotation forest crops.

4.3.3.4 Geothermal

Geothermal resources have long been used for direct heat or, where ground water temperatures above 100°C exist, for conversion to electricity using binary power plants (with low boiling point transfer fluids and heat exchangers), organic Rankin cycle systems, or steam turbines (when natural temperatures are above 250°C). Fields of natural steam are rare and most are mixed steam and hot water requiring single or double flash systems to separate out the hot water which can then be used in binary plants or for direct use of the heat (Martinot, 2005). Reinjection of the fluids (to increase the life of the plant and overcome concerns at river water pollution) and binary systems have become acceptable technologies but often at added cost.

The present installed generation capacity of over 8900 MW_e in 24 countries produce 56.8TWh (0.3%) of global electricity and is growing at around 20% / yr (Bertani, 2005). Plant capacity factor ranges from 40-95%, thus making some plants suitable for base load (World Energy Council, 2004). Over 10,000 MW_e of proven resources are not yet utilized from which over 1,000 TWh/yr of electricity could be produced (Martinot, 2005).

The thermal resource can be abundant from wells drilled to depths of 1-4 km. If not in the form of natural steam, the heat can be used directly for industrial process heat, district heating and domestic water and space heating. Deeper drilling up to 8km may be cost effective in future to reach the molten rock magma. Drilling technology will also help to develop the hot dry rock and wet rock resources which are abundant everywhere if drilling is deep enough to reach rock temperatures high enough for viable heat extraction.

Growing sustainability concerns which relate to land subsidence, the long term outlook for a project where the heat is extracted faster than it can be naturally replenished (Bromley & Currie, 2003), chemical pollution of waterways (eg with arsenic), and CO_2 emissions have resulted in some geothermal resource consents being declined.

Several technologies are becoming available to enhance the use of geothermal heat including combined cycle for steam resources, trilateral cycles for binary total flow resources, remote detection of hot zones during exploration, absorption/regeneration cycles and improved power conversion technologies (World Energy Council, 2004). It is expected that improvements in characterizing underground reservoirs, low-cost drilling techniques, more efficient conversion systems, and utilization of deeper reservoirs, will improve the uptake of geothermal resources as will the market value for extractable co-products such as silica, zinc, manganese, lithium etc (IEA, 2006?).

The increasing uptake of ground source heat pumps for the heating and cooling of buildings results from lower capital costs from mass production and improved heat exchanger loop systems. However drilling the bores to install the loops used to deposit or extract the heat can be up to half of the capital costs.

4.3.3.5 Solar thermal

4.3.3.5.1 High temperature

Concentrated solar power (CSP) plants are categorized according to the way the sun's ray are concentrated:

- parabolic trough-shaped mirror reflectors;
- central tower receivers requiring numerous heliostats; and
- parabolic dish-shaped reflectors.

The receiver transfers the solar heat to a working fluid which then transfers it to a solar thermal power conversion system, based on Rankine, Brayton, combined or Stirling cycles. To give a secure and reliable supply, intermittency problems can be overcome by using supplementary energy from natural gas or thermal bioenergy systems at night and during cloudy periods as well as the storage of surplus solar heat.

High temperature solar thermal power generating plants are best sited in areas with good direct solar radiation, usually at lower latitudes (Fig. 4.3.16). In these areas 1 km^2 of land is enough to generate 125 GWh from a 50 MW plant (Philibert, 2004). Thus about 1% of the world's desert areas could theoretically be sufficient to meet global electricity demand (IEA, 2006?).

INSERT **Figure 4.3.16 Regions of the world with high direct insolation** (WEC, 2004)

Installed current capacity in California was 354 MW from nine plants connected to the Southern California grid during 1984–1991 and ranging from 14 to 80 MW each. With over 2 million m^2 of parabolic troughs they generate 0.001 EJ/yr (World Energy Council, 2004). The current global installed capacity of 21 GW_e is estimated to generate approximately 1 EJ/yr (IEA, 2004). New projects totaling over 1400 MW are being constructed or planned in 11 countries including Spain

(500MW supported by a new feed-in tariff) (ESTIA, 2004; Martinot, 2005) and in Israel for the first of several 100MW plants (Sagie, 2005). The African Development Bank has financed a 50MW combined cycle plant in Morocco which will generate 55GWh /yr and a new 700MWe Stirling dish project is planned in the Mojave desert of the USA (ISES, 2005).

Solar trough technology is the most mature CSP technology with a maximum peak efficiency of 21% in terms of conversion of direct solar radiation into grid electricity. Tower technology has been successfully demonstrated by two 10 MW systems in the USA with commercial development potential giving long term levelized energy costs similar to trough technology.

Advanced technologies include troughs with direct steam generation, Fresnel collectors to reduce costs by 20%, molten salt energy storage, integrated combined cycle systems and advanced Stirling dishes. The latter are arousing renewed interest in solar thermal power generation, and could provide opportunities for further cost reductions (World Energy Council, 2004; IEA 2004b). In addition the hybrid operation with high temperature biomass combustion to avoid intermittency problems is being investigated (IEA, 2006?).

4.3.3.5.2 Low temperature

Small scale, low temperature solar thermal systems can supply heat for domestic hot water (DHW) and space heating in residential, commercial and institutional buildings, schools and hotels; swimming pools; crop drying facilities; industrial processes; desalination plants and solar-assisted district heating. The main collector technologies include unglazed and glazed flat plates and evacuated tubes. Solar thermal energy may also be used to generate hydrogen (photochemical, photo-electrochemical, photo-biochemical).

More than 100 million m^2 of solar thermal collector area were in operation around the world at the end of 2001 with an annual installed area at more than 10 million m^2. Unglazed collectors, mainly used to heat swimming pools, cover 28 million m^2 mostly in the USA. Glazed solar collectors cover 49 million m^2 of which evacuated collectors were almost half that area and mostly in China (IEA, 2004).

DHW systems are expanding rapidly in some developing countries. For example over one-third of homes in Barbados are equipped with DHW systems and in India DHW is considered among the country's most commercialized renewable energy technologies (Milton, 2005). China is the world leader in uptake of systems (Zhang *et al.,* 2005).

Estimating annual solar thermal energy production based on the collector areas in operation also depends on the solar radiation available and the solar thermal technology used. For example, in Austria annual solar yields were estimated to be 350 kWh/m^2 for flat-plate collectors, 550 kWh/m^2 for vacuum collectors and 300 kWh/m^2 for unglazed collectors. Estimated annual yields for glazed flat-plate collectors are 700 kWh/m^2 in Australia, 400 kWh/m^2 in Germany and 1000 kWh/m^2 in Israel. The estimated annual global solar thermal collector yield of all recorded systems is around 42 TWh (0.15 EJ) (IEA, 2004).

4.3.3.6 Solar photovoltaic (PV)

The proportion of solar radiation which reaches the Earth's surface is more than 10,000 times the current annual global energy consumption. The average annual surface insolation varies with latitude ranging between 1000 kWh/m^2 in temperate regions and 2500 kWh/m^2 in dry desert areas.

Current global installed capacity is hard to assess with estimates of 3100 MW (Mayrock, 2003), 2400 MW (Greenpeace, 2004) and >4000MW generating more than 21 TWh in 2004 (Martinot, 2005). Annual production grew from 740MW in 2003 to 1150MW in 2004 as new manufacturing plant capacity was built to meet growing demand for PV.

During the last few years the annual global production has increased by about 35% (Fig. 4.3.17) with Japan the world market leader producing over half the present annual production (IEA, 2003f). Expansion is also taking place at around 30% per year in developing countries where around 20% of new PV capacity was installed in 2004, mainly in rural areas where grid electricity is either not available or unreliable (World Energy Council, 2004). Decentralised generation by solar PV is already economically feasible for villages with long distances to a distribution grid and providing basic lighting and radio is socially desirable.

INSERT **Figure 4.3.17. Annual production of PV modules (Mayrock, 2003)**

The cost of solar PV power is continually decreasing (Fig. 4.3.10) due to solar cell efficiency improvements as a result of R&D investment, mass production of solar panels and learning through project experience giving a 20% cost reduction for every doubling of accumulated capacity. In new buildings costs can be reduced because PV systems are well designed to be an integral part of the roof, the walls or even windows.

Most commercially available solar PV modules are based on crystalline silicon cells with monocrystalline (with around 18 % efficiency) having 33.2% of the market share in 2003 and polycrystalline (at around 15% efficiency but at a lower cost /W_p) having 56.3%.

Other PV-cell types using thinner and cheaper solar cell materials may have greater prospects for cost reduction including
thin film silicon cells (8.8% of production in 2003);
thin film copper indium diselenid cells (CIS, 0.7% of production);
photochemical cells; and
polymer cells.
Commercial thin film cells have efficiencies up to 8%, but commercial efficiencies of 10-12% seem to be within reach during the next years (Risø, 2002). Experimental cells have reached laboratory efficiencies of up to 37 % for super thin flexible cells (Martinot, 2005) but their commercial cost is very high. Work on reducing the cost of manufacturing, using low-cost polymer materials, and developing new materials such as quantum dots and nano-structures, will allow the solar resource to be more fully exploited. The challenge is to replace crystalline silicon cells by thin film designs which are simpler and cheaper to make. Continued R & D investment is needed for PV to realize its potential and, in developing countries, economic and social welfare benefits should be considered (IEA, 2006).

4.3.3.7 Passive solar

Buildings can be designed to use efficient solar collection for passive space heating, heating water, and cooling using absorption chillers or desiccant regeneration (U.S. Climate Change Technology Program, 2003). In a typical mid-latitude temperate region, 30 % of energy use is for space and water heating and is often around 50 % of total building energy use with cooking and appliances making up the balance (World Energy Council, 2004).

Solar heating and cooling of buildings can reduce energy loads (otherwise met by purchased energy inputs) by around 50% at no extra construction cost. Building design criteria and thermal properties of glass and construction materials are well understood but good selection based on energy use is often not implemented. Up to 75% load reduction may be possible for modest investment (IEA, 2006?). This would provide energy security and can reduce peak electricity loads. A wide range of design measures, technologies, and opportunities are covered by the IEA Solar Heating and Cooling implementing agreement (www.iea-shc.org) and also described in Chapter 6.

For all solar energy applications, particularly in urban applications, there is a risk of the investment benefits being reduced by the shading of the solar collector by new buildings or trees growing nearby. Local municipalities have a role to play in preventing such conflicts by identifying a protected "solar envelope" (Duncan, 2004).

4.3.3.8 Ocean energy

The ocean energy resource involves capturing the energy in wind-driven waves, the gravitational tidal range, thermal gradients between warm surface water in tropical and sub-tropical latitudes and the colder water at depths of 1000 m or greater, salinity gradients, and marine currents induced by tides and gradients. All the related technologies (with the exception of tidal range which is similar to hydropower systems) are at an early stage of development with several prototypes deployed. Initial commercial projects are few and include three tidal barrages amounting to 260MW (and no more are planned) and two commercial wave power projects with a total of 750kW peak power. To combat the harsh environment and withstand extreme weather conditions, installed costs of a marine energy technology are usually high.

Good wave energy climates exist at Tierra del Fuego, Western Australia and to the west of the British Isles (Fig. 4.3.18) where a deep water power density of 60-70 kW/m exists but falling to about 20 kW/m at the foreshore (Heath, 2004).

INSERT **Figure 4.3.18. Annual average wave power flux (kW/m) across the oceans (Wavegen, 2004).**

Many wave devices are still at the R&D stage with only a small number of devices tested or deployed in the sea. More than 1000 patents for wave power machines have been registered (e.g. articulated rafts, nodding ducks, compressible floating bags, tethered buoys, bottom standing oscillating water columns, over-spilling systems and submerged pressure chambers). Most of these patents are in the theoretical stage and few plants have been built and tested. Examples include a 250 kW on-shore oscillating wave column plant connected to the grid at the Island of Islay where tunnels were cut into the cliffs on the shoreline to form the chamber, which captures the energy (www.wavegen.com). Also a 237t wave dragon machine with an installed capacity of 18.2 kW has been tested in Denmark since 2003. Full scale 4-11 MW units have since been designed. No fully commercial plants have been built to date though one is planned off the coast of Portugal. The wave energy industry is now in a similar stage of development that the wind industry was in the 1980s.

From a theoretical standpoint, marine currents offer an immense source of renewable energy. Preliminary investigations of the Agulhas current off the coast of South Africa, the swiftest sea current in the world, showed that on the 100m deep seabed, a 1km stretch of permanent turbines would produce 100MW (Nel, 2003). Demonstrations of marine current prototype devices have been undertaken off the west coast of southern England (WREC, 2004).

Ocean thermal energy conversion is still in the research stage and it is too early to estimate the energy that might be recovered from this potential resource. Initial applicability will likely be for tropical island nations where power is presently provided by expensive diesel generators.

4.3.4. Recovered Energy

The use of surplus heat generated during the manufacturing process by some industries (such as fertilizer manufacturing) can be used on-site to provide process heat and power. It is covered in Chapter 7.

4.4. Energy Carriers and Services

Energy carriers include electricity and heat as well as solid, liquid and gaseous fuels. They occupy intermediate steps in the energy supply chain between primary sources and end-use applications. An energy carrier is thus a transmitter of energy. Technology issues surrounding energy carriers involve the conversion of primary to secondary energy, transporting the secondary energy, in some cases storing it prior to use, and converting it to useful end-use applications (Fig. 4.4.1).

INSERT Figure 4.4.1. Dynamic interplay between energy sources, energy carriers and energy end-uses.

Note: Energy sources are at the lower left and end-uses at the upper right. Energy carriers appear as vertical lines in the middle. Important energy conversions are noted for transformations to solid carriers (small blue circles); to liquid or gaseous carriers (small pink circles); and critical transformations for future energy systems (large green circles) (WEC, 2004a).

Where a conversion process transforms primary energy near the source of production (e.g. solar heating) a carrier is not involved. In other cases the primary energy source also becomes the carrier (e.g. natural gas). The carrier can also store energy either in place (e.g. woody biomass) or as transportable energy (e.g. liquefied natural gas), or both. For long distances, the primary transportation technologies for gaseous and liquid materials are pipelines or shipping tankers or road tankers; for solids by rail, boats and trucks; and for electricity by wire conductors.

Each energy conversion step in the supply chain invokes a cost (from both energy losses and capital costs for equipment) and therefore directly affects the ability of an energy path to compete in the marketplace. The final benefit/cost calculus ultimately determines market penetration of an energy carrier and hence the associated energy source and end-use technologies. Thus, utilization of a cost-effective and efficient energy carrier will help promote the source and end-use technology.

Hydrocarbon substances produced by fossil fuels and biomass are utilized widely as energy carriers. They divide into solid, slurry, liquid, and gas based on an energy form (Table 4.4.1).

INSERT Table 4.4.1. Energy carriers of hydrocarbon substances

Liquid hydrocarbons have high energy density, which is superior in transport and storage properties. Crude oil is the most energy-efficient fuel to transport over long distances from sources to refinery and to demand points. When petroleum, diesel oil, and other light and medium distillates are extracted, the residues are used to produce bitumen and heavy fuel oil used as an energy source for industrial processes, oil-fired power plants, and shipping fuel. Oil products are particularly important for the transportation sector that depends almost exclusively on carbon-based petroleum products such as gasoline, diesel fuel, and jet fuel. At present, 99% of the energy consumed in road transportation is derived from oil products.

4.4.1 Electricity

Electricity is the highest value energy carrier today because it is clean at the point of use, and can be used in so many end use applications for relatively little cost. It is effective as a source of motive power (motors), for lighting, heating and cooling, and as the prerequisite for electronics and computer systems. Producing electricity involves converting a primary energy source (EPRI, 2003). Although global energy intensity (energy/GDP) continues to decrease, the percentage of primary energy used to generate electricity has steadily increased (Fig. 4.4.2) such that the ratio of electricity produced to GDP has remained constant. Therefore electricity production will probably keep pace with future global GDP growth if the world economy continues to grow and develop at expected rates.

INSERT Figure 4.4.2 Ratio of electricity to total primary energy in the U.S. since 1900 (EPRI, 2004).

Traditional electricity conversion technologies such as coal-fired, steam power plants are expected to be displaced over time with more advanced technologies such as combined cycle gas or advanced coal with carbon capture and storage (CCS), nuclear, fuel cells, wind, concentrated solar thermal, photovoltaics, and biomass. All of these would reduce the production of greenhouse gases and increase the overall efficiency of energy use. Previous IPCC and WEC scenarios (TAR, 2001; WEC, 2001) suggested that nuclear and combined cycle natural gas technology (CCGT) with CCS may become the dominant technologies for electricity production early this century. Solar PV and hydrogen fuel cells may eventually become commercially viable and even dominate, but because of their complexity, current cost and state of development, they may only do so later this century, even though they will begin to penetrate the market earlier.

A major possibility for emissions reduction from electricity production is substitution from coal and oil to natural gas through the use of more advanced technologies. Conversion efficiencies vary and GHG emission savings (gC/kWh) were calculated for before and after each of the mitigation options based on IPCC (1997) factors (56.1g CO_2/MJ natural gas, 74.1g for diesel; 77.4g for fuel oil and 94.6g for coal). There is also a large potential CO_2 emission reduction to be gained from efficiency improvement in power generation technology using the same fuel. A 27% reduction is possible by replacing a normal coal-fired steam turbine with advanced steam, pulverized coal technology, and a 36% reduction by replacing a single cycle gas turbine with a CCGT.

Table 4.4.2. Reduction in CO_2 emission coefficient by fuel substitution in electricity production. (Danish Energy Authority, 2004)

Comparing life cycle GHG emissions of alternative electricity production systems, fossil fueled plants have high CO_2 emissions per GWh particularly for lignite, hard coal, heavy fuel oil, and natural gas (Fig. 4.4.3). Where fossil fuel is replaced by renewable energy, the decrease in emissions is the full value per kWh of the emission coefficient (Sims *et al.*, 2003). Direct CO_2 emission from combustion of fossil fuel in a power plant are 10- 20 times higher than the indirect emissions associated with the total energy requirements for plant construction and operation during the plant's life (Uchiyama, 1996).

INSERT Figure 4.4.3. GHG emissions from alternative electricity production systems (WEC, 2004b).

From the supply point of view, the restructuring of liberalized electricity markets in many countries is expected to strengthen incentives to improve production efficiency. In the longer run, it could lead to investment in more efficient facilities with an expansion in the use of relatively less-polluting natural gas facilities because of their high efficiency, low capital construction and operating costs, and low risk (Burtraw et al, 2000; Sondreal et al, 2003). However, the net environmental impact of new natural gas-fired generation will depend upon what type of load is being serviced and what generation mode it may be displacing. In the short run, expanding electricity consumption could lead to growth in the use of existing, relatively more polluting, coal-fired facilities. In addition, because of the relative short supply and price volatility of natural gas, coal may still remain cheaper and relatively attractive (Sevi, 2004). Finally, in the absence of specific policies applying to renewable or nuclear technologies, a decline in wholesale electricity prices due to greater competition may undermine the opportunities for their penetration since in many cases they remain relatively expensive compared with fossil-based generation (section 4.3).

Most electricity technology development efforts are aimed at improving the reliability of the power delivery system to prevent cascading outages. Novel conversion processes available commercially or under development are summarized below, along with commentary on the technology development needed to bring these technologies into popular utilization.

4.4.1.1. Power technology development

4.4.1.1.1. Distributed energy

The bulk of global electricity production is traditionally from large scale systems where energy conversion takes place in centrally located power plants, with transmission over copper wires to consumers. Similarly heat and transport fuels are normally produced at large scales then distributed. However, there is an increasing trend towards distributed energy resource (DER) systems, especially distributed electricity generation (DG), in which local energy sources (often renewable) are utilized or energy is carried to a point at or near the location of consumption where it is then converted to electricity and distributed locally. As well as wind, geothermal and biomass, DG systems incorporate diesel generators or small gas turbines. Batteries or flywheels can be used for storage on critical local systems where reliability is an important feature. In future, fuel cells operating on hydrogen (either reformed on-site from natural gas, electrolyzed from water, or fed directly with fossil fuel based hydrogen from a pipeline) may be used for DG applications. A critical objective however will be to first increase the power density of fuel cells and reduce their installed cost to less than $100/kW.

The general use of DER could fundamentally change the relationship between power suppliers and consumers and, in time as usage increases, also the network architecture of the power distribution system. The concept can use a myriad of renewable and fossil fuel resources in numerous small-scale heat and power generating systems to meet local demands. Such technological infrastructure could enable the two-way flow of power and information and enable competitive markets to develop for a broad range of distributed services. The intermittent nature of many forms of renewable energy may require a mix of energy sources to be used to provide system reliability.

Technology development in the near- and intermediate-term will be focused on the demonstration of advanced DER technologies, particularly “hybrid” systems that for example, integrate high efficiency fuel cells with advanced micro-turbines. Flexible AC transmission systems (FACTS) are now being employed as components for solid-state electronics to control power flow whereby numerous generators can then be controlled by the line company to match the ever changing load demand. Superconducting transmission technologies are under development for the power system of the future, possibly incorporating hydrogen (see 4.4.3.1) as both a cryogenic coolant and an energy carrier.

The recent growth in fossil fuel based DG technologies is apparent in North America (Fig. 4.4.4). Increasingly sophisticated consumers who value the ability to choose among unbundled services understand that electricity is embedded in virtually all goods and services. Technology advances will set the stage for the emergence of a new generation of higher-margin energy services, including power quality and information-related services.
INSERT Figure 4.4.4. Recent growth in distributed electricity generation using fossil fuel distributed energy resources in North America (from EPRI, 2004).

4.4.1.1.2. Coal gasification.
Gasifying coal prior to conversion to electricity reduces the emissions of sulphur, nitrogen oxides, and mercury, resulting in a much cleaner fuel while reducing the cost of capturing and sequestering CO_2 emissions from the flue gas where that is conducted. Early-stage commercial implementation of integrated gasification combined cycle generation (IGCC) is planned over the next decade to demonstrate the technological and economic feasibility of this “clean coal” technology. Currently the incremental costs are too high compared with traditional steam plants for many countries to consider this option in spite of the environmental and health benefits. IGCC systems can produce both electricity and “syngas”, a mixture of hydrogen and carbon monoxide. Other gaseous chemical compounds such as methane are also achievable, depending on system design. Currently, there are four coal-based IGCC systems operating world-wide and in 2005 several US utilities announced plans for building grid-connected IGCC systems. China is also planning to build a 120MW_e pilot plant using two 42MW_e gas turbines and a 38MW_e steam turbine with a follow-up full scale plant planned for 2010-2015 (Zheng, 2005).

4.4.1.1.3. Combined heat and power (CHP)
Up to two-thirds of the primary energy used to generate electricity in traditional thermal power plants is lost in the form of heat. CHP (or cogeneration) systems produce electricity but also capture the excess heat for process use and district heating schemes such that current designs can boost conversion efficiencies to over 80% leading to cost savings (Table 4.4.3). The converted heat energy used in CHP usually comes from steam turbines and internal combustion engines. In the future, this energy may also come from Stirling engines (Whispergen, 2005), micro-turbines, fuel cells, and gasification. CHP is usually implemented as a distributed energy resource, installed in municipalities, commercial buildings or industrial facilities where it meets both electricity and thermal local needs.
INSERT Table 4.4.3 Characteristics of CHP (cogeneration) plants.

CHP schemes can range from an electrical capacity of less than 5 kW_e to 500 MW_e and be based on a wide variety of fuels with individual installations accepting more than one fuel. By increasing conversion efficiency to useful energy, cogeneration significantly reduces emissions. Cogeneration is an option that can provide environmental benefits as part of an economically attractive investment. Each kWh of cogeneration can save between 160 and 500 g of CO_2 if the alternatives for electricity and heat are fossil fuel based (Fig. 4.3.2). Bioenergy based CHP plants also have potential between 1-20 MW_e (Kirjavainen *et al.,* 2004).

4.4.2. Liquid and gaseous fuels

For reasons of both convenience and economics, energy carriers have shown a continual shift, from solids to liquids and more recently from liquids to gases (WEC, 2004b) which will continue. Coal, natural gas, petroleum and biomass can be used to produce a variety of synthetic liquids for transport fuels, industrial processes and in some regions of the world for domestic heating. These include petroleum products from crude oil or coal, methanol from coal or natural gas, ethanol and fatty acid esters (biodiesel) from biomass, liquefied natural gas, diesel fuel from coal or petroleum, and di-methyl ether from biomass.

The transportation sector will eventually need to make the transition from conventional oil to less carbon related fuels. Liquid biofuels currently supply only a small percentage of motor fuel, but their use is growing rapidly and might increase dramatically (IEA, 2004g; section 4.3.3.3; Chapter 5). If not used as blends with gasoline or diesel, separate handling and preparation processes for each fuel and for each conversion system will need developing. At present it is not clear whether the costs of biofuel production or the volumes available can make them competitive with petroleum products, compressed natural gas, other hydrocarbons or coal derived liquid fuels. However, biomass-derived liquids already provide benefits as additives to gasoline to boost octane and reduce some emissions.

Gaseous fuels include natural gas (a primary energy source and a carrier), methane from coal or biomass, and hydrogen from coal, natural gas, biomass gasification, electricity, or very high temperature breakdown of water. They already provide the majority of heating requirements in the developed world. In any future market penetration, CO_2 reduction and urban air pollution reduction will be benefits, especially if ultimately hydrogen fuel can be made and used without releasing CO_2 into the atmosphere.

4.4.2.1. Natural gas processing

Processing of natural gas is at times needed to remove CO_2 and other contaminants from the output of a gas well. The processing requirement may increase if future gas fields are high in contaminants. Ocean methane gas hydrates also have high levels of CO_2, which may have to be cleaned up to produce pipeline quality gas. The management of this CO_2 will be important in any future expansion of natural gas utilization. Future increases in global natural gas usage (for direct use by the industrial and commercial sectors as well as for power production) will require development and scale-up of liquefied natural gas (LNG) as an energy carrier. In addition the need to improve the transport and handling of LNG technology and the prospects for expanded use of LNG depend critically on cooperation among the producing countries and consuming nations. Geopolitical issues will at least be as important as economic and technology solutions in determining the global future of LNG.

4.4.2.2. Hydrogen

The advantages and motivation of a future hydrogen economy essentially depend on hydrogen production costs and the efficiency at which this energy carrier can be utilized. Government incentives can be beneficial to the introduction of this carrier and related conversion technologies. The International Partnership for the Hydrogen Economy (IPHE) is an international cooperative programme for advancing RD&D on hydrogen and fuel cells across the application spectrum with the goal of making the hydrogen economy a reality (IEA, 2003g; EERE, 2005). Also the IEA's Hydrogen implementing agreement (IEA, 2005f) has encouraged international research collaboration for over 25 years.

Plans for a future “electricity/hydrogen economy” will require low-cost, high-efficiency methods for producing, transporting, and storing the hydrogen. Currently several methods for hydrogen production are under study. Most commercial hydrogen production today is based on steam reforming of methane, but electrolysis of water may be a viable approach in the future, depending on natural gas and electricity prices. Current costs of electrolysers are high but declining.

Large hydro and nuclear power plants also offer promise for hydrogen production as they can either provide off-peak power for electrolysis or high-temperatures for the thermal decomposition of water giving the potential for increasing the efficiency of production and reducing the cost. Hydrogen transport and storage issues include the energy lost during compression, and developing optimal approaches for storage, both stationary for re-conversion to electricity, or transportable for use in vehicles. Storage options include pressurized gas, cryogenic gas, liquefied hydrogen, and solid storage (e.g. as a metal hydride). Storing hydrogen as ammonia is also used for some current applications and could be scaled up for power production, although ammonia is toxic. A number of pathways to produce hydrogen from solar energy is also feasible (Fig. 4.4.6).

Figure 4.4.6. Sustainable paths to hydrogen energy carriers from solar energy sources (EPRI, 2004).

4.4.3 Heat

Heat is a critical energy source for all economies. It is used in industrial processes (for food processing, petroleum refining, timber drying, pulp production, etc), and in commercial and residential buildings for space heating and hot water.

Many industries generate both heat and electricity as an integral part of their production process, in most cases being used within the industry but in some cases sold for other uses outside the industry. Heat is also used for district heating of buildings (Chapter 6), whether from natural gas, coal, or geothermal sources. Efficient use of district heat can play a very important role in the development of transition economies (IEA, 2004a).

Heat pumps are experiencing rapid uptake as their retail price decreases, in particular in countries with an ample supply of cheap electricity from domestic resources. They can be used for simple air to air space heating, domestic air to water heating and for utilizing waste heat in domestic, commercial and industrial applications.

Heat from renewable carbon-free energy can be provided by biomass, geothermal and either passive or active solar thermal. Biomass already provides about 10 % of world primary energy supplies for cooking and heating (section 4.3.3.3; Johansson, 2004). Biomass derived energy used for heat has a unique energy carrier profile. The preparation of the fuel for combustion in a boiler is often the critical step in assuring that the biomass can be used effectively and efficiently due to the wide variation in the characteristics of the readily available fuels. In some instances, the best use of biomass will be co-firing with coal or natural gas using 5 to 10% biomass.

4.5 Mitigation costs and potentials

Assessing future costs and potentials for the range of energy supply options is difficult. It is linked to the uncertainties of political support initiatives, technological development, rate of public acceptance, the possible rates of learning and capacity building and future levels of subsidies. The time of commercial delivery of the concept of a future hydrogen economy is one such example that encompasses all these uncertainties leading to considerable debate on its future technical and economic potentials and even if a hydrogen economy will ever be feasible at all (US Climate Change Technology Program, 2005; IEA 2003b).

4.5.1 Energy source substitution

Natural gas and nuclear power have taken market share away from oil especially in the electric utility sector since the 1970 oil shocks. Increased shares of gas and nuclear in the energy supply mix mainly in developed countries has played a dominant role in lowering GHG emissions since carbon intensity has improved from 20 gC/MJ in 973 to 17 gC/MJ in 2000 (based on Rotty, 1984 and BP, 2005b). Hydropower is also a large contributor to improve carbon intensity, mainly in developing countries. The IEA World Energy Outlook (2004) “Alternative” scenario anticipates a lowering of the predicted demand for coal, oil and gas by 2030 due to energy efficiency and a small increase in total renewable energy uptake.

4.5.2 Hydrocarbon and its efficiency

As conventional oil supplies become scarce, and extraction technology develops, unconventional energy sources will become more economically attractive but perhaps offset by environmental impact costs. This will extend the life of the conventional oil resource through to the next century. It was estimated that production capacity could be as high as 4.6 EJ/yr by 2020 based on crude oil prices of $25/bbl (USGS World Petroleum Assessment, 2000).

Higher oil prices have drawn attention to the potential for developing uneconomical natural gas reserves such as those associated with oil extraction or isolated gas fields which lie far from markets. Gas to liquids (GTL) technology to bring these gas resources to market has recently become attractive because it is cost competitive with diesel fuel at world oil prices above $20 per barrel (Annual Energy Outlook, 2005). At present, at least nine commercial GTL projects are progressing at various development stages in gas-rich countries such as Qatar, Iran, Russia, Nigeria, Australia, and Algeria. Worldwide GTL production is estimated at 580 thousand barrels per day and Qatar is set to produce about 394,000 barrels per day by 2011 (FACTS, 2005). CCGT plants remain competitive with a typical investment cost around €570 – 830 /MW or €35 – 70 /MW for a larger 100-400 MW plant with efficiency around 58% (DEA, 2004).

Carbon capture and storage

Costs for the various components of a CCS system vary widely, depending on the base case and the wide range of source, transport and storage situations (Table 4.5.1). In most system, the cost of capture (including compression) is the largest component but could be reduced by 20-30% over the next decade using new technologies still in the R & D phase. The costs of transport and storage of CO_2 could decrease slowly as the technology matures further and the scale increases (IPCC, 2005)

INSERT Table 4.5.1 Current cost ranges for the components of a CCS system, applied to a given type of power plant or industrial source. (IPCC, 2005)

Estimates of the technical potential for different geological storage options (Table 4.5.2) show saline formations have the largest potential. Overall the upper limits to the potentials have a high degree of uncertainty, reflecting conflicting views in the literature and the fact that the knowledge of saline formations is quite limited in most parts of the world. (IPCC, 2005). A concern is that captured CO_2 will probably contain contaminants that may limit its disposal in the oceans or in certain geological reservoirs.

INSERT Table 4.5.2 Storage capacity for several geological storage options (IPCC, 2005).

4.5.3 Renewable energy

Renewable energy sources are captured, converted into energy carriers and used to provide similar energy services to fossil fuels. Typical construction costs for new power plants are high, being up to US$2500/kW for some technologies, but on good sites they can generate power for around 3-4USc/kWh (Martinot, 2005). On poorer sites the costs are very variable (Table 4.3.1). In areas where the industry is growing, many of the best sites with good resources for wind, geothermal, biomass and hydro have already been utilised, so more costly projects might be predicted in the future. Conversely learning experience from the previous projects will help to drive down the development costs (Fig 4.3.10).

Comparisons of potentials between various energy sources and conversion technologies for electricity generation must include assessments of losses as well as plant capacity factors (Fig 4.5.1). The average capacity factor of PV systems in Japan is below 15 %, which is much smaller than the 70-80% for nuclear and fossil fuels plants. Taking a gross power output of 1,000 MW(e) and a plant life of 30 years, thermal and nuclear power plants have considerable energy losses but the net electricity generated is greater than comparable renewable power generation plants of the same total output. For example the net electricity supplied by 1000MW_e of nuclear plant capacity is over six times higher than that of a similar size PV system.

INSERT Figure 4.5.1 Net electricity supplied by a range of power generation systems each of 1,000MW_e total capacity over 30 years plant life (Data updated from Uchiyama, 1996)

Hydro power

It is estimated that there is the capability to produce 60 EJ of energy from large hydropower systems (BP, 2004) but obtaining consents is often a constraint due to environmental concerns. In addition about 25 % of water reservoirs in the world have associated generation facilities, but many more irrigation and urban water supply schemes could have small hydro-power generation retrofits added.

Small (<10MW) and micro (<1MW) hydropower systems have provided electricity to many rural communities in developing countries such as Nepal, but in total they only generate slightly less than 1 EJ/yr (World Energy Council, 2004). The global technical potential of small and micro hydro is around 150-200GW with many unexploited good resource sites available at generating costs between 2-6USc/kWh but with additional costs needed for power connection and distribution. These costs can be prohibitive in remote areas, even for mini-grids just for local communities, and some form of financial assistance from aid programmes or governments will be necessary.

Wind power

Total installed costs of a wind farm range from US$1000-1400 /kW depending on location, road access, proximity to load etc. Operation and maintenance costs vary from 1% of investment costs in year 1 rising to 4.5% after 15 years. Thus power generated is around 3 - 4 USc/kWh on good sites with capacity factors exceeding 35% (IEA, 2006). By 2010 the cost of wind power should be 2.4-3.0 USc/kWh depending on the mean annual wind speed and the roughness class of the site (Morthorst, 2004). A good overview of wind potential (http://www.stanford.edu/group/efmh/winds/global_winds.html) gives 72TW which, assuming a 20% average capacity factor, could generate 126,000 TWh/yr and exceeds current world primary energy production. It is double the 600EJ potential calculated by Johansson et al., (2004). The socio-economic potential is likely to be much lower however as already in areas where wind power is growing, objections from local residents is increasing. Off-shore wind farms can reduce this barrier to some degree. In addition the amount of intermittent wind power acceptable to a transmission grid is debatable but around 20-30% seems to be the practical maximum without expensive back-up required (Gul & Stenzel, 2005).

Biomass

The available global economic potential from biomass residues and wastes (which would have no-regrets use and avoid disposal costs), is estimated to be around 100 EJ/yr (World Energy Council, 2004). To increase this biomass potential would require changes to agricultural and forestry production and active energy crop growth. Hall & Rao (1999) estimated 2900 EJ of potential biomass energy was available of which only 270 EJ could be utilized on a sustainable basis at competitive prices. Hoogwijk (2004) analysed potential biomass use for 17 different scenarios and showed the “research focus” supply side potential by 2025 to 2050 was between 67 EJ and 450 EJ and the “demand driven” potential between 28EJ to 220 EJ. The global technical potential of bioenergy is therefore large and could provide around 200-300 EJ /yr at competitive costs by around 2050.

It is estimated that also by 2050 about 130 – 270 EJ/yr of energy crops may be produced at costs below US$2/GJ (equivalent to the current highest cost level of coal) (Hoogwijk, 2004). Such low costs presume significant productivity improvements over time, land and water is available, and cost reductions will occur due to technical learning and capital-labour substitution. Commercial energy crops are already grown extensively in Brazil (sugar cane for ethanol), USA (maize for ethanol) and Europe (oilseed rape for biodiesel) but such land use is often heavily subsidized and may involve non-sustainable agricultural practices (OECD, 2004b). Bioethanol and biodiesel have potential to rise to over 50 EJ in 2050 based on economic analysis (Fischer & Schrattenholzer, 2001) with production costs currently ranging between 40 – 80USc/l.

Commercial bioenergy options using small-scale steam turbines, Stirling engines, organic Rankin cycle systems etc. can generate power for between 7 to 12 USc/kWh, but with the opportunity to further reduce the capital costs by mass production and experience (Martinot, 2005). Incentives for market penetration, such as the renewable electricity directive in the EU and the 10% renewable energy law in China, are proving to be crucial for the technical potential to be realised.

Experience curves will also play a part. For example capital investment costs for a high pressure, biomass, direct gasification combined-cycle plant up to 50MW are estimated to fall from over US$2,000/kW to around US$1,100/kW by 2030, with operating costs, including delivered fuel supply, also declining to give generation costs around 10 to 12 USc/kWh (Martinot, 2005).

Geothermal

Generation costs from new geothermal fields running at base load will vary from 3-8USc/kWh depending on size of field, resource consent conditions and quality of resource (high quality being >250°C, low being <150°C) (IEA, 2006). Capital costs have declined by around 50% from around US$3000-5000/kW in the 1980s for all plant types (with binary being the more costly). Operating costs will increase if related CO_2 emissions released from the bore are included in future.

Solar thermal

The generating costs for concentrated solar power trough & tower plants could fall from 10-12.6 USc/kWh for the existing Californian concentrating solar power (CSP) plants to compete with mid-load power at around 3.5-6.2 USc/kWh by 2020 (Sargent & Lundy, 2003). A world CSP capacity of 21,500MW is envisaged by 2020 which would produce 54.6 TWh with a further possible increase leading towards 5% coverage of world electricity demand by 2040 (ESTIA, 2003).

Solar thermal costs differ with location and government support. In Greece a domestic hot water thermo-siphon system for one family unit of 2.4 m^2 collector and 150 l tank costs €700 whereas in Germany, where solar radiation is lower, a similar system (4–6 m^2 and 300 l tank) costs around €4500. Cheaper systems are manufactured in China where it is commercially viable and has the highest share of the 40 million units installed worldwide (BIREC, 2005).

Solar photovoltaics

Electricity generated directly by utilizing solar photons to create free electrons in a PV cell is estimated to have a technical potential of at least 1600 EJ per year (Renewables, 2004; WEC, 2004). The purchase price for 14-17% efficient monocrystalline modules is currently about US$3.6 /$W_p$ (Risoe, 2002) from which electricity can be generated for around 30 USc/kWh in high sunshine regions (U.S. Climate Change Technology Program, 2003).

Assuming an annual production growth of 27% /yr, cost reductions of solar modules are expected to fall to $US2 /$W_p$ by 2010 and to $1/$W_p$ by 2015 (UNDP, 2000). If achieved the installed PV capacity by 2020 will be 205 GW generating 282 TWh/yr and amounting to about 1% of global electricity demand (EPIA, 2004). More than half of new capacity will be installed in non-OECD countries and by 2040 over 20% of global electricity demand could be met by PV (Jäger-Waldau, 2003).

Ocean energy

The economically exploitable resource in deep water waves using current wave energy device designs is estimated to be around 7 EJ/yr (World Energy Council, 2004) while the theoretical potential is in the millions of EJ (Renewables, 2004). Generating costs are difficult to estimate since no commercial plants exist but are claimed to be around 8-11USc/kWh on good sites (IEA, 2006).

Extracting electrical energy from marine currents could yield in excess of 10 TWh/yr (0.4 EJ/yr) if major estuaries with large tidal fluctuations like the Bay of Fundy or the Solway Firth could be tapped, but the cost estimates range from 45-135c/kWh (IEA, 2006). In order for these new technologies to enter the market, just like for the wind industry in the 1980s, sustained government and public support will be needed.

4.5.4 Nuclear Power

Power reactors being built today are of safer and more economical third-generation designs. The worldwide operational performance of nuclear power plants has improved and the 2001-2003 average unit capacity factor was 83.7% (IAEA PRIS, 2005). The average capacity factors in USA increased from less than 60% to about 90% between 1980 and 2003, while average electricity production costs declined from US 3.3¢/kWh in 1988 to US 1.7¢/kWh in 2003 (Nuclear Energy Institute, 2005).

Costs of 27 coal-fired, 23 gas-fired and 13 nuclear power plants in several countries were compared including construction costs, the expense schedule for the construction period and where applicable, refurbishment and decommissioning costs (NEA/IEA, 2005). At a 5% discount rate nuclear was cheaper than coal by a margin of >10% in seven countries (including one case in the US) for one or more combinations of plants. It was cheaper than gas by a margin of >10% in nine countries. Gas was never cheaper than nuclear. At a 10% discount rate nuclear was cheaper than coal by a margin of >10% in Canada, the Czech Republic, France, the Slovak Republic and for two plants in Germany. Coal was cheaper than nuclear by a margin of >10% in only the United States and for one plant in Germany. Nuclear was cheaper than gas by a margin of >10% in Canada, the Czech Republic, France, Germany, the Netherlands, the Slovak Republic, the Republic of Korea and for two plants in Switzerland. The difference between gas and nuclear was less than 10% in the United States and Japan and for one plant in Switzerland.

The economic competitiveness of different energy production forms is dependent on local conditions. For example the cost of £12.6 billion (US$500/kW undiscounted) for decommissioning the 4452 MW Magnox nuclear reactors in the UK with a further £43.2 billion for decommissioning other nuclear infrastructure (NDA, 2005), was estimated to be higher than for light water reactors. When comparing generation costs between systems therefore, care must be taken to ensure full life cycle costs are included.

4.5.5 Comparative costs and potentials

Analyses of costs and potentials of energy supply options have been numerous (see for example IPCC, 2001; Sims *et al.,* 2003; NEA/IEA, 2005; IAEA 2001). The TAR showed the emissions from energy supply (excluding energy end use emissions across all sectors) was 1,620 MtC in 1990 and growing at 1.5% per year. Potential emission reductions mainly at less than $100/tC were estimated to be between 50-150 MtC by 2010 (but with an “unlikely” probability) and between 350-700 MtC “probable” by 2020.

These reductions resulted mainly from switching from gas to coal; gas and coal to nuclear; gas and coal to wind, hydro, biomass and solar thermal; co-firing of biomass with coal; and carbon capture and storage (CCS). Assessing the probability for fuel switching and CCS is closely linked with the carbon price which is difficult to predict out to 2030. For example RIVM analysis (den Elzen, 2004) showed a carbon equivalent price of around €60 /t would be necessary by 2030 if atmospheric concentrations were to be stabilized at 550ppm by 2100 or closer to €30 /t if 650 ppm was the 2100 stabilization goal. In the electricity sector cost uncertainty also exists from the rate of market liberalization and the level of intermittent renewable energy sources acceptable to the grid without giving reliability issues (NEA/IEA, 2005).

An updated summary of costs and potentials out to 2050 shows abundant supplies of primary energy resources remain available (Table 4.5.3). A large number of assumptions were used to provide the data and the level of uncertainty is high. It does however indicate that proven and probable fossil fuel reserves are large and concern at the environmental impacts from combusting them is the main driver for wishing to make the transition to non-carbon primary energy sources. These renewable energy and uranium resources are also in sufficient supply to meet the current 450 EJ/yr global primary energy demand (IEA, 2005b). How rapidly the transition can occur will depend on the speed with which the investment costs can be driven down and/or whether the externality costs can be properly valued in order to provide heat, electricity and transport fuels in a more sustainable manner.

INSERT Table 4.5.3 Primary use, technical potentials and projected costs for a range of primary energy resources

4.6 Risks

4.6.1 For baseline technologies

The risk factors relating to the development of the range of energy supply systems involving new or improved energy conversion technologies and project implementation pathways have been identified (US DOE, 1997; WEC, 2004). They include:

- technical risks to meet cost or performance objectives and hence to assess the probability of commercialization;
- commercial risks and vulnerabilities hindering deployment such as there being inadequate infrastructure in place and insufficient investment available;
- human health risks as a consequence of noise, emissions to air and water, and waste disposal;
- ecological and environmental risks from related adverse effects of a technology on non-human species and ecosystems;
- economic risks leading to consumers preferring cheaper competing technologies; and
- regulatory risks as a result of newly introduced regulations which hinder technology development (though if carefully designed these could assist desirable project deployment).

For a private development or finance company, the economic risk of not gaining a satisfactory return on investment in a project relating to energy supply and infrastructure remains paramount. Risk and risk avoidance from energy security and terrorism now also commonly enter the public policy debate on energy supply project development, as well as economic efficiency and environmental protection. Generation plants, transmission lines, sub-stations, and gas and oil pipelines exemplify accessible centralized targets. As traditional energy resources become more constrained, world peace and political stability will be further threatened (Schwartz & Randall, 2004). The high costs to maintain energy supplies and provide energy security are often hidden in defense and national security expenditure (Goldemberg, 2004). The potential for conflict, sabotage, and the disruption of production and trade of fossil fuels and fissionable materials cannot be dismissed.

Energy market reforms have created opportunities in that a competitive energy market usually increases efficiency in the sector, broadens the choice of energy sources, and hence contributes to supply security. However there are risks from poorly designed markets that supply problems will eventuate as a result of more cautious investment decisions or simply bad or malicious decisions. For example electricity markets do not always ensure sufficient margins in generation capacity to sustain reliability. Market price signals tend not to be strong enough to stimulate adequate and timely investment in generation plant, peaking capacity and transmission capacity (IEA, 2002). A regulatory framework is needed to ensure that the market delivers price signals and balances them with public service obligations to provide energy supply security when making investment decisions.

Risks to energy systems within a country also arise from the vulnerability of utility networks as a result of poor engineering design, the potential for unreliability of the components, and operator error (Aitken, 2004). Each country must design its own unique energy supply system and develop specific relevant policies based on risk avoidance, energy needs, prevailing circumstances and available resources.

A diversified portfolio of energy supply options would reduce many of the risks including those resulting from energy security and fuel price volatility. It would also offer a hedge against the risk that new technologies will not develop as fast or perform as planned. It would provide greater learning experiences, which may prove valuable to speed up technology deployment should the need for future greenhouse gas emission reductions become more essential than currently anticipated. A broad portfolio of supply options also offers insurance against future uncertainties such as population growth, rate of increasing energy demand, and speed of new technology development.

Research and development investment (section 4.9) can minimize risks resulting from the impact each energy technology option might have on such issues as the cost of climate stabilization, oil price shocks and cartel pricing, urban air pollution and energy supply disruptions such as electricity grid failures (Schock *et al,* 1999). The total insurance value alone for reducing the potential cost of these four risks to USA society alone was estimated conservatively to be over $12 billion/year.

Global energy trade in oil, gas and coal is likely to double by 2030 (IEA, 2003c). This will increase mutual dependence among nations but will intensify concerns about the world's vulnerability to energy-supply disruptions. Oil will be exported mainly from the Middle East; cross-border gas-pipeline and electricity transmission projects will multiply; and shipping trade in LNG will expand. These will involve additional risks compared to local production for domestic markets due to the greater number of stakeholders involved including different governments and investors. Long-term contracts to balance the interests of all stakeholders will be needed.

Price volatility, particularly in oil, has resulted from unpredictable shifts in OPEC's production policy and political disruption in several oil producing nations. It causes economic problems in many countries, poses great risks for large regions of the world's economic and political stability, and disrupts global economic growth. The capability and willingness of Middle East oil producers to exploit their relatively low-cost reserves is also a major source of uncertainty.

There is future opportunity to provide people with greater knowledge in order to identify and choose preferred energy services based on information technologies (www.choices.undp.org). The lack of transparent and reliable oil statistics currently creates price volatility to the detriment of both producers and consumers. Improved and reliable data is needed (IEF, 2002). This in turn has contributed to increased volatility of natural gas and electricity prices.

When conventional oil supplies deplete, unconventional oil sources can be expected to offer transport fuel substitutes and extend the life of oil as a primary energy resource into the next century (section 4.3.1.1.3). However, according to Hallock *et al* (2004), the geographic concentration of conventional oil production, and its inevitable peaking, followed by an irreversible decline in supply volumes at some stage within the next few decades, will have economic impacts that could result in wide-ranging social-economic disruption. What is more likely is a transition from conventional to unconventional oil resources that will transform the industry but will be largely invisible to the end user other than higher prices. Once the world demand for oil exceeds the daily production from all sources, then the economics of world energy resources will be altered forever and intense competition for the remaining resources will result.

High oil prices will have greatest impact on those countries most dependent on imported fuels, particularly where energy intensive manufacturing accounts for a large share of economic activity. Reducing oil dependence is a high priority in developing countries where a large fraction of their foreign currency earnings, up to half in some cases (Goldemberg, 2004), is spent on energy imports. Indebtedness, balance of payments and terms of trade will worsen and the additional import costs will at times exceed the levels of incoming international aid (IEA, 2001).

4.6.2 Mitigation options

Energy prices are likely to rise as a result of mitigation against greenhouse gases as more expensive technologies are employed and where a carbon charge on greenhouse gas emissions is enforced. This is already the case or soon planned to be introduced in Sweden, Norway and New Zealand etc. The international trading of carbon is new and will probably result in widely fluctuating and unpredictable prices over the medium to long term (Grubb, 2003) which could discourage the desired level of investment in zero or low greenhouse gas emitting technologies.

The EU Emission Trading System (EUETS) commenced operations on 1 January 2005. Emission allowance prices rapidly rose to much higher levels than initially expected (Point Carbon, 2005). This type of scheme acts to bring benefits to industries producing or using carbon-neutral energy forms. The first experiences showed that the price of allowances had a significant effect on the competitiveness of different fuels since the cost of using carbon intensive fuels is effectively increased. For instance, in northern Europe, an allowance value of €18/tonne CO_2 meant a doubling of fuel costs for coal. This had a secondary effect in that the price of wood based fuels initially increased when the EUETS started operations because their competitiveness was improved and this in turn caused concern in the forestry industry about the possibility that timber products were flowing to the bioenergy sector. Increasing imports of fossil-fuel based electricity into countries that have reduced their emissions from carbon based fuels can possibly increase overall greenhouse gas emissions due to greater transmision efficiency losses, the use of inferior supply side technologies and increased demand for available fossil fuel resources in the exporting country.

Geosequestration of CO_2 from large scale coal combustion, gasification and potentially liquefaction plants must be proven to be viable at the “giga-scale” if coal is not to remain a major greenhouse gas contributor (Williams, 2004). The rapidly growing coal industries in China, India and elsewhere are being restructured to improve safety and boost productivity. Sufficient investment is required in new and retrofit plants to ensure state-of-the-art, efficient, clean coal technologies are constructed and environmental impacts are minimized (IEA, 2003e).

Emergency response strategies and mechanisms will enhance and protect the collective energy supply (IEA, 2003a). Responses to oil supply disruptions due to volatility in the world oil market require decisive actions taken collectively for which the IEA has a lead role. In most non-member countries of the IEA emergency response systems including reserve oil stock-holdings are not well developed so they are vulnerable to supply disruptions. Building up their stocks would improve resilience to disruption and allow them to better contribute to a global security network.

Rising loss burdens from increasing numbers of extreme weather events are presenting the insurance industry with new challenges which cannot be met through premium increases alone (Munich Re, 2005). There may be a loss of economic value and some regions have already become uninsurable. Climate and environmental protection and risk management are of strategic importance for the industry. Both the number of events and the monetary losses have increased perceptibly in recent decades. Insurance losses from natural disasters were 15 times higher in the 1990s than the 1960s (adjusted to $2003 values) and the number of events, excluding earthquakes, rose from 15 in the 1950s, 16 in 1960s, 28 in 1970s, 44 in 1980s to 74 in 1990s (Munich Re, 2004). In 2003 global economic losses from tropical storms, winter blizzards, tornadoes, hail storms, floods, heat waves, droughts and forest fires, landslides, and frosts were around US$58.6 billion of which US$15.8 billion was covered by insurance.

Global government subsidies for fossil fuels and nuclear energy have been around $250-300 billion per year since the 1990s (Geller, 2003; UNDP, 2000) and other indirect subsidies also exist (section 4.7.1.1). If continued this will risk the slower uptake of less subsidized renewable energy technologies than would otherwise happen (Sawin and Flavin, 2004). Arguably, subsidies for renewable energy are also high in some regions (e.g. investment tax credits or fixed feed-in tariffs) so accurate cost comparisons between technology options are hard to make. Nuclear power, despite the investments put into its development, probably suffers most from public perception and the risk to the capital markets that there will not be a viable return on investment.

4.7 Polices and instruments

4.7.1 Emission reduction policies

There are a multitude of technologies, behavioural changes, and infrastructural developments that society could adopt to counter climate change and reduce the environmental impacts of current energy supply systems. This is covered in more detail in the multi-sectoral treatment in Chapter 13. With specific reference to energy supply, the reduction of GHG emissions from these systems is being actively pursued through a substantial variety of government policies and measures. Whereas planning policies provide background for climate change mitigation programmes and for implementation of particular instruments, most climate policies relating to energy supply tend to come from three policy “families” (OECD, 2002a).

Economic instruments (subsidies, taxes, tax exemption and tax credit) are widely used to play a central role in national climate strategies by modifying markets to introduce the new and emerging clean energy technologies. Such policies seek to change resource allocations or the price of goods in order to promote these technologies.

Regulatory instruments (mandated targets, minimum performance standards, vehicle exhaust emission controls and other regulations) are employed to modify a legal framework and are commonly used to promote the uptake of energy efficiency and renewable energy sources.

Policy processes (strategic planning, dissemination of information, research investment and consultation) and their outreach are often the precursor to more concrete measures. For example two common policy instruments relating to energy supply and use are voluntary energy efficiency agreements and tradable permit systems (IEA, 2002; IEA, 2004a). Voluntary agreements rely on co-operation between governments and stakeholders from various energy-intensive sectors and can offer a flexible and integrated approach compared to traditional policy instruments. Tradable permits (also involving emissions trading, green certificates and other flexible mechanisms), initially experienced a relatively slow uptake due to the inexperience of using such options as well as the complex framework required to exploit the flexible and efficient nature of these measures. However, this has changed dramatically since the European Union’s emission trading system came into operation in January 2005. There are also voluntary tradable permit systems operating in Japan and Norway, and proposed systems in Canada together with several individual states of the USA and Australia.

In addition to fiscal measures and regulatory instruments, governments support R D&D programmes aimed to stimulate the development of new innovative energy conversion technologies and to create markets for a wide range of climate-friendly energy technologies (section 4.8).

Many government policies undertaken to date that impact on greenhouse gas emissions aim to achieve multiple policy objectives including market and subsidy reform, particularly in the energy sector (Table 4.7.1). In addition, governments are using a variety of approaches to overcome market barriers to energy efficiency improvements and other “win-win” actions.

INSERT Table 4.7.1. General policy objectives and options used to reduce energy demand and hence greenhouse gas emissions from the energy supply sector.

4.7.1.1 Limitations of emission reduction policies for energy supply

Subsidies and other incentives

The harmful effects of various policies and subsidies supporting fossil fuels have been reviewed (IEA, 2001; OECD, 2002b; Saunders & Schneider, 2000). Government subsidies in the global energy sector are in the order of $250 -300 billion /yr, of which only around 2-3% supports renewables (De Moor, 2001). An OECD study showed global carbon dioxide emissions would be reduced by more than 6 % and real income increased by 0.1 % by 2010 if subsidies on fossil fuels used by industry and the power generation sector were removed (OECD, 2002b). However subsidies are notoriously difficult to remove and reforms are usually conducted in a gradual and programmed fashion to soften the financial pain of those who stand to lose, need time to adjust, enable staff to be re-trained, and allow time for alternative policy mechanisms to take effect.

Support for renewable energy and energy-efficient technologies can help to reduce harmful atmospheric emissions depending on market conditions and how mechanisms are structured. Subsidies encourage market development and could become a major element of sustainable energy policies. For both environmental and energy security reasons many industrialized countries have introduced, and later increased, grant support schemes for producing electricity, heat, and transport fuels based on capturing renewable energy resources, and on installing more energy-efficient thermal combustion plant.

Emission taxes and charges

The “polluter pays” principle removes support for energy production and consumption and levies charges (or taxes) on carbon based fossil fuels in order to internalise their environmental impact. A carbon charge imposes an additional cost on fuels based on the carbon content and results in competitive gains for renewable energy and nuclear projects. Sweden (where the original €28 /t CO_2 imposed in 1991 was raised to €84 /t CO_2 in 2003) showed that a significant penetration of renewable energy and low carbon emitting projects can be achieved as a result (Johansson & Turkenburg, 2004).

Quantitative targets

Setting goals and quantitative targets for renewable energy at both national and regional levels increase the size of the markets, including biofuels and heat, thereby providing more policy stability for project developers. For example European Union members have agreed on targets to increase the share of renewable primary energy from 6 % in 1995 to 12 % and the proportion of electricity generated from renewable sources from 14 % in 1997 to 22 % by 2010 (EU, 2001). Further, the EU Transport Biofuels Directive set targets of 5.75% of total transport fuel consumption coming from renewables by 2010 (EU, 2003; Chapter 5). The Latin American and Caribbean Initiative, signed in May 2002 in Sao Paulo, included a target of 10 % renewable energy by 2010 (Goldemberg, 2004). The South African Government mandated an additional 10 TWh renewable energy contribution to final energy consumption by 2013 that is approximately 4% of the projected electricity demand and additional to the estimated existing renewable energy contribution of 115 TWh/yr mainly from fuelwood and waste (DME, 2003b). Many other countries outlined similar targets at the major renewable energy conference in Bonn (Renewables, 2004) attended by 154 governments. Renewable portfolio standards, tradable green certificates and feed-in tariffs have all been used successfully in many countries to accelerate the transition to renewable energy systems (Martinot, 2005). A strong case can be made for retaining all systems as they essentially serve different purposes but each is important for the promotion of renewable energy (Lauber, 2004).

Feed-in tariffs

Price-based feed-in tariffs have been compared with quantity-based instruments including quotas, green certificates, and competitive bidding (Sawin, 2003a; Menanteau *et al*, 2004; Lauber, 2004). In 2001 the total level of support provided for preferential power tariffs in Europe (EU-15, particularly in Germany and Italy) exceeded €1 billion (EEA, 2004). In the longer term however such a system may become difficult to sustain as the cost will be high when the generation of green electricity accounts for a significant share of total power production (Sijm, 2002).

Experience confirms that incentives to support the value of "green" power produced by rewarding performance are preferable to a capital investment grant (Neuhoff, 2004) since they encourage market deployment while promoting increases in production efficiency. In terms of installed renewable energy capacity, much better results have been obtained with price-based than quantity-based approaches. In theory, this difference should not exist, as bidding prices that are set at the same level as feed-in tariffs should logically give rise to comparable capacities being installed. The discrepancy can be explained by the higher feed-in tariffs and the stronger incentive effect of guaranteed prices, which makes this system more stable and more predictable in the eyes of investors. On the other hand, quantity-based approaches are more efficient as bidding to define and adjust the overall goals, and then adjust the quotas, provides an indirect way of controlling overall costs (Menanteau *et al*, 2004).

The potential advantages offered by green certificate trading systems based on fixed quotas are encouraging a number of countries to introduce such schemes to meet ambitious renewable energy goals in an economically efficient way. Such systems can encourage more precise control over quotas, the creation of competition among producers, and incentives to lower costs (ECN, 2005; Menanteau *et al*, 2004).

Tradeable permit systems

Domestic and international tradable permit systems are gaining recognition as a means of lowering the costs of meeting climate change targets. Creating new carbon markets can assist economies in locating and realising economical ways to reduce GHG emissions and other energy related pollutants, or to improve efficiency of energy use. Modelling showed that with emission trading in an international regime, the cost of achieving the Kyoto Protocol targets in OECD regions could fall from 0.2 % of GDP to 0.1 % (Newman *et al*, 2002).

Technology development

Programmes supporting "clean technology" development and diffusion are a traditional focus of energy and environmental policies because energy innovations face barriers all along the energy supply chain (from R&D, to demonstration projects, to widespread diffusion). Direct government support is more likely to be needed for radically new technologies.

After a steep increase in the 1970s relating to the oil crises, public expenditure for energy RD&D fell steadily in industrial countries from $15 billion in 1980 to about $7 billion in 2000. About 8 % of this was for renewable energy, 6 % for fossil fuel, 18 % for energy efficiency, 47 % for nuclear energy and 20 % on other items (IEA, 2004b). About two thirds of the reduced total expenditure occurred in the United States but cuts also happened in Germany, United Kingdom and Italy. At the same time public spending on energy R D&D increased in Japan, Switzerland, Denmark and Finland but remained stable in other OECD countries (Goldemberg & Johannson, 2004).

The need for further investments in R & D of all low carbon emission technologies, tied with the efficient marketing of these products, is vital to climate policy. Besides providing direct research investment, governments can also foster industry R & D investments through a variety of fiscal instruments, such as tax deduction incentives.

Information instruments

Education, technical training and public awareness policies are an essential complement to other GHG mitigation policies. They provide direct and continuous incentives to think, act and buy “green” energy and to use energy wisely. Green power schemes, where consumers may choose to pay more for electricity generated primarily from renewable energy sources, are an example of combining information with real choice for the consumer (Newman *et al*, 2002).

Further, voluntary energy and emissions savings programs, such as *Energy Star* (EPA, 2005a), *Gas Star* (EPA, 2005b) and *Coalbed Methane Outreach* programmes (EPA, 2005c) serve to effectively disseminate relevant information and reduce barriers to the efficient and clean use of energy. These are not just public education programmes, but also industry/government partnership programmes. Similarly eco-labeling projects, such as the *German Blue Angel* scheme (UmweltBundesAmp, 2005) can serve a similar purpose in shaping perceptions about the effective use of energy.

4.7.1.2 Implementation issues

Renewable energy technologies have made significant progress during the last few decades and contribute significantly to the global energy mix. However an IEA (2004) study *Renewable Energy Market and Policy Trends in IEA Countries* revealed that almost 98% of renewables (measured as primary energy) are traditional biomass burning, hydropower and geothermal energy. These are growing at a lower rate than the total primary energy supply such that the share of renewable energy has actually been declining since 1990. Although “new” wind, solar and modern biomass projects are increasing, their growth rate does not compensate for the loss of traditional forms of renewable energy. Challenges associated with deployment of these different technologies vary, and so the strategies to encourage their growth will also be different.

IEA (2003) assessments *Experience Curves for Energy Technology Policy* and *Renewables for Power Generation* concluded that technology deployment is a critical activity and demonstrated that market learning is fundamental to the complicated process of advancing the technology toward economic efficiency while encouraging the development of a large scale, private sector infrastructure. This not only endorses the justification for new technology deployment support by governments, but also the challenge to determine *how much, for how long, and how to make investments most cost-efficient.* For these reasons the IEA has established a new Implementing Agreement on “Renewable Energy Technology Deployment”.

4.7.1.3 Experience - successes and failures

Wind power has been the main element of the Danish renewable energy policy and its penetration has been rapid, supplying about 19% of Danish electricity consumption in 2003. This fast penetration was due to the regulated, favourable feed-in tariff. A new energy act in 1999 changed the policy to one based on the trading of green certificates. This change has created considerable uncertainty for investors and has led to a significant reduction in annual investments in wind power plants during recent years (Johansson & Turkenburg, 2004).

A comprehensive renewable energy promotion approach launched at the beginning of the 1990s led to Germany becoming the world leader in terms of installed wind capacity (exceeding 13.5 GW in 2003 being nearly 40% of global capacity), and second in terms of installed photovoltaic capacity (accounting for 350 MW in 2003). The basic elements of the German approach are a combination of policy instruments, favourable feed-in tariffs and security of support to reduce investment risks (Johansson & Turkenburg, 2004).

When Spain passed a feed-in law in 1994, relatively few wind turbines were in operation. By the end of 2002, the country ranked second in the world but had less success with solar PV in spite of having high solar radiation levels and setting PV tariffs similar to those in Germany. Little PV capacity was installed because no grid connection regulations were established. This issue was resolved in 2001 by implementing national technical standards for grid connection. But PV producers who sold electricity into the grid, even households, had to register as businesses in order to pay income tax on their sales (Sawin, 2003a). While there has been significant growth in Spanish PV manufacturing in recent years, most of this is attributable to the neighbouring German market (Ristau, 2003).

In 1990, the UK government launched several rounds of competitive bidding for renewable energy contracts, known as the Non Fossil Fuel Obligation (NFFO). The successive tendering procedures resulted in regular decreases in the prices for wind projects etc awarded to successful bids. The average price for project proposals, irrespective of the technology involved, decreased from 6.7 €cents/kWh in 1994 to 4.2 €cents/kWh by 1998, being only 0.15 €cents/kWh above the wholesale electricity pool reference purchase price for the corresponding period (Menanteau, 2001). Since this support mechanism only showed limited success, the government decided to implement a more market-driven support mechanism by placing an obligation on electricity suppliers to sell a minimum percentage of power from new renewable energy sources. The annual growth rate of electricity generation by eligible plant has significantly increased since the introduction of the obligation in April 2002. In 2003-2004 a total of 7,546,787 Renewable Obligation Certificates (each for 1MWh) were issued compared with 5,583,560 in 2002-2003 (OFGEM, 2005). However, the obligation has not yet been able to stimulate many new large- scale developments.

Swedish renewable energy policy during the 1970s and 1980s focussed on strong efforts in technology R,D & D. Market development took off during the 1990s when taxes and subsidies created favourable economic conditions for new investments and fuel switching. The use of biomass increased substantially during the 1990s (for example wood fuels for district heating increased from 13 PJ in 1990 to 65 PJ in 2001). Increased carbon taxes for heating fuels (but not for fuels used for electricity production) created strong incentives for fuel switching in district heating other than for biomass-based cogeneration. The increase of biomass utilization in turn led to a development of the technology for biomass extraction from forests and in the implementation of more efficient technologies used in district heating system (Johansson, 2004).

Japan launched a “Solar Roofs” programme in 1994 to promote PV through low-interest loans, a comprehensive education and awareness program, and rebates for grid-connected residential systems. Government promotion of PV included publicity on television and in newspapers (IAE, 2003). The rebates declined gradually over time, from 50 % of installed cost in 1994 to 12 % in

2002 when the programme ended. In 1997 the rebates were opened to owners and developers of housing complexes and Japan become the world's largest installer of PVs (Haas, 2002). Japan is now the world's leading manufacturer and user of solar PV, having surpassed the United States in the late 1990s. Total capacity increased at an average of more than 42 % annually since 1992 to give more than 420 MW installed between 1994 and 2002 with a 75 % cost reduction in $/W (Maycock, 2003; IAE, 2003).

4.7.2 Other policies affecting emissions

4.7.2.1 Energy access

Access to energy is a prerequisite for sustainable development, income generation, improvement in welfare, and poverty alleviation. Analysis from 125 countries in seven regions indicated that well-being and level of development is correlated to the degree of modern energy services consumed in each country (Bailis, 2004) (Fig. 4.7.1).

Figure 4.7.1 Global energy consumption by region (tonnes oil equivalent per capita) (BP, 2004).

Poverty alleviation depends on the level and quality of the energy supply and its affordability. Villavicencio (2001) noted the inability of solar home systems to contribute significantly due to the low power capacity level available and the relatively high cost per energy unit delivered. Even accounting for high investment in grid infrastructure needed for other systems, solar PV systems cannot always cost-effectively be used for economic development. The GHG emission savings from solar home systems also tend to be negligible (Begg *et al*, 2000) whereas the social benefits from providing lighting and power for radio and television to enhance the education of the users where grid connection is unlikely have been well realized (Renewables, 2004). With the advent of energy sector reforms culminating in privatization, there is evidence that in many developing countries with poor access to modern energy, considerable effort and investment by governments and donors will continue to be necessary (Wamukonya, 2002; ESMAP, 2001; ESMAP 2000).

Despite advances in science and technology, the absolute economic gap between the least and the most developed countries is generally increasing, although on a strictly per capita basis it may be decreasing as China and India, the two most populous countries, develop their industrial bases (Economist, 2004). For instance, primary energy use per capita in Africa (with 13% of the global population) is only 26 GJ /yr in contrast to 336 GJ /yr in the United States which has only about 5% of the global population.. Annual electricity consumption in Africa is 482 kWh per person versus almost 13,000 kWh in the United States. Resolving the discrepancy of one-third of the world's population living without access to basic energy services is a prerequisite for sustained global development and poses a security threat of international dimensions (WEC, 2004). Because there will be four to five times as many people in the developing world as in the developed world (Fig. 4.1.2), an unchanged situation will likely be unstable, with uncontrolled migration across borders being perhaps the least harmful outcome and the breeding of international terrorists the worst.

Energy services are fundamental requirements to achieve sustainable development. Energy provides comfort, convenience, and mobility; enables labour productivity and information access; and, along with human resources, drives the development process. Those who lack access to modern energy services rely on poor quality sources such as fuelwood with negative health and other environmental consequences. Hence one of the most important issues for new and emerging energy technologies is their impact on developing countries. Eradicating extreme poverty by 2015 will require more than 700 million people to switch from using traditional biomass (Fig 4.7.2) to more efficient and clean commercial fuels.

Figure 4.7.2 Biomass as a percentage of total primary energy use in selected African countries. (AFREPREN/FWD, 2003)

Historically, economic growth of 1 % per capita in a developing country has been associated with an increase in the consumption of electricity, oil and natural gas of 1.3 to 2% per capita. Combined with population growth and massive economic inequities in many developing areas, this translates into a daunting requirement for additional energy supplies in order to support sustainable development. Projections developed for the 1992 United Nations Conference on Environment and Development suggested that total global energy supplies must be increased by a factor of eight or nine if the gap between the world’s rich and poor is to be narrowed. Another assessment of the challenge of achieving an equitable and sustainable world within 50 years suggested that total global energy supplies must be increased by a factor of at least three or four during this period (NAP, 1999). The environmental implications of such an enormous increase in supplies, and the financial implications are equally staggering, considering that energy sector investments already amount to a sizeable proportion of the borrowing of many developing country governments. Achieving this level of increase while keeping environmental impacts no higher than at present will be a challenge to the sustainable development process.

What people want are not commodities such as kilowatt hours and litres of fuel but the energy services they provide. If those services can be delivered affordably using less primary energy consumption due to emphasis on improving the energy efficiency of supply systems, delivery systems, and end uses, then demands on energy supply and environmental management institutions and practices will be reduced (Wilbanks, 1992; Wilbanks 1994).

Since energy efficiency gains are limited and fossil fuels are finite, in the longer term the need is for a transition from traditional fuels and readily available fossil fuel supply sources to supply options that are as sustainable as the economies they support. In many cases, this means realizing potentials for the development of local renewable energy sources although the ability of these options to meet the growing energy needs of developing urban-industrial complexes remains a significant challenge in many areas.

There are many barriers to accessing energy services in an adequate, reliable, affordable and environmentally sound manner. There are also gender dimensions relating to lack of access to appropriate energy services for women under some cultures which intensifies the inequities.

Actions suggested to overcome these barriers include innovative financial arrangements brokered between industry and government to enable appropriate infrastructures to be constructed to deliver energy, especially electricity, and increasing the priority that governments place on energy supply improvements. Some energy end-use technology issues are specific to developing countries (Johansson & Goldemberg, 2002; Goldemberg, 2000).

- The developing world may not have to follow the path already followed by OECD countries. Rather, the latest technology might be immediately implemented in some areas by so-called *technology leapfrogging* (as was the case for cellular phones which avoided the need to develop a land line infrastructure). Yet, fundamental hurdles of capitalization and manpower skills remain. The respective roles of industry and government in sustainable development and in enhancing new energy technologies need to be defined.

- Remote stationary electric power distributed generation (DG) has been advanced as a primary need for developing countries, particularly for uptake in rural areas. DG is integral to the supply of energy for a range of end-use technologies (Fig 4.4.3 and section 4.4.2.2) and offers significant benefits to rural communities beyond the value of electricity alone (e.g. water pumping and purification, health clinics, heating and cooling etc.). Sustainable and affordable DG could provide improved power quality and reliability over centralized power generation and transmission systems and possibly at a cheaper price as a number of DG technologies advance down their experience curves. It remains to be seen which alternative, if any, will dominate and in which regions.
- Building-sector needs in developing countries are vastly different from those in the developed world. Building standards are also very different as are the requirements of their inhabitants (Chapter 6). Adequate building code standards will be required in order to improve new building stock in terms of energy use in the short term. Zero and low emission, passive solar building designs are technically possible but have received scant attention by building designers to date in spite of their relatively lower total capital and energy costs over their lifetime.
- Industrialized countries with good energy supplies provide most of the world's paper. Since access to paper is usually a basic prerequisite for societal development, the highest future rate of increase in markets for paper is likely to be from imports into developing countries. Governments recognizing the opportunity for local production from a range of raw materials (straw, kenaf etc) should solve the increased heat and power generation required by encouraging the industry to use forest or crop by-products.
- Service industries will play an increasingly important role in developing countries in terms of economic growth and employment, as exemplified by the strong build-up of a knowledge-based service industry in China and India. If other nations follow suit the consequences will be the need to develop core industries such as metals and chemicals.
- A promising approach for developing countries is to package and finance in an integrated system, energy sources, energy carriers, and end-use technologies. As a result community-based services, such as electric power, wastewater treatment, water delivery, telecommunication for medical clinics and schools, and water purification, could be a model for the future. Clean and abundant water is crucial to the health and well-being of a population and to develop a vibrant economy. Globally available fresh water per person has decreased from 20,000 m^3 per person in 1950 to less than 8,000 m^3 today, mostly due to population growth (EPRI, 2000). Energy is a prerequisite to run pumps, treat and purify existing water supplies and desalinate. Thus, an important set of energy end-use technologies are also those associated with clean water. More energy efficient systems need to be developed using reliable and cheap energy if the global water supply problem is to be resolved (Hoffman, 2005).

Agriculture typically accounts for about 6–7% of global GDP or more in developing countries, (15% in sub-Saharan Africa and 24% in South Asia). End-use technologies used by the sector demand energy including indirect energy inputs for the production of fertilizers and agri-chemicals and manufacture of machinery.

Information and communication technologies (I&CT) now enjoy a high importance in all areas of human life, including energy supply and end-use technologies (UNDP, 2005). This is obvious in the developed world, but I&CT is also a necessary first step in developing countries to give people and institutions knowledge to identify and provide energy services.

Subsidies can be used to facilitate access to modern energy services but this remains controversial. Supporters claim that subsidies contribute to poverty alleviation while opponents maintain that subsidies are often poorly targeted and mainly benefit those who do not deserve such assistance. For example the subsidization of LPG for the household sector in India benefited mainly the higher expenditure groups who tended to shift away from kerosene to LPG and had little impact on biomass use and the welfare of the poor (Gangopadhyay *et al*, 2004).

In general, overall price subsidies for energy are on the decrease as many governments have forfeited the role of price control to regulatory bodies. Whereas many people continue to lament the high cost of subsidies, in relative terms subsidy costs are not particularly high. For example in India in 2002-2003 the petroleum subsidy was US$1.3 billion, accounting for a little over 1% of the total expenditure of central government (UNDP/ESMAP 2003).

Air quality and pollution

The Johannesburg Plan of Implementation (UNDESA, 2002) called on all countries to develop more sustainable consumption and production patterns. Policies and measures to promote such pathways will automatically result in a reduction in greenhouse gas emissions and also be useful in controlling air pollution. Climate change is largely associated with the emissions of non-toxic CO_2 from combustion processes, with no detrimental effects on a local or regional scale. On the other hand, air pollution concerns the impacts from toxic emissions such as SO_2, aerosols and particulates which can have local health impacts as well as potentially detrimental environmental impacts. These differences are not always clearly understood.

On average each day a human being requires from 14-18 kg of clean air to breathe, 1.5-2.0 kg of water to drink and 0.7 kg of dry food. The need for uncontaminated food and clean water to maintain general health have been recognized and addressed for a long time. However only in recent years has the importance of clean air to health been seriously noted (WHO, 2003). Air pollutants may be classified according to their physical and chemical properties. Ozone can affect vegetation growth and destroy crops whereas particulate matter, in the form of solid particles or liquid droplets with a size of $<10\mu$, can have devastating effects on human health.

Up to one billion of the world's population are exposed to pollution at levels of up to 100 times higher than World Health Organization guidelines (BBC World Service, 2001). The worst of these sufferers are rural villagers in developing countries who have to cook over open fires, often in poorly ventilated camps and houses. Feasible and cost effective solutions to poor air quality in both urban and rural areas, particularly in developing countries, need to be urgently identified and implemented (World Bank, 1998).

Major health problems suffered by women and children can be attributed to a lack of access to high quality modern energy for cooking. Increasing access to modern energy services can therefore have a double benefit. Inefficient practices, such as using coal or firewood in an open fire brazier to provide space heating (DME, 2003a), remain the norm in many countries. This often results in chronic air quality degradation, which can have very significant health impacts (Held *et al*, 1996). Increasing access to modern energy services would not only help alleviate this problem but, as greater overall efficiency is often achieved over the entire domestic energy cycle starting from the provision of primary energy up to the eventual end-use, an overall decrease in the emission of greenhouse gases would also be realised.

Indoor levels of particulate matter, a primary cause of acute respiratory infection, greatly exceed WHO recommended levels in households using combustion of biomass for cooking. It is estimated that half a million children and women die in India annually from indoor air pollution (Smith *et al*, 2000). Acute respiratory infections are the leading causes of deaths of children under 5 years old with 75% caused by pneumonia (Fig 4.7.3). EPA standards for acceptable annual levels of respirable particulates are $50\mu g/m^3$ (ITDG, 2003). A study of smoke levels conducted in two areas in

Kenya revealed that in Kajiado, the 24 hour average of respirable particulates was 5526µg/m^3 and in West Kenya, the levels were 1713µg/m^3. Another comprehensive study of 3559 children from 0 to 59 months old in Zimbabwe showed that those who came from households using wood, dung, or straw for cooking were more than twice as likely to have suffered from acute respiratory disease than those from households using LPG/natural gas or electricity (Mishra, 2003).

Figure 4.7.3 Indoor levels of particulates emitted from woodfuel in selected developing countries (Karekezi & Kithyoma, 2003).

Climate change and air quality are linked in many ways through the physical and chemical processes that take place in the atmosphere (Borrego *et al*, 2000; Shackleton *et al*, 1996; Chen *et al*, 2004). Although there remains an incomplete understanding (Grambsch, 2002), the International Global Atmospheric Chemistry programme provided major insights into the roles of nitrogen, ozone, aerosols and other gases when defining the interactions that take place between atmospheric chemistry, climate change, and its impacts (Brasseur, *et al,* 2003).

West & Fiore (2005) showed mitigation of methane emissions for global warming purposes would also have beneficial impacts on the background concentrations of toxic tropospheric ozone which are currently increasing. They estimated that global methane abatement measures could reduce anthropogenic methane emissions by about 10% with valuable cost-savings and decrease surface ozone by 0.4-0.7 ppb. Further controls on methane emissions beyond those likely to be taken for climate change purposes could have even greater benefits. They concluded by saying that air quality planning should consider reducing methane emissions alongside NO_X and NMVOCs, and because the benefits of methane controls are shared internationally, industrialized nations should consider emphasizing methane in the further development of climate change or ozone policies.

Ancillary effects are inextricably linked to human welfare, both through direct impacts on the weather and climate and, indirectly, through effects on other sectors (such as agriculture and forestry) as well as water resources, natural ecosystems, industrial emissions and many others (Janetos &Wagener, 2002). Policies and measures aimed at increasing sustainability through energy efficiency improvements, switching away from the use of fossil fuels, and reducing the production of process wastes, will usually result in a simultaneous lowering of GHG emissions and reduced air pollution.

Conversely, there are cases where measures taken to improve air quality at a local or regional level can result in a simultaneous increase in the quantity of GHG emitted. This is most likely to occur in those developing countries experiencing a phase of strong economic growth but where it may not be economically feasible or desirable to move rapidly away from the use of an indigenous primary energy source such as oil or coal (Brendow, 2004).

A number of legislative mechanisms are used by different countries to regulate for air pollution, but such legislation usually has common elements. Most schemes rely on limiting emissions of one or more criterion pollutants, with or without linkages to ambient air quality guidelines or standards (Sloss *et al*, 2003). No country presently has legislation that directly regulates the quantity of CO_2 emitted from any process. Although such regulation could, in theory, be incorporated as command and control clauses in most of the existing legislative schemes, emissions trading has emerged as the preferred method of effecting global mitigation, both within and outside the auspices of the Kyoto Protocol (Sloss *et al*, 2003). Even so, there can be conflicts between clean air legislation and the mitigation of CO_2 emissions, especially in countries where existing regulatory requirements are being strengthened through law reform processes such as in South Africa (DEAT, 2004).

Ambient air quality standards or guidelines are usually set in terms of protecting health. They are thus applicable only at or near ground level where acceptable concentrations of gaseous emissions such as SO_2 can often be achieved through atmospheric dispersion, using a tall stack, as opposed to physical removal by scrubbers. Although abatement can also be effected by adopting technologies that intrinsically give lower emissions, such as efficient, integrated gasifier, combined cycle generating plant, tall stacks are still in use at the majority of existing industrial installations and power plants around the world to avoid excessive ground level concentrations of gaseous pollutants. If the use of tall stacks is precluded due to either stringent limits being set for ambient SO_2 concentrations or if regulations directly mandate the use of SO_2 scrubbers, then the equipment used for removing the SO_2 will require energy for its operation. Thus energy is diverted away from the production process. In the case of a power plant, the net result is that more primary energy will be required to generate a given amount of exported electricity. This amounts to an overall decrease in cycle efficiency with a concomitant increase in CO_2 emissions.

Sorbent extraction or other processes necessary to support scrubber operations will also have GHG emissions associated with them. The estimated costs of damage due to unmitigated CO_2 emissions will greatly exceed those from regional acidification impacts arising from insufficient control of SO_2 emissions (Chae & Hope, 2003). This effectively amounts to trading off a potential local or regional acid rain problem against a much larger global climate problem.

Air quality management and control can work both for and against the mitigation of CO_2 emissions. Legislation needs to be approached using the principles of integrated pollution prevention and control if unexpected and unwanted climate impacts on a global scale are to be avoided (Nalbandian, 2002). This suggests that a multi-parameter approach could be adopted for air quality management, as is currently being developed for the United States. Their proposal calls for a cap and trade scheme for the power sector simultaneously covering SO_2, NOx, mercury and CO_2 that would specifically avoid conflicts with conventional regulations. Facilities would be required to optimize control strategies across all four pollutants (Burtraw & Toman, 2002). Similarly, an approach developed for Mexico City showed that linear programming applied to a database comprising emission reduction information derived separately for air pollutants and GHGs, could provide a useful decision support tool to analyze leat-cost strategies for meeting co-control targets for multiple pollutants (West *et al*, 2004).

4.7.2.3 Dematerialization

Dematerialization is the replacement of a physical product with a non-physical product or service thereby reducing production, demand and use of physical products and the end-users' dependence on them. This should then realize cost-savings in materials, transportation, consumables and the need to manage the eventual disposal and/or recycling of the physical product. It also reduces energy demand. Dematerilization can be achieved by making products smaller and lighter or replacing material products with an immaterial substitute, such as replacing postal mail with electronic mail (NRC, 2003).

In spite of a significant degree of dematerialization occurring, energy consumption can still be expected to rise due to economic development, albeit at a somewhat slower rate. For example the probable aggregate energy demand in the EU-15 countries will have increased from 258 Mtoe in 1997 to 426 Mtoe by 2010, but with dematerialization slowing this demand by an incremental decrease in energy intensity from -73Mtoe to -225 Mtoe by 2010 (Sun, 2001).

To the contrary, some analysts believe that the reductionist trend of equating sustainable development with sustained economic growth needs to be reversed (Bartelmus, 2003). Attaining sustainability through integrated policies needs the support of both shareholders and stakeholders of sustainable development.

Eco-efficiency is fundamentally disruptive when promoted as a universal prescription for environmental policy (Hukkinen, 2001) since it runs against the cognitive and institutional bases of sustainable human-environment interaction. However energy use is a very significant component of eco-efficiency. The criterion for adopting eco-efficiency should be the extent to which it promotes the recoupling of human perception of environmental issues with human action on the environment, and the concomitant recoupling of collective local organization with local ecosystem management. Increasing the efficiency of resource use is seen as a major ecological-economics goal. Opportunities for large efficiency increases, particularly in the use of energy, are myriad and will persist for a long time to come (Craig, 2001).

4.7.3 Co-benefits of mitigation policies

The variety of co-benefits stemming from utilization of new energy technologies, the dynamics of innovation and mitigation, and other non-climate policies should be understood as an essential part of economic policies striving for sustainable development at the local, regional, national and international levels. Co-benefits of GHG mitigation policies such as improved health, employment, and industry development, arise in addition to direct reduction of emissions. Different climate policies have different impacts and may initiate different concrete actions to reduce GHG concentrations. Consequently, they imply different co-benefits. Consideration of co-benefits may influence policy design by determining what policies are adopted, the extent of mitigation action taken, the timing of any such action and which sectors of the economy are the focus of the policies. Climate change mitigation policies in the energy supply sector (energy efficiency, fuel switching and renewable energy uptake) have several objectives which may imply a large range of co-benefits. Pollution effects can be local (public health, material damage, vegetation effects); regional (acid deposition, ground-level ozone); or global (stratospheric ozone layer). Non-pollution effects include energy supply security (less dependency on imported fuel); energy diversity; technological innovation and economic benefits such as reduced fuel cost and employment.

Reducing GHG emissions in the energy sector yields a global impact but co-benefits are typically experienced on a local or regional level. The full benefit of GHG mitigation may only be expected by future generations but the co-benefits are often detectable to the current generation. Improvements in air quality can be achieved in the short term, helping to offset current mitigation costs.

One of the most important co-benefits associated with GHG mitigation in the energy supply sector is fewer health effects due to local air pollution reduction. Health effects associated with improved air quality typically account for 80% of the total value of the ancillary effects of GHG mitigation policies (Burtraw & Tonan, 2000).

Energy efficient technologies lead to energy demand reduction and therefore to less dependence on expensive fuels, lower energy costs to the economy, slower source depletion and less pollution (Swart *et al*, 2003). Reduced imports of energy resources have a positive effect on the balance of payments, while optimised use of a country’s power stations will delay the need for investment in increased generating capacity. This is particularly relevant where installed capacity is lagging behind demand for electricity (Bennett, 2001). As end-use efficiency can generally play a major role in the mitigation of GHG emissions, it is covered in detail in other chapters.

The co-benefits of renewable energy can be divided into energy security and diversity, air pollution and economic growth. Energy supply security remains at the top of energy policy concerns, as renewable energy is a domestic resource and can reduce dependency on energy imports. Renewable energy based generating capacity closer to the end-user minimises both transmission losses and costs. While there are relatively high capital costs, for most renewable energy technologies the fuel input has minimal cost. This means that electricity or heat supplied is not prone to price fluctuations, as is the case with fossil fuels (Janssen, 2002).

New energy technologies are expensive during their market introduction phase but substantial learning experience is usually achievable to reduce costs (Barreto, 2001; Herzog *et al*, 2001; IEA, 2000; McDonald & Schrattenholzer, 2001; NCOE, 2004). The reduced cost of new technologies due to learning effects and the incentives for further technological improvement due to technological competition are co-benefits of climate change policy (Jochem & Madlener, 2002).

Increased net employment as a co-benefit of mitigation is an important issue, given the high unemployment level in many countries. Renewable energy, for example, offers economic co-benefits of employment creation and increased trade of technologies and services. Employment is created at different levels, from research and manufacturing to distribution, installation and maintenance. Renewable energy technologies are more labour intensive than conventional technologies for the same energy output (Kamman *et al.*, 2004). Investment in renewables also generates more jobs per dollar invested than the fossil fuel energy sector. Solar PV generates 5.65 person-years of employment per $1M in investment (over 10 years) and the wind energy industry 5.7 person-years. In contrast, every million dollars invested in the coal industry generates only 3.96 person-years of employment over the same time period (Singh *et al*, 2001).

In South Africa the development of renewable energy technologies will lead to the creation of 36,400 direct jobs by 2020 (Austin *et al*, 2003) whilst more than 900,000 new jobs will be created across Europe by 2020 as a result of the increased use of renewable energy (EUFORES, 2004). Further, there is increasing concern globally about urbanisation and the loss of economic opportunities in rural and remote regions. A shift from traditional energy sources to renewables could assist local, regional and rural development by creating employment and economic opportunities. Biomass production in particular has the potential to provide useful opportunities in the agricultural sector where they are often most needed.

Renewable energy technology manufacturing and related services, while often driven by local needs, can also be stimulated to meet growing international demands. Many of the technologies are taking advantage of economies of scale to expand manufacturing capability oriented to export markets. For example, according to industry sources, the Danish manufacturers of wind turbines had a world market share of approximately 38% in 2003 (Danish Wind Industry Association, 2003).

Energy source switching can lead to air quality improvements and economic benefits as well as reduced GHG emissions. Switches away from fossil fuels to renewable energy and nuclear sources and the growth of energy efficiency programs would seem to deliver the largest benefits (Beg, 2002).

In most cases co-benefits of GHG mitigation are defined from the macro-economic point of view or as social welfare improvements. Quantitative information about co-benefits remains limited primarily to health effects. The quantification of health benefits (mainly mortality) from energy mitigation strategies is most common, even though this is still methodologically difficult. Many co-effects are still not being quantified due to a lack of information.

Jochem & Madlener (2002) argued that co-benefits of mitigation are an important decision criterion for policy makers, but often neglected decision elements. There are many cases where the net co-benefits are not monetised, quantified or even identified by decision-makers. The consideration of co-benefits can significantly influence policy decisions about the level and timing of GHG mitigation action. They are important decision criteria not only for policy makers, but also at the company level. At the national and international level, there may be significant economic advantages to the stimulation of technical innovation and possible spill over effects with developing countries benefiting from innovation stimulated by GHG mitigation in industrialized countries. Most aspects of co-benefits have short-term effects but they support long-term mitigation policies by creating a central link to sustainable development objectives.

4.7.4. Implications of energy supply systems on sustainable development

In considering energy system choices, countries may face the challenge of achieving the correct balance between environmental protection and economic growth.

4.7.4.1 Health and environment

Energy interlinks with health in two contradictory ways. It is essential to support the provision of health services but energy conversion and consumption can have negative health impacts. For example, in the UK a lack of insufficient home heating has been identified as a principal cause of high levels of winter deaths (London Health Commission, 2003).

The dilemma between energy supply and health is clearly demonstrated in the oil sector since exploration and extraction have negative health impacts. A Kazakhstan study compared the health costs between the city of Atyrau (with a high rate of pollution from oil extraction) and Astana (without). Health costs per household in Atyrau were twice as high as in Astana. The study also showed that the annual benefits of investments in abatement technologies were at least five times higher than the virtual annual abatement costs. A key barrier to investment in these technologies was the differentiated responsibility as household health costs are borne by individuals while the earnings from oil extraction accrue to the local authorities (Netalieva *et al*, 2005). Epidemiological studies have shown that oil production in developed countries is not accompanied by these types of health risk. The technology to control the emissions causing these problems exists and is being used in other parts of the world.

Another study conducted in San Carlos, an oil producing area in Ecuador, found that males faced a 2.3 times higher risk of getting cancer compared to those living in Quito. Analysis of the water in San Carlos showed levels of polycyclic aromatic hydrocarbons 40,000 times greater than that allowed by the USEPA (Sebastian & Cordoba, 2000).

Accidental spills during oil product transportation are damaging to the environment and health. There have been many well documented spills at sea resulting in the destruction of fauna and flora and the natural restorative ability of areas of beaches and foreshore has been largely curtailed. However, the frequency of such incidents has declined sharply in recent times (Huijer, 2005). Less reported are the spills originating from cracks in pipelines. For example it was estimated that the trans-Ecuadorian pipeline alone has resulted in the spilling of 400,000 litres of crude oil since the pipeline opened in 1972.

Spills at oil refineries are also not uncommon. Verweij (2003) reported that in South Africa more than one million litres of petrol leaked from the refinery pipeline systems into the soil in 2001 hence contaminating ground water. One of the most recent spills occurred in Nanchital, Mexico in December 2004, where it was estimated that 5000 barrels of crude oil spilled from the pipeline with much of it going into the Coatzacoalcos river. Pemex, the company owning the pipeline, indicated a willingness to compensate the more than 250 local fishermen and the owners of 200 homes hit hardest.

Most oil producing countries rely on this industry as their principle source of revenue, which may in turn have significant implications for sustainable development in those countries concerned. Countries that rely on coal as their primary energy resource may be similarly affected.

Coal mining has witnessed an increasing level of accidents, largely due to poor safety measures, although this is mainly due to a proliferation of such incidents in Chinese mines, prompting urgent state intervention (China, 2004). China sustained 3,413 coal mining accidents during the first 11 months of 2004, which claimed the lives of 5,286 miners (People's Daily On-line, 2004). Exposure to coal dust has also been associated with accelerated loss of lung function (Beeckman *et al*., 2001).

Indoor air pollution emanating from wood and coal fires has been labelled the silent killer as it causes acute respiratory infection, chronic obstructive lung disease, cancer and pulmonary diseases which have been attributed to deaths among women and children (Smith, 2002; Smith *et al*, 2000; Lang *et al*, 2002; Bruce *et al*, 2000). WHO (2002) ranked indoor air pollution from solid fuels as the fourth most important health risk factor in least developed countries where 40% of the world's population live. It was estimated that about 1.6 million people die annually from indoor air pollution from cooking with solid fuels.

Improved stoves have been widely advocated (Ezzatti & Kammen, 2002; Albalak *et al*, 2001; Wafula *et al*, 2000) but evidence on their ability to reduce indoor air pollution is contentious as it has been reported that such stoves can actually increase indoor emissions (Bruce *et al*, 2002; Naeher *et al*, 2000). Edwards *et al*, (2003) noted in their study on fuelwood stoves in China that thermal efficiency is improved at the expense of combustion efficiency, resulting in increased emissions of human-damaging pollutants and GHGs.

Domestic electricity generating sets also have health issues. In Nigeria for example deaths through CO emanating from them have been on the increase as has an increase in deafness from the noise.

4.7.4.2. Equity and shared responsibility

The bulk of the energy industry, particularly oil, is concentrated in the hands of multi-national companies which have superior access to capital and technology. In many developing countries energy resources are often misappropriated and rarely benefit the majority of the population despite being major sources of income. However there are now some genuine efforts to address such injustices (World Bank, 2005). Revenue sharing is disproportionately distributed among a few stakeholders often into foreign private accounts and not used for investment into sustainable energy systems. Some studies confirm that the greater the dependence of a country on oil the worse the growth performance (Leite and Weidmann 1999).

Inadequate returns to the energy resource-rich communities have resulted in organized resistance against oil extraction companies. The local energy needs of the countries are often overlooked in the quest for foreign earnings from energy exports. Insecurities associated with oil supplies also result in high military expenditure. From 1984-94 military expenditure in OPEC countries was three times as much as in developed countries and two to ten times that of non-oil producing countries (Karl & Gary, 2004).

Inequity between multi-nationals and their host countries can have adverse impacts on development. Not only are many multi-nationals financially stronger than poor developing nations but they also tend to get the backing of their developed mother countries at the expense of the poorer countries (Gary and Karl, 2003). Multi-nationals often apply less stringent environmental protection practices in poor countries than in developed countries and exploit the environment during extraction of oil and gas (Bonifaz, 2004).

The advent of reform in the energy sector is intensifying inequalities as the multi-nationals benefit at the expense of the poor and local companies. Notably the electricity tariffs have generally shifted upwards after commencement of reforms (Wamukonya, 2003; Dubash, 2003) making it even more inaccessible to the low income earners.

4.7.4.3 Employment opportunities

In many countries throughout South America, Africa and Asia, the advent of energy sector reforms has resulted in trade unions protesting against the possible loss of jobs resulting from commercialization and privatization of energy utilities. This contrasts with the employment opportunities arising from renewable energy project developments and has led to civil unrest and violent protest (US DOE, 1997; Hall 2004). The scaling down of staff is not limited to the energy industry but extends to the government agencies and regulators who, to the disadvantage of the consumer, cannot subsequently perform their duties efficiently (World Bank, 1995; Bouille *et al*, 2001).

For a utility company the number of customers per employee is used as a measure of performance efficiency, a necessary stipulation for countries seeking conventional multilateral financing. The internationally accepted standard is about 160 customers per employee (Kwoka, 1997), but many developing countries have tended to have lower ratios and are thus considered overstaffed. Karekezi & Kimani (2001) noted that by 1998 seven of the twelve reported sub-Saharan African countries had ratios ranging from 40 to 110 customers per employee, way below the international standard. It is worth noting that the international average performance indicators normally used as a reference assume an electricity coverage that has scarcely been attained in many developing countries.

The extractive industries generally tend to have poor records on employment (CEE Bankwatch, 2002; Global Witness, 2000; Pegg, 2003; Ross 2003). Further, the poor employment status in various energy resource rich countries has often justified unsustainable and environmentally damaging practices. In Benin, for example, lack of alternative employment triggered riots in 2004 among sellers of relatively dirty black market gasoline when government authorities tried to clamp down on its sale (Toure, 2004).

4.7.4.4 Barriers to providing energy for sustainable development

The high investment costs to build energy system infrastructure is a major challenge for sustainable development. The IEA (2004) estimated that US$5 trillion will be needed to meet electricity demand in developing countries by 2030. The UN Millennium project study calculated that to meet all the eight Millennium Development Goals will require an annual average of US$20 billion of investment in the development of energy infrastructure and delivery of energy services (UNDP, 2004a). Yet access to finance for investment in energy systems especially in developing countries has been declining.

Lack of necessary infrastructure also dictates energy types and use patterns. In a study on Peruvian household demand for clean fuels, Jack (2004) found that urban dwellers were more likely to use clean fuels than rural householders, largely due to availability of the necessary infrastructure. Investment costs necessary to capture natural gas and divert it into energy systems and curb flaring and venting are also a barrier. It is estimated that over 110 billion m^3 is flared and vented worldwide annually, equivalent to the annual gas consumption in both France and Germany (ESMAP, 2004).

The level of investment varies across regions, with the most needy receiving the least interest. Between 1990 and 2001 private investments to developing and transition countries for power projects was about US$ 207 billion. Nearly 43% went to Latin America and the Caribbean, 33% to East Asia and the Pacific and approximately 1.5% to sub-Saharan Africa (Kessides, 2004).

Accessibility and affordability of clean fuels remains a major barrier in many developing countries. This is mainly due to complex supply systems that result in high transaction costs. In Niamey, Niger, a 40kg bag of coal costs about US$7.5 while fuelwood to provide the same amount of heat costs about three times as much. In Benin a large share of the population rely on black market gasoline (poorly refined and thus releasing toxic vapours), largely because it is cheaper at 52 c/l compared to 66 c/l at the pump (Toure, 2004).
Increasing renewables is a way to help isolated people in poverty. This includes landfill gas as part of an energy security strategy to use domestic resources and as a way to reach communities in rural areas not easily accessible by an electric grid or pipeline but costs often remain a barrier.

Corruption has often prevented the use of proceeds emanating from extraction of energy resources for energy systems to meet the needs for sustainable development. High levels of corruption have been witnessed in the power sector as reforms are being implemented, ultimately at the expense of sustainable development. Forms of corruption have encompassed such schemes as the granting of lucrative power purchase agreements with politicians benefiting from receiving a share of guaranteed prices considerably higher than the international market price (Shorrock, 2002; Vallete & Wysham, 2002); suspending plant operations, thereby compromising access to electricity and persuading government agencies to pay high premiums for political risk insurance (Hall & Lobina, 2004); and granting lucrative sole supplier trading rights for gas supplies (Lovei & McKechnie, 2000). Corruption may hinder development through denying government revenue from taxes and allowing stakeholders to make uncharacteristically huge profits. In addition corruption compromises quality of supply, improvement in modern energy access levels and hence development.

Mismanagement of energy resources has resulted in waste and missed opportunities to invest in sustainable energy systems. The World Bank has cited mismanagement of rich oil resources as one of the main factors fuelling civil war in Africa (World Bank, 2000). Further, oil backed loans have contributed to high foreign debts in many oil producing countries at the expense of the poor majority (IMF, 2001; Global Witness 2004). Despite heavy debts such countries continue to sign for oil backed loans (AEI, 2003) and potential revenues are used as collateral to finance government external debt. These loans are typically provided at higher interest rates than conventional concessionary loans (World Bank, 2004) and thus the majority of the local population fail to benefit from high oil prices (IRIN, 2004).

Absence and poor implementation of legal frameworks to facilitate transfer of revenue to communities affected by energy resource extraction for investment into sustainable energy systems remains a key barrier to sustainable development. Although several countries including Peru, Nigeria and Gabon have mandated enabling mechanisms for such transfers, progress in implementing these measures has been slow (Gary & Karl, 2003).

Poor policies in the international financing sector also hinder establishment of energy systems for sustainable development. A review of the extractive industries (World Bank, 2004) for example revealed that the World Bank group and the International Finance Corporation (IFC) have been investing in oil and gas extractive activities that have negative impacts on poverty alleviation and sustainable development. The review recommended that the banks should pull out of oil, gas, and coal projects by 2008.

Population growth and higher per capita energy demand are forcing supply patterns from potentially sustainable systems to unsustainable ones. Use of modern biomass fuels when produced in a sustainable manner is generally considered favourably. However their sustainable production remains a challenge and forces a shift towards other more unsustainable energy systems. In Niger for example, despite the concerted efforts through a long-term World Bank funded project, it is not possible to provide sufficient woody biomass on a sustainable basis. As a result the government has launched a campaign to encourage consumers, particularly industry, to shift from wood to coal and has re-launched a 3000 t/yr production unit, distributed 300 t of coal to Niamey, and produced 3800 coal burning stoves (ISNA, 2004).

The power imbalances between energy companies and the governments of countries they invest in hinders sustainable development, mainly because the countries lack the power to enforce the necessary regulations. The playing field is normally unequal with the multi-national companies at times having a better balance sheet than the host country's GNP. In some cases, such as Angola, oil company revenues dwarf the nation's entire revenue stream (McMillan, 2005).

Finally, in the electricity sector, power purchase agreements (PPAs) that are not favourable for establishment of sustainable energy systems are increasingly common. These include long term PPAs with payments made in foreign currency denominations, leaving the power sector extremely vulnerable to macro-economic shocks as demonstrated in the Asian crisis in 1998 (Wamukonya, 2003).

4.7.4.6 Strategies for providing energy for sustainable development

Access to energy can greatly facilitate sustainable development. Subsidies and other financial instruments including CDM projects are clearly very influential in facilitating or denying access to appropriate energy products. At present securing affordable energy supplies in many countries overrides any environmental and GHG impacts from energy use.

Social pressure can facilitate change of policy among the key stakeholders towards sustainable development practices. The Extractive Industries Review (World Bank, 2004) provides a good example. After publication of the report the World Bank agreed to adopt an approach that is more sensitive to the needs of the poor and sustainable development. The documentation of corruption in the

Angolan oil sector and consequent campaigns against corruption (Global Witness, 1999) led to the decision by some of the oil companies to adopt a policy of full disclosure (Global Witness, 2001) and this could eventually become a standard practice for all such companies.

Establishment of funds for development of energy systems can contribute to sustainable energy. In recognition of the need for low-cost loans to facilitate rural electrification the government of Peru established a fund which provides loans ranging from US$10,000 to 50,000 at a 10% interest rate for micro-hydro power development. One of the conditions for accessing this loan is demonstration of use of the power for income generation and creation of employment. By 2003 22 loans had been provided enabling an additional installed capacity of 1.5MW (ITDG, 2003).

Creation of socially responsible funds can be one way to facilitate allocation of revenue generated for social services. The challenge remains in using such funds for the stated purposes. The Chad-Cameroon pipeline project established a trust fund aimed at using part of the US$2-3 billion in oil revenues over a 25 year period to fund social programmes for affected communities as well as replenish a fund for future generations, which by February 2005 had reached US$13.3 million (World Bank, 2005) even though it appears that the initial US$25 million paid to the government may not have been used for the designated purposes (OECD, 2002c). This situation was also evident in 2004 when US$84.6 million was transferred to Chad with US$67.7 million targeted for poverty reduction sectors (World Bank, 2005).

4.7.4.7. Vulnerability and adaptation

Article 2 of the UNFCCC states that the ultimate objective of the convention is to stabilize greenhouse gas concentrations in the atmosphere to a level that will allow the ‘ecosystem to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner’. Given the importance of energy issues to sustainable development (Spalding-Fecher *et al*, 2005), it is necessary to look at how the various components of the energy supply chain might be affected by climate change. At the same time it is desirable to assess current adaptation measures and their adequacy to handle potential vulnerability.

Assessing the vulnerability of the energy supply to climatic events and longer term climate changes needs to be country or regional specific. The magnitude and frequency of extreme weather events such as ice storms, tornadoes and cyclones is predicted to change, as may annual rainfall, cloud cover and sunshine hours. This is likely to increase the vulnerability of the various components of the energy supply infrastructure such as transmission lines and control systems. Further, many developing countries are particularly vulnerable to extremes of normal climatic variability and this is expected to be exacerbated by climate change. Investments in developing countries are more focused on recovery from disaster than on the creation of adapative capacity and lending agencies and donors will need to reform their investment policies accordingly to mitigate this problem (Monirul, 2004).

Possible structural damage by a combination of factors including sea level rise, tropical cyclones and ocean waves may hamper offshore oil and gas exploration and extraction of these fossil fuels. Higher ambient temperatures expected from global warming may affect the efficiency and capacity ratings of fossil fuel powered combustion turbines. In addition, electricity transmission losses may increase due to higher ambient temperatures.

Renewable energy systems may be negatively affected by future climate changes (Sims, 2003). For example solar power generation and water heating will be impacted where increased cloud cover occurs. Lower precipitation and higher evaporation due to higher ambient temperatures may cause lower water levels in storage lakes or rivers which will affect the outputs of hydro electric power stations. Energy crop yields could be reduced due new pests and weather changes and more extreme storm events could damage wind turbines and ocean energy devices.

Although the technologies already exist to combat climate change threats, there is no single solution to the problem, but rather a choice of technologies that will be gradually implemented over a period of several decades (Pacala & Socolow, 2004). Thus the need to take measures to lessen the impacts on energy systems resulting from their intrinsic vulnerability to climate change will remain a very real challenge for the foreseeable future.

4.8 Technology R D &D and Deployment

There are several steps in the "life" of an energy technology as covered by the term RD^3. The *research, development and demonstration* phase precedes the commercial use of a nascent technology, and the *deployment* or "learning" phase consists of commercialization, diffusion, and eventually product saturation (Sagar, 2005). In order for a new technology to achieve a major breakthrough, all components of RD^3 must be present and work together.

Discoveries and innovations beyond current scientific and technological frontiers are required together with advancing the state of knowledge about technologies that are on the frontier by "technology learning" (Grübler, 1998). In addition to new and improved energy conversion technologies, such concepts as novel supply structures, distributed energy systems, grid optimization techniques, energy transport and storage methods, load management, co-generation and community based services will have to be developed and improved (Luther, 2004). Then the knowledge base required to support the transformation of the energy supply and utilization system will need to be created and expanded.

The major innovations of the future that will shape society will require a foundation of strong basic research (Friedman, 2003). Areas of generic scientific research in material-, chemical-, bio- and geo-sciences that could be particularly important to energy need to be undertaken and reviewed. Progress in basic research should lead to new materials and technologies that can radically reduce costs or reveal new approaches to providing energy services. For example the development of fibre optics from generic research investment resulted in their current use to extract greater volumes of oil or gas from a reservoir than had been previously possible.

Examples of more specific energy related research topics include conducting polymers, nanomaterials, hydrogen storage, multi-product bio-refineries, bio-mimic materials, carbon sequestration, biocatalysts for fuel cells, plasma science, metering and controls, mechatronics, genomics, super-conductors, separation membranes, predictive modeling, and nuclear fuel recycling. Cross-disciplinary collaborations between many scientific areas, including applied research and social science, are needed for successful introduction of new energy supply and end use technologies necessary to combat the unprecedented challenge of supporting human growth and progress whilst protecting global and local environments.

Integrating scientific progress into energy and environmental policies is difficult and has not received the attention it deserves (IEA, 2003a). Successful introduction of new technologies into the market requires careful coordination with governments to encourage, or at the least not to hinder, their introduction. Industry must also play a part. For example the 10 year, USD 225 million, industry sponsored Global Climate and Energy Program, launched at Stanford University in 2002 with the support of four international companies, is one of many research programmes currently underway to provide the type of research to help meet future critical needs (GCEP, 2004).

There is no single area of research that will secure the future supply of energy. A diverse range of energy sources will be utilized and hence a broad range of fundamental research will be needed. So how can a country or region prioritise investments in RD^3? A "World Energy Research Co-ordination Programme" established within the UN systems has been suggested (WBGU, 2003) aiming to draw together the various strands of national level energy research activities, encourage collaboration, identify promising novel technologies and provide advice on prioritisation. Setting global priorities for technology development could be based on quantitative assessments of possible emissions and their abatement paths, but guidelines would first need to be developed.

Investment in energy RD^3 aims to reduce technology and deployment costs; remove the barriers to implementation; improve the performance of energy conversion technologies; produce lower cost fuels; enhance exploration, recovery and extraction; and reduce fuel supply chain costs. Further, for developing countries, technology can play a crucial role in poverty reduction. Thus, in such cases, sustainable development must be understood in terms of the creation of human capital and the effective deployment of solutions through appropriate technology applications supported by research. In order for sustainable development to take place, rural and urban communities should have access to innovations that accelerate development and provide new and more effective solutions than those utilized previously. New innovations are not readily used to address poverty and procurement processes are inherently conservative. Thus people need to be assured that new technological approaches will also have social benefits since most technologists underestimate the social processes that are required for new technology adoption (DST, 2002).

Identifying gaps in R&D programmes to make new and improved technologies available and affordable, to encourage their implementation, and to develop the necessary supporting infrastructure is a challenge. Another is to find the necessary funding to see the introduction of the energy technology through the costly deployment and learning phase (World Energy Council, 2004).

RD^3 often results in the establishment of new industries. Technology breakthroughs can produce competitive advantages for industries and the host country whilst advancing knowledge for the benefit of all nations. Support for both fundamental and applied energy research should therefore be included in all government policies. Co-operation between nations, as through the numerous IEA Implementing Agreements, is encouraged to enhance the global benefits from such research.

4.8.1 Diffusion and transfer

Learning, a key element of early deployment, is a natural extension at the deployment stage of what the RD^3 process produces at the technological development stage. New technologies, even after their technical feasibility has been demonstrated, face a number of barriers such as cost, infrastructural needs, slow capital stock turnover, market organization, information and financing (Sagar, 2005).

Increasing improved technology uptake and use is as important as developing new technologies. Much energy RD^3 proves the feasibility of new, clean, energy efficient technologies but many remain untested. Deployment policies are then necessary to help provide market experience processes in order to make these technologies cost effective in large-scale markets. Barriers to market uptake need to be overcome so that market growth occurs and then stimulates private R&D investment to improve the production chain.

Energy technology R&D investments could be complemented with programmes to support the deployment of new technologies that emerge. These are best conducted by institutional infrastructures designed and supported for that specific purpose. In this regard the IEA has established a new "Renewable Energy Technology Deployment" implementing agreement to encourage international collaboration in this area (IEA, 2004). This should have the added benefit of reducing technology redundancy on a global scale (PCAST, 1999).

With technology learning and experience curves, the experience gained with a certain technology is expressed as a learning rate, that is, the percentage by which the unit cost decreases with every doubling of cumulative production. However, learning curves do not explain precisely why cost reductions occur and much is yet to be understood about how learning is achieved and what it really involves (Sagar, 2005).

Governments play an important part in the research phase of a technology development, but they are usually less effective at technology transfer and diffusion. The private sector does a better job of this and dealing with the problems of the market (Flannery & Kheshgi, 2004). However, the private sector needs an agreed public framework to operate within. Public/private partnerships can therefore catalyze the deployment of new technologies. An example of this was the "Methane to Markets" partnership between public and private stakeholders in 14 countries launched by the USA in November 2004. The goal was to promote international technology diffusion of methane mitigation options for landfill gas, coal mine methane and the natural gas sector (http://www.methanetomarkets.org).

4.8.2 Public and private funding

Government investment for energy technology RD[3] is important. Until recently 98% of total R&D investment was by only 10 IEA member countries (Margolis *et al*, 1999; World Energy Council, 2001) and this declined by 50% between the peak of 1980 (following the oil price shocks) and 2002 in real terms (Fig. 4.8.1). Expenditure on nuclear technologies was many times higher than on renewable energies. The end of the cold war and lower fossil fuel prices decreased the level of public attention focused on energy planning in the 1980s and global energy R&D investment has yet to return to these levels in spite of the concerns about energy security and climate change.

Figure 4.8.1 IEA member government budgets for energy R&D

Ultimately it is only by creating a demand-pull market (rather than supply-push) that technological development, learning from experience, economies of scale in production and related cost reductions can result. As markets expand and new industries grow (the wind industry for example) more private investment in R&D results, which is often more successful than public research (Sawin, 2003b).

The private sector invests a significant amount in energy R&D to seek competitive advantage relevant to risk avoidance. However firms tend to invest in R&D at less than socially optimal levels and, for business reasons, focus on incremental technology improvements to gain profits in the short term. R&D spending by firms in the energy industry is particularly low with utilities investing only 1% of total sales in USA, UK and Netherlands compared with the 3% R&D-to-sales ratio for manufacturing, and up to 8% for pharmaceutical, computer and communication industries (Battelle, 2002). Even in Japan and USA, private sector energy R & D investment has declined significantly, partly as a result of the more competitive energy market. Programmes designed to create new lower carbon-emitting electricity generation technologies in Europe are also suffering from insufficient R&D investment.

If government policies can ensure long-term markets for new technologies, then industries can see their potential, perform their own R&D, and complement public research institutions (Luther, 2004). Although fixed pricing laws to encourage the uptake of new energy supply technologies do not usually result in novel concepts, further innovation is encouraged once manufacturers and utilities begin to generate profits from a new technology as they then invest more in R&D to lower costs and further increase profit margins (Menanteau *et al,* 2003). Under government mandatory quota systems (as used to stimulate renewable energy projects in several countries – section 4.7.1), consumers tend to benefit the most and hence producers receive insufficient profit to invest in R&D.

Recent trends in both public and private energy R & D funding indicate that the role of technology in reducing GHG emissions is often overlooked and may not be fully understood (Battelle, 2002). Subsidies and externalities (both social and environmental) affect energy markets and tend to support conventional sources of energy. Intervention to encourage R&D and adoption of renewable energy technologies, together with private investment and the more intelligent use of natural and social sciences is warranted (Hall *et al,* 2004). Obtaining a useful balance between public and private research investment can be achieved by using partnerships between government, research institutions and firms.

Current low levels of public and private energy supply R&D investment are unlikely to be adequate to reduce global GHG emissions while supplying the world with the energy needs of the developing nations. Energy supply technology R&D, like all R&D, takes time and financial resources. So developments sought in the long term are associated with near term research investment to ensure future energy services are delivered cost effectively and barriers to implementation are identified and removed. Successful uptake requires financial support, supportive policies from governments, acceptance through market forces and promotion by private sector stakeholders.

To accelerate the rate of deployment needs direct government funding, incentives to stimulate private investment, government procurement and buy-down actions, facilitation of international collaboration, and removal of barriers to technology use. Sustainable development and providing access to modern energy services for the poor have added challenges from R&D investment in order to make markets work better, reduce energy subsidies, provide energy security, mobility and energy efficiency and provide greater support for renewable energy in ways that safeguard health, safety and the environment, (WEO, 2002; IEA, 2006).

Long term outlook

4.9.1 Decision making

The effectiveness of the decision making process regarding long term energy options will depend open the availability of robust future scenarios and a knowledge of the risks associated with each one. According to the IEA (2001), scenarios can be defined as alternative images of how the future might unfold, thus assisting the decision making process by offering the possibility to identify problems, threats and opportunities. In contrast, modeling work seeks to project forward using a rigorous analysis of current and expected future trends to determine a likely future. To be effective, such projections need to take cognizance of the newer approaches to setting GHG stabilization policies. Since the IPCC Third Assessment Report, there has been a change in focus in the research community towards multi-gas scenarios (IPCC, 2005). A representative set of scenarios to support the decision making process for long term energy supply are given in Table 4.9.1. They have been selected from several comprehensive scenario sets that have been published by various organizations.

INSERT Table 4.9.1 Summary of energy supply and related carbon emissions to 2020 and 2050 from various scenarios

GEP A1 is a high economic growth scenario that goes beyond conventional wisdom on the availability of gas and oil. It assumes that there are no remarkable developments favouring coal or nuclear technologies. Technology focuses on tapping conventional and unconventional oil and gas. Liquids from coal could replace oil and gas.

GEP A3 is a high economic growth scenario but with a transition away from fossil fuels and large scale use of renewables with an intense biomass focus together with a new generation of nuclear technology. This transition would not be complete until 2100 but would be underway in 2050.

GEP C2 is a reduced energy consumption scenario with a great deal of technical challenge. It assumes unprecedented international cooperation on environmental protection and equality and probably changes in lifestyles, including many with an improvement and some with less. Fossil energy is a transition fuel.

IEA SD is derived from the SRES A1 scenario but with a strategic emphasis on targets and assuming that there is the political will to achieve them. It is based on the pre-conditions of long-term sustainability and security of energy supply and obviously assumes unprecedented international cooperation.

WEA A and WEA C are similar and represent the range spanning the GEP A3 and GEP C2 scenarios.

SRES A1-B is characterized by economic and market forces predominating and is global in outlook. It is also characterized by a mix of fuels and technologies that is balanced between fossil and non-fossil sources.

SRES B2 is characterized by much more focus on the environment but not as drastically as in the GEP C scenarios.

As an illustration of what can be achieved in energy planning for the future, Figure 4.9.1 is a flow chart of a future energy system with low emissions compiled from the SRES B2 scenario.

INSERT Figure 4.9.1 Predicted world energy sources to meet growing demand by 2030 based on the relatively conservative SRES B2 scenario (IPCC, 2001). Source: IIASA, B2 Message Scenario, update 2005

4.9.2 Inertia

There is considerable inertia in national energy systems and, as low carbon technologies are not part of conventional energy systems, changes of direction will be difficult to achieve. To do so will require clarity of purpose in all parts of Government and at stakeholder level (PIU, 2002). According to the IEER (2001), the failure of available technologies to be in more widespread use in the market place has several broad causes:

- institutional (whether governmental or corporate or both) roadblocks to the use of efficient technology, despite the fact that it is economical;
- corporate resistance to government-set standards combined with a corporate failure to pursue vigorous voluntary approaches to improving efficiency for motor vehicles, with some notable exceptions, such as the marketing of hybrid cars by Toyota and Honda;
- the lingering of nearly commercial technologies at the margins of implementation by the lack of a steady market and the inertia of vast and powerful vested interests in present inefficient technology;
- the lack of adequate governmental standards that would combine security, environmental, safety, and economic criteria; and
- a lack of widespread business and institutional structures to implement energy efficiency technologies in the residential and commercial marketplace that are economical today.

4.9.3 Decision Tools

Decision tools often provide interesting opportunities for decision makers in their energy strategy choices at regional, national and international level. Energy models can be classified by temporal coverage into short, medium, and long terms. While short and medium-term models answer specific sectoral or sub-sectoral concerns within the existing set of fuels and technologies, long-term models tend to address sectoral or economy wide concerns with long term implications at national or global level (Pandey, 2002). Short and medium term energy models may not consider decisions involving new investments. Long-term energy models however, often analyze issues of technology stock turnover, fuel substitution, and resource depletion. A number of energy models have been developed and used to analyze the evolution of the energy supply system from a long-term perspective. Such models include MARKAL, MESSAGE, AIM, MARIA and DEN 21.

MARKAL is a bottom-up-technology-based linear optimization model, and comprises the whole energy chain, from supply resources through conversion and transformation, distribution to end use (Smekens-Ramirez Morales, 2004). The purpose of MARKAL is to optimize the energy system for the medium and long-term and it has been an important decision tool for analyzing long-term energy strategies in developing countries such as China (Wu et al, 1994; Larson et al 2003; Chen and Wu, 2004), India (Shukla and Kanudia, 1997) and Brazil (La Rovere et al, 1994). Recently MARKAL has also been used to develop Europe's long-term scenarios for changes in energy mix, technology deployment and electricity production with carbon emission reduction targets being introduced, compared to a reference case (Smekens-Ramirez Morales, 2004).

MESSAGE, developed by IIASA Austria, is a dynamic linear programming model that calculates cost-minimal supply structures under the constraints of resource availability, the menu of given technologies, and the demand for useful energy. Useful energy is derived from the Scenario Generator (SG) model based on extensive historical data about economic development and energy systems, and exogenous assumptions about population and per capita economic growth by region. There are 10 regions in the MESSAGE model which has been linked with a macro-economic model, MACRO to consistently reflect the influence of energy supply costs calculated by the energy supply model in the optimal mix of production factors included in the macroeconomic model (Messner & Schrattenholdzer, 2000).

The Asian-Pacific Integrated Model (AIM) is a large-scale computer simulation model for scenarios analysis of GHG emissions and the impacts of global warming in the Asian-Pacific region. The main goal of this model is to assess policy options for stabilizing the global climate in the region from the two perspectives of reducing GHG emissions and avoiding the impacts of climate change (Matsuoka *et al*., 1995). AIM comprises three main models: the GHG emission model (AIM/emission), the global climate change model (AIM/climate), and the climate change impact model (AIM/impact) (Kainuma *et al*., 2004). The AIM/emission model consists of country level, bottom-up type energy models and global level, top-down type energy and land-use models. AIM could be regarded as a typical integrated assessment model (Springer, 2003).

The Multi-regional Approach for Resource and Industry Allocation (MARIA) is also an integrated assessment model to interpret the interrelationships between the economy, energy, resources, land use, and global climate change. MARIA is formulated as an inter-temporal nonlinear optimization model which includes around 18,000 variables and 15,000 constraints. The model aims at assessing the potential contribution of fossil fuels, biomass, nuclear, other energy technologies and land-use changes to future GHG emissions. Its energy supply module includes fossil fuel, renewable energy, nuclear power, and carbon sequestration technologies. Recently MARIA was extended to evaluate a new hydrogen production process through steam-methane reforming at a significantly lower temperature (300 – 500^{o}C) than that of conventional processes. This could become a significant source of liquid fuels under the scenario of long-term global warming (Mori & Saito, 2004).

The integrated assessment model, DEN 21, comprises an energy systems, macro economic and climate change models. The energy systems model is the main component formulated in bottom-up fashion with about 50 kinds of technologies covering natural gas, oil, coal, biomass, hydro, geothermal, photovoltaic, wind and nuclear energy. DEN 21 basically seeks the optimal trajectory for the development of the global energy system which will minimize global warming through maximizing the cumulative discounted present value of the world macro economic consumption over a given time range (Akimot *et al*., 2004). The model covers a time horizon spanning the whole 21st century and divides the world geopolitically into 10 regions.

All the energy models mentioned above originated in countries with developed economies. They are thus of limited use for undertaking comprehensive policy analyses for developing countries as they are unable to adequately represent some of the key characteristics of such economies (Pandey, 2002). While researchers in developing countries have been working on adapting these models to meet their actual local situations, they have also made efforts to develop their own energy models. A good example is China's energy systems model, INET and its updated version, the 3Es Model which is an integrated energy-economy-environment assessment model developed at Tsinghua University (He *et al*., 1996; Zhang *et al*., 2002).

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