FOSSIL FUELS: RESERVES AND ALTERNATIVES — A SCIENTIFIC APPROACH

Extended abstracts of the lectures presented during the symposium *Fossil Fuels: Reserves and Alternatives – A Scientific Approach*, organised by the Earth and Climate Council of the Royal Netherlands Academy of Arts and Sciences and Clingendael International Energy Programme, 9 December 2004

Royal Netherlands Academy of Arts and Sciences

Fossil fuels

RESERVES AND ALTERNATIVES — A SCIENTIFIC APPROACH

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Foreword

On Thursday 9 December 2004, the Clingendael International Energy Programme (CIEP) and the Earth and Climate Council of the Royal Netherlands Academy of Arts and Sciences (RAK/KNAW) organised a symposium entitled *Fossil Fuels: Reserves and Alternatives – A Scientific Approach* at the Royal Netherlands Academy of Arts and Sciences (KNAW) Het Trippenhuis, Kloveniersburgwal 29, Amsterdam.

The symposium provided a scientific insight in the discussion on the future contribution of fossil fuels to the global energy system and what technologically feasible alternatives are currently and in the future available in order to meet the world's rapidly rising energy demand. Extended abstracts of the presentations are bundled in this booklet providing an up-to-date view on the subject.

Interest in fossil fuels has gained momentum. Petroleum experts around the world speculate on remaining oil and gas resources and reserves. Easy-to-produce crude oil and natural gas are non-renewable finite resources. Many analysts estimate that world oil production will peak before 2020, marking the start of a long period of decline. At the same time, potential demand will be very strong as economies like India and China industrialize. Currently new conventional oil fields are being discovered at a rate of less than one third of the world's annual production on average. The same holds for gas albeit with greater uncertainty, whereas coal reserves are still large though less preferable as an energy source for environmental reasons. In any case, our geological heritage is being depleted at a fast rate.

Meeting the world's future energy demand is going to be a major challenge. There is little doubt that we will eventually change to a new energy system. Timing however, is still an issue of concern. The drivers of this change are a combination of the geology and geopolitics of fossil fuels, the rising CO_2 concentrations in the atmosphere and oceans, and the options made available by new technologies. It is predicted that the energy system of the future will continue to show substantial diversity with no single primary source, nor a single energy carrier.

The need to ensure a long-term supply of energy creates a renewed interest in the large existing non-conventional hydrocarbon resources (heavy oil, tar sands, gas hydrates etc.) and for coal. Key technologies which make it possible to transform these different resources into clean fuels and energy while minimising CO_2 emissions are required. Will clean fossil energy be the technologists' answer to global warming? Will wind, biomass and solar win over hearts and minds sooner than might be expected? Or will nuclear energy, highly advanced nuclear fission and in particular nuclear fusion, provide a solution?

Energy will be on the scientific and political agenda for a long time to come. We hope that the contributions in this volume will provide readers with a fresh insight on where we stand today and fuel the discussions of the future.

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HARRY DOUST

Petroleum systems and the hunt for oil and gas

Summary

The importance of petroleum as a fuel for the World's economies cannot be exaggerated – it has proved to be one of our most adaptable and valuable commodities. In its gaseous, liquid or solid form, it is a uniquely common, cheap and efficient natural resource. Though widespread in sedimentary rocks below the Earth's surface, useful quantities are typically confined to *petroleum systems*, portions of sedimentary basins where a source horizon and reservoirs are combined with appropriate structural geometries. Within petroleum systems, oil and gas is produced from concentrations that form *accumulations* or *fields*. Geologists who hunt for petroleum make use of a range of principles and technologies, coupled with local knowledge of the subsurface, to identify situations where it may occur. In spite of major advances, however, our knowledge of both the process of petroleum generation, accumulation and retention, as well as of the subsurface geology is in many areas not adequate to make very confident predictions. Exploration for new fields remains a risky undertaking, therefore, while the definition of volumes located continues to be accompanied by uncertainties. For these reasons, predictions of where future reserves may be encountered and of the volumes that may be discovered continue to be controversial.

Petroleum and its significance

Petroleum is formed of a very complex mixture of organic compounds of carbon and hydrogen called *hydrocarbons*. Hydrocarbons repel water and are essential to all life forms. Through our ability to match living compounds with chemical fossils found in oil, we know in fact that all significant quantities of petroleum are derived from the thermal conversion of dead plant and animal material, or *kerogen*, into natural gas, liquids (oil) or solids (tar or asphalt).

Oil is one of the most important and adaptable commodities that man has ever found, and it is largely thanks to its ready availability in the past century that whole societies have been able to build and enjoy standards of living that would previously have been considered unthinkable. Petroleum products touch every aspect of our lives today, providing feed-stocks for electricity generation and petrochemical products as well as, notably, transport and heating fuels. Gas and oil currently provide about 65% of the World's energy needs and ready access to supply is of crucial importance to the economies of most countries.

The Petroleum System and how it works

Considering the importance of petroleum to society, the public's perception of where and how petroleum occurs, is found and subsequently produced is astonishingly rudimentary. This is perhaps due to the very specialized nature of the geological understanding required to search for and exploit oil and gas and of the remarkably small nature of the community that carries out the work, but it is certainly not helped by lack of public attention and education on the subject.

All decisions and strategic plans related to the hunt for petroleum rely on geologic predictions of conditions below the Earth's surface. Through the past century, geologists have built experience in identifying the essential elements that lead to the accumulation of petroleum, and have encapsulated this experience in the concept of the *Petroleum System*.

Petroleum is a relatively common constituent of the shallower parts of the Earth's crust, but useful quantities are found only within the areas of petroleum systems, where they reside in concentrations called *accumulations* or *fields*. What are the elements needed to satisfy such conditions? They can be summarized as follows:

– A *source* rock, a sediment relatively rich in organic material (kerogen) which, when heated to a certain temperature through burial can yield significant quantities of volatile hydrocarbons (oil and gas),
– A *reservoir* rock, a sediment with sufficient pore space between the grains to allow oil and gas to reach a suitable concentration. Typical reservoirs include sandstones and limestones, where the pore space may constitute up to 30% of the rock,
– A *seal* to prevent the leakage and loss of oil and gas from the reservoir; this is usually a clay or other impermeable rock type,
– A *structure* to collect and hold the concentration below the Earth's surface: This will usually be a convex-upwards fold in the sedimentary layers called a *trap*.

The accumulation of oil and gas depends on the upward movement or migration of hydrocarbons from the source rock through the sediment pore space into a reservoir sealed in a trap structure. This occurs under the influence of buoyancy. Needless to say, a sufficiently thick pile of sedimentary rocks is required to allow buried kerogen to generate its hydrocarbons – petroleum systems are therefore limited to *sedimentary basins* – and that all the essential elements must be present and have the appropriate relationship to each other.

Geologists study the characters of different types of petroliferous sedimentary basins and the families of accumulations they contain, and try to predict the distribution and character of the elements described above. They use these to identify promising locations for drilling new traps, called *prospects*.

Why some areas are rich in petroleum and others have none

Oil and gas fields are distributed very unevenly in the World's sedimentary basins. There may be several reasons for this, but the main ones are related to variations in the development, character and quality of the elements essential for the process of petroleum accumulation. Scientists and engineers involved in the hunt therefore devote a huge amount of time and resources to the study of both the processes involved as well as in investigation of the local geographical development of source rocks, reservoir-seal combinations and traps.

Perhaps the most celebrated petroleum province is the Middle East, surrounding the Gulf. Here the elements are of good quality over large areas and are juxtaposed with each other in a particularly favourable fashion. Two particularly rich source rocks are present and large quantities of their generated hydrocarbons are efficiently collected and trapped in large, simple traps – an example of a large area with a favourable and simple petroleum system. Other areas tend to be smaller and considerably more complex, with more local variations in the essential parameters. In such areas accumulations are often smaller, more complex and more difficult to find, while many promising traps contain nothing. It is important to appreciate how little of the total amount of hydrocarbons generated from source rocks eventually reside in accumulations that can be commercially produced: Often this will be between 1 and 5% – the remainder is simply lost, partly to low concentrations in the sediment, partly to the Earth's surface.

Looking for oil and gas – considerations and strategies

Exploration for petroleum carries huge risks, due to our imperfect understanding of the processes that lead to hydrocarbon accumulation (although this is constantly improving) and the generally limited knowledge of the particular area that is being explored (although this will improve over time as experience is gained). For these reasons, worldwide exploration success is rarely sustained at more than about 30%, while commercial success rates are usually lower.

To protect themselves from risk and to balance short and longer term objectives, most companies will seek to invest in a varied portfolio of drillable prospects, usually with a spread of risk versus reward potential; e.g. a mixture of those with a high risk, but large potential volume/reward from less well-known areas and those with lower risk/lower reward from better-known areas. Thus the hunt can be divided into different categories, depending on the level of knowledge:

– *Frontier* exploration involves areas from which production has not yet been achieved. These are the least known, and the most risky. In order to justify the risk of exploring in such areas, with overall success rates rarely better than 10 – 20%, the potential rewards must be high. Thus, in frontier areas, geologists look for 'high risk/high reward' potential. If successful, achieving production will often take several years.
– *Emergent* areas. These are recently successful areas, where potential for more discoveries is good. To succeed in such provinces against competition, it is essential to identify them very early, preferably while they are still frontiers. They represent relatively risky, but very important mid-term elements of a company's portfolio.
– *Mature* areas. These consist of areas that have been producing for a long time, but where room for exploration still exists, particularly that classified as 'near-field/facility exploration'. Typically, both risk and rewards are low, but the activity can be very profitable as it makes use of existing facilities and any oil or gas can be produced immediately: Cut-off volumes for economic development are typically lower than for the other categories.

By diversifying the portfolio, a company avoids undue reliance on one type of area or risk category and aims to combine short-term needs with provision for a secure future.

Exploration objectives and the strategies to address them vary according to the nature of the economic and political climate, forecasts of oil price and the quality of opportunities available versus alternative investment opportunities. Exploration may require years of patient investment before profitability can be realized, so the nature of the organization will be an important influence too: Large international companies usually aim for a broad portfolio spread across several countries, while smaller companies tend to have more specific goals. National (state) companies will be concerned with understanding the magnitude of the resources available and ensuring long-term domestic supply.

Success may have a major impact on a company, but also on the host country, its government and the local population. In recognition of the fact that oil/gas exploration has an important impact on a wide spectrum of people, much effort is spent of ensuring that operational activities not only address the 'bottom line' or the company's financial interest, but also consider the best interests of the local population and the environment.

Making predictions in an uncertain world

Risk and uncertainty are inherent to exploration and most processes supporting strategic decision-making revolve around management of them.

Because understanding and knowledge is always incomplete, explorers' predictions invariably involve some guesswork. Exploration strategies are therefore concerned with objectively estimating the risk that the subsurface concept may be wrong or only partially correct, and evaluating the range of possible error in the assumptions. Both risk (the chance that the outcome of drilling is unwelcome, for instance that no hydrocarbons are present in a prospect) and uncertainty (the range of possible volumetric outcomes, assuming that hydrocarbons are identified) are involved.

Because of the multiple risks and uncertainties, most predictions of expected volumes are expressed in terms of probabilities and are subjected to probabilistic economic screening.

What may the future bring?

Petroleum is produced from reserves that were discovered some years ago. Current rates of production (which are forecasted to rise) are considerably higher than the rate of new reserves identification – in the case of oil by twice as much. Unless this changes, a supply shortage is bound to arise at some stage within the next century. Precisely when this may be is currently highly controversial. Two schools of thought exist: the 'Neo-Malthusians' believe that such an energy crisis may not be far off; in fact they predict that World production may start to decline within the next few years, leading to an oil famine after 2020. The other school, the 'New Cornucopians', predict that considerable new reserves can and will be accessed in the coming years, and that the World's demands will be easily met at least for the next half century.

The assumptions that underpin these views are based on petroleum system analysis, geological models, analogue studies and a variety of statistical techniques. The fact that they can be so divergent emphasises the very significant uncertainties related to predicting the results of future exploration: In addition, all sorts of issues, technical, financial and political will have an impact, while all statistical projections are made difficult by constantly changing frames of reference.

In spite of the above, we can be fairly certain that in the short to medium term the hunt will result in the identification of significant new reserves, especially in currently productive or mature provinces like the Middle East, perhaps through the application of new technologies and better accumulation models. Exploration in less well known frontier areas, like the deeper waters of continent margins and the Arctic will be more risky, but here we can expect to see considerable activity that will result in discoveries of new reserves – It is, however, difficult to predict the scope of such volumes.

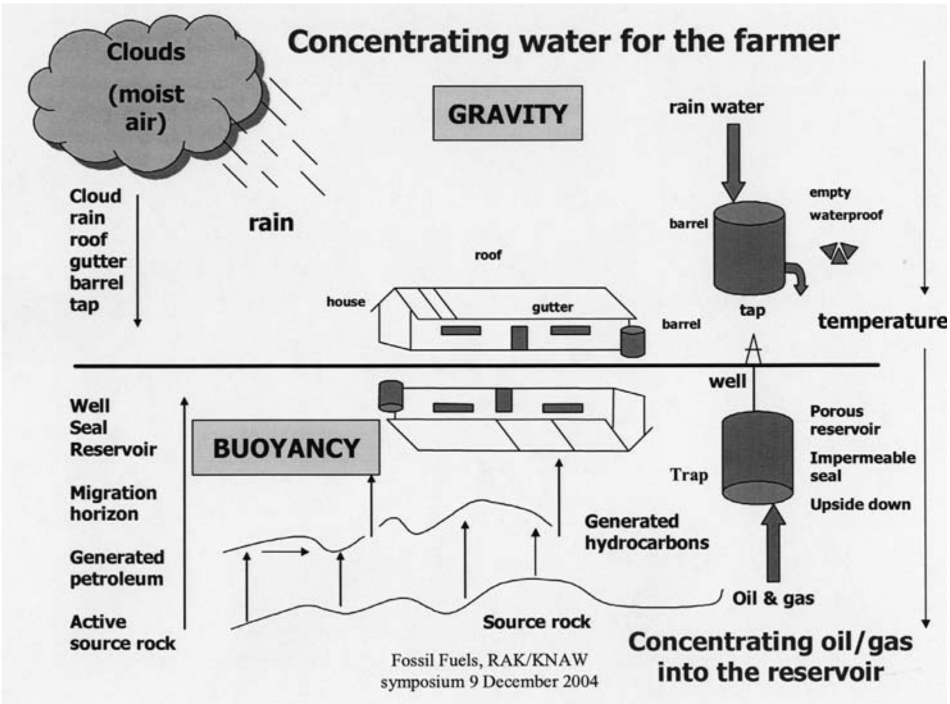

Fig. 1. Cartoon illustrating a comparison between fluid movement processes in the atmosphere, where they take place under the influence of gravity, and below the ground where they are controlled by the buoyancy difference between gas, oil and water. A farmer wishing to save water will concentrate the rain that falls on his roof in a barrel (which needs to have several specific characteristics) and tap it off when needed. The process of of petroleum generation, accumulation and trapping into a usable concentration is in many ways similar, though it acts in an opposite direction below ground. In this case the barrel is represented by a trap containing an oil or gas field.

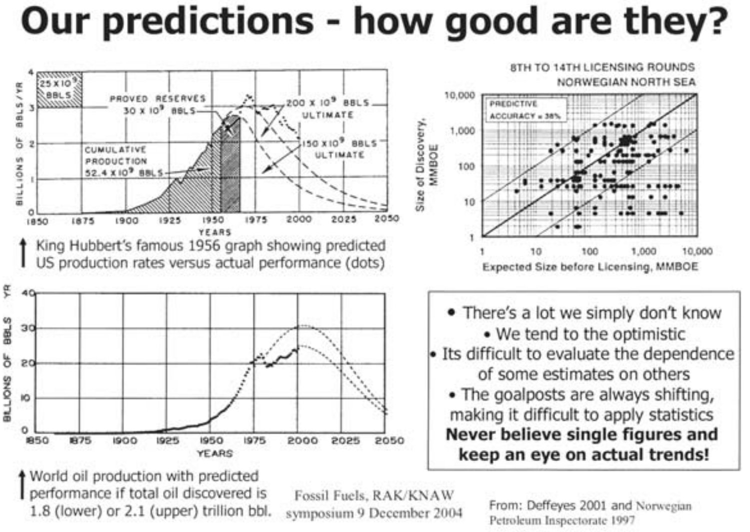

Fig. 2. This figure shows some of the means that are used in the petroleum industry to predict the volumes of oil and gas that might be found in the future. On the left total production versus time has been plotted for the US and the World. Assuming that the eventual profile will follow a bell-curve, it is possible to extrapolate the trends to an end point, and predict the volume still to be found and produced. Such statistical techniques are subject to great uncertainties (see some of the caveats in the box) and should be viewed as possible scenarios only. One of the potential influences may be related to optimism in the hunt – as shown by the results shown top right from recent industry activity in Norway.

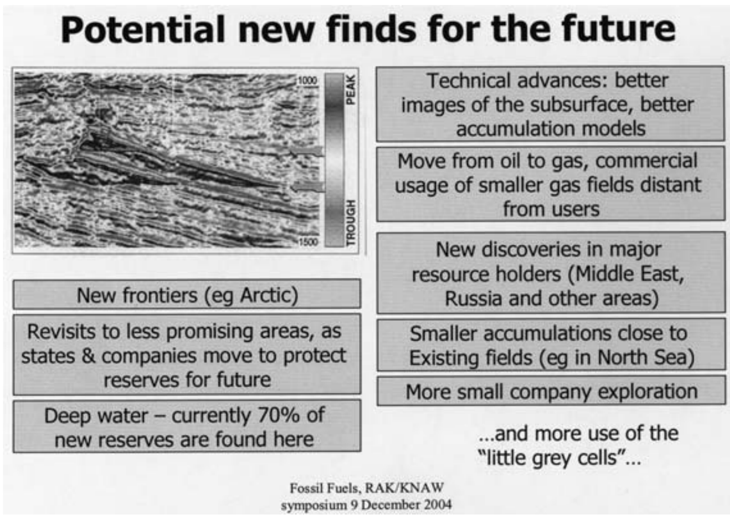

Fig. 3. Some of the areas where oil and gas may be located in the future. Currently most discoveries are made in deep waters along continental margins, largely guided by direct seismic evidence for oil and gas (top left). Advances in knowledge and technology are expected to permit new and incremental reserves to be identified in traditionally rich areas like the Middle East. A return to areas that have been lightly explored, and are therefore poorly known in the past can be expected too – such provinces occur in many countries and include the margins of the Arctic Ocean. A general move towards exploitation natural gas can be noted and non-traditional fuels, like tar sands are assuming a larger profile.

COR VAN KRUIJSDIJK

Resources, reserves and peaking

Resources

Hydrocarbons in various forms are present in the subsurface. Hydrocarbons in gaseous or liquid form may exist in porous and permeable deposits. Currently most of the oil and gas produced comes from these reservoirs. Some oil and gas are produced directly from the buried and transformed organic material called source rock including coal. Three key questions need to be answered before the usually large investments that are required to bring a given field into production can be allocated:
– How much oil and gas is present?
– How much of it can we get out?
– How quickly can we get it out?

Hydrocarbons Initially in Place (HIIP)

The size of the hydrocarbon accumulation (HIIP) is determined by estimating the volume the hydrocarbons occupy in the subsurface. This requires delineating the 3D structure that bears the oil and gas (rock bulk volume, RBV), predominantly using seismic data. Although current 3D seismic is of unprecedented quality, many error sources (time depth conversion, interpretation error) still exist that result in a large uncertainty of the rock bulk volume. Moreover, this volume (RBV) needs to be corrected for those parts that are not considered reservoir rock (net-over-gross, N/G). Subsequently the rock fraction (1-ϕ) and water (S_w) that will be present need to be subtracted. This information is derived from various measurements taken along the wall in the available wells that penetrate the reservoir (well logs). The well logs, however, measure these quantities in a very indirect way and are calibrated on core samples taken from the wells. Unfortunately most reservoirs tend to be heterogeneous and the wells effectively only sample a very small part of the reservoir. Again this introduces a significant source of error. Finally the volume of oil is corrected for the volume change when it is transported from the subsurface to atmospheric conditions (*B*). The entire process is summarized by the following equation HIPP=RBV. N/G.ϕ(1-S_w)/B.

All data sources introduce uncertainty. Moreover, many of the errors are strongly correlated and non-gaussian. Consequently the HIIP is best represented by a probability density curve. It is not unusual that the 'best' and 'worst' case are more than 70% up or down from the best estimate (i.e. the standard deviation is easily half the mean).

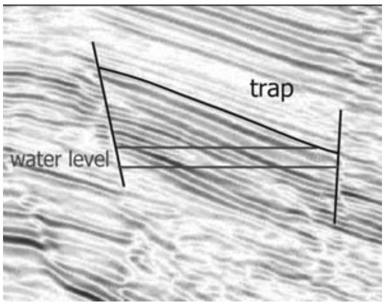

Fig. 1. The background shows the reflectors calculated from the seismic data. From this a bounding structure (trap) is derived.

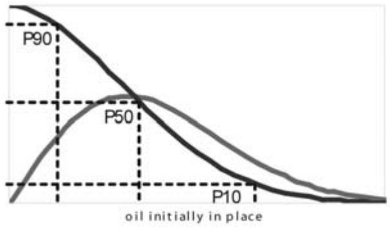

Fig. 2. The light (grey) curve illustrates the HIIP probability density function. The dark (black) curve is the cumulative pdf. In addition the P10, P50 and P90 points are indicated.

Recovery factor (RF)

The fraction of the oil or gas we can produce is a function of the recovery process and is called the recovery factor (RF). Gas is produced by expansion due to pressure decline which is a very efficient process for strongly compressible fluids. The recovery factor for gas is usually quite good and generally falls between 70 and 90%. Unfortunately it is far more difficult to produce oil. Over half of the world's oil is produced by water injection, where water displaces the oil. The current average recovery factor for oil is 33% with a range from 2 to 50%. These numbers depend strongly on the heterogeneity of the reservoir and the fluid mobility. Lower heterogeneity and higher mobility usually leads to higher recovery factors.

Production rate

The rate at which the oil or gas is produced has to be high enough to justify the upfront cost of building the production infrastructure (wells, surface facilities, transport etc.). The production rate depends strongly on the mobility of the fluids in the rock which is defined by the fluid viscosity and rock permeability. Both properties can vary many orders of magnitude. The viscosity is easily obtained from a fluid sample. The rock permeability on the other hand can only reliably be measured on a rock sample. Unfortunately reservoirs tend to be extremely heterogeneous.

Reserves

Finally combination of HIIP and RF leads to the technical reserves probability density functions. The industry works with three definitions: *proved*, *probable* and *possible* reserves. These often are interpreted as the P90, P50 and P10 points. *Proved* reserves are subject to a few additional contractual and legal constraints. The SEC rules are somewhat out of step with the industry. They require certain test data to be available which companies today do not consider to be necessary (i.e. cost effective) from a business point of view. Companies will and have started development (commissioning platforms etc.) without the data required by the SEC. Of course the related reserves may not be classified as *proved* for SEC reporting.

Productivity profile

A typical production profile for a medium to large sized field starts with a ramp up as the wells are brought into production. Initially the production will be limited by the capacity to handle the fluid streams (surface facilities). This results in a plateau that can be maintained for a period from five to twenty years typically. After this period the well productivity will have dropped to the point were they become the bottleneck and if no measures are taken the production will go into a decline phase. This period is terminated when the field is shut in based on economic constraints (e.g. negative cashflow). However, the plateau phase can be extended by additional investments in the field such as infill wells. These are additional wells that target bypassed oil and/or boost total field production. In addition, or in a later phase, enhanced oil recovery techniques may be applied. Enhanced oil recovery techniques rely on the use of chemical additives (e.g. surfactants, polymers etc.) and/or the addition of external energy (e.g. through steam injection). Again this requires additional investment both in terms of capital expenditure and operational costs.

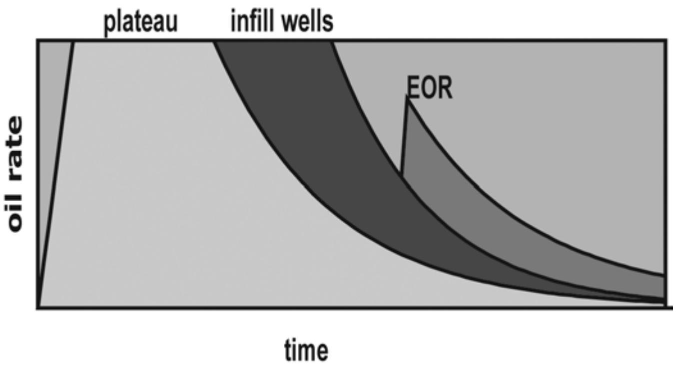

Fig. 3. Typical production profile of a field from start to abandonment.

Peaking

Straightforward summation of the production decline curves of the fields in operation may lead to the conclusion that global oil production has or soon will (5-8 years) reach a peak after which a rapid decline is inevitable. However, this analysis ignores the fact that the past two decades investments in the oil industry have been severely reduced. This has resulted in premature production decline that may be repaired by stepping up investments. In addition technology is progressing rapidly. Moreover, with a sustained high oil price, enhanced oil recovery and unconventional hydrocarbons will add to the reserves. The current technical outlook foresees a move into ever deeper water adding reserves in the deeper offshore. In addition instrumented fields operated under a measurement and control approach (smart fields) have the potential to add 5 to 15% to the current recovery factors for oil. Moreover, this technology allows for an ever decreasing environmental footprint. Better technology and higher oil prices will also bring on stream more unconventional sources such as tar sands, gas hydrates and coal bed methane.

Oil price pressures

The oil supply influences the oil price in two ways. Given that oil is a finite resource, ultimately the remaining reserves will start to influence the oil price. However, currently it is the limited production capacity that dictates the current high oil prices. Systematic underinvestment (infill wells, EOR, etc.) has eroded the spare capacity on the supply side. Together with the growing demand this has created the current market.

Increasing capacity

Once the production goes off plateau there are a few options to (significantly) extend it, such as drilling infill wells or switching to an EOR process. This however, does require additional investments and takes time to implement. The time scale to significantly increase production capacity from existing fields is on the order of one or two years. Bringing on new reserves requires at least five years. To prevent short term pressure on the oil price these activities and investments have to be planned significantly ahead of time. This also requires a good handle on the development of the demand for fossil fuel.

Conclusions

Estimating hydrocarbon reserves is characterized by large uncertainties resulting from the lack of direct access to these resources. Current estimates are very conservative, particularly those related to *proved* reserves. Nevertheless the hydrocarbon reserves are finite and will have to be replaced in time by more sustainable energy sources. However, the crossover point from fossil fuel to sustainable energy dominated supply is not expected to take place before mid this century. The timing may even be driven by cost breakthroughs in sustainable energy rather than by dwindling hydrocarbon reserves. The current high oil prices are related to capacity problems rather than decreasing reserves.

The dominant role that fossil fuels will play the next fifty years demands a clean fossil fuel strategy. Recent technological advances based on a measurement and control paradigm allow a significant reduction of the environmental footprint of hydrocarbon production. The Dutch geo-energy sector is in an excellent position to play a leading role in this. However, the current political research agenda is dominated by sustainable energy. Realignment of the energy policy, acknowledging the dominant role of fossil fuels in the next half century, is required to capitalize on the strong position of the Dutch geo-energy sector.

PETER GERLING

Non-conventional hydrocarbons: What, where, how much

Introduction

Primary energy consumption has increased by 70% over the last three decades. Recent studies dealing with future energy supply (e.g. IEA 2004) predict that oil and gas will remain playing the key role during the coming decades. The IEA – as well as the EIA in the USA – predict that the earth's energy resources are even more than adequate to meet a 60% increase in demand until 2030. Some experts from the 'supply side' doubt that these predictions will become reality.

How is the current supply situation? According to BGR (2004), reserves (that part of total resources which can be recovered economically using current technology) of non-renewable fuels at the end of 2003 are estimated to amount to about 35,500 EJ (Table 1). Coal has the largest reserves (50.3%), followed by conventional oil (18.8%), and conventional natural gas (15.9%). Resources (that part of the total resources which are (i) either proved but at present not economically recoverable or (ii) geologically indicated) of non-renewable fuels amounted to about 196,500 EJ at the end of 2003. Again, coal is estimated to have the largest resource amounts, with a share of 53.6%, followed by non-conventional natural gas (24.8%), and lignite (6.1%).

Table 1:

Type of energy	Reserves		% of total	Production 2003	static lifetime	Resources		% of total
	[EJ]	specific unit			[years]	[EJ]	specific unit	
Hard coal	17,885	763 Gt	50.3	4,421 Mt	173	105,334	4,401 Gt	53.6
Oil, conventional	6,686	160 Gt	18.8	3,549 Mt	45	3,515	82 Gt	1.8
Natural gas, conventional	5,639	178 T.m³	15.9	2,697 G.m³	66	6,886	207 T.m³	3.5
Oil, non-conventional	2,301	66 Gt	6.5	ca. 100 Mt	> 200	10,460	250 Gt	5.3
Lignite	1,602	182 Gt	4.5	928 Mt	225	11,925	1,017 Gt	6.1
Uranium	874	1.7 Mt	2.5	34,997 t	49	8,738	17 Mt	4.4
Thorium	495	1.2 Mt	1.4	n.n.		964	2.4 Mt	0.5
Natural gas, non-conventional	63	2 T.m³	0.2	> 130 G.m³	n.n.	48,633	1,533 T.m³	24.8
Total	**35,545**			**361 EJ**		**196,455**		

Table 1 : Reserves, production and resources of non-renewable energy resources at the end of 2003 (BGR 2004). n.n. = unknown; EJ = Exajoule = 10^{18} J

Considering the current annual consumption of 3,549 Mt[1] oil and 2,697 G.m^3[2] natural gas, the so-called static lifetimes[3] for these fossil fuels are only 45 years and 66 years. These numbers seem to indicate that there is sufficient oil and gas, and plenty of time to transfer resources into reserves or to base the world's economy on other energy sources. However, the important moment is the one when demand and supply do not correspond any more. And this moment may be closer than anticipated by many people. It will most probably appear when the world oil/gas production will reach its peak which may be even earlier than the depletion mid-point (= consumption of 50% production of reserves). Consequently, it seems appropriate to include non-conventional hydrocarbons into the world's production portfolio as much and as soon as possible.

Non-conventional oil

Non-conventional oils have a large potential. Reserves amount already to more than 40% of the conventional oil, the resources exceed those of conventional oil by three times (Fig. 1). Non-conventional oils comprise heavy oil (20-10°API, 0.934-1.000 g/cm^3 density), extra heavy oil and tar sand/bitumen. Both latter ones are heavier than water, only differentiated by their viscosities (</> 10,000 mPas.s). Heavy oil will not be discussed in the following text, because this type of oil is often not clearly separated in oil reserve reports given by countries or organisations. Oil shale – it should better be named shale oil – is a specific category since this sediment contains per se not oil but kerogen which can be converted into oil when exposing it to heat.

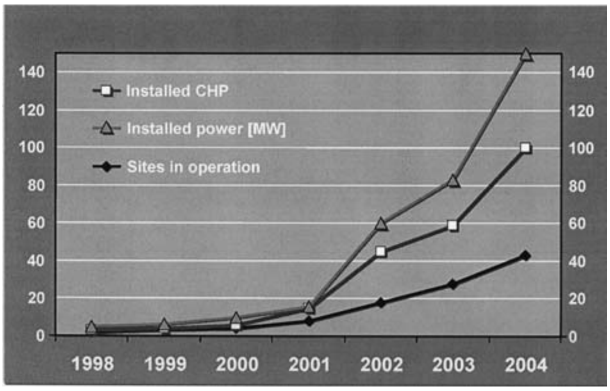

Fig. 1. Worldwide reserves and resources of conventional and non-conventional oils

Tar sands/bitumen

Tar sands are naturally occuring mixtures of bitumen, water, sand, and clay. On average, tar sands contain around 12% bitumen by weight. The product generated from tar sand is called crude bitumen or synthetic bitumen. Around 580 Gt[4] of tar

[1] Mt = mega tons = million tons = 10^6 t
[2] G.m^3 = giga m^3 = billion m^3 = 10^9 m^3
[3] static lifetime = ratio of currently known reserves and last year's production. This term is only useful for orientation since both reserves and production change permanently.
[4] Gt = giga tons = billion tons = 10^9 t

sands (oil in place) are reported to exist in around 70 countries worldwide, always occurring in rather shallow deposits (Meyer & Attanasi 2004). Due to technical progress acquired during the last two decades in exploitation and processing, about 39.3 Gt of this 'oil' are already classified as reserves.

The major proportion – 27.8 Gt – of the reserves is located in Alberta/Canada covering an area of 77,000 km². At the same location, another 22.3 Gt are classified by the Alberta Energy and Utilities Board as resources. The bitumen is bound to highly porous and highly permeable, unconsolidated Cretaceous sandstones, from shallow depth down to 600 m below surface.

Around 20% of this deposit can be exploited by surface mining, allowing a recovery rate of about 90% of the bitumen. Mining shovels dig the unconsolidated sediment and load it into big trucks. Tar sand is taken to crushers where it is prepared for extraction. Hot water is added, and the slurry is then fed via hydrotransport to the extraction plant. The bitumen will be extracted in separation vessels, the tailings are pumped afterwards into settling ponds from where the water (up to 80%) is recycled.

The other 80% – in sediments more than 75 m below surface – can only be recovered by in-situ treatments. Currently, cyclic steam stimulation (CSS; huff & puff) or steam assisted gravity drainage (SAGD) are in operation. During CSS, the cycle starts with several weeks of steam injection through the vertical well into the reservoir. The viscosity of the bitumen is reduced, supported by pressure-induced microfractures allowing a better migration. After shutting in a certain time, heated oil and water are pumped to the surface. Though this cycle can be repeated several times, the overall recovery rate does not exceed 15-20%. SAGD involves drilling a pair of horizontal wells separated vertically by about 5 m at the bottom of a thick unconsolidated reservoir. Steam is injected into the upper well. The heat reduces the oil viscosity and develops a 'steam chamber'. While steam and gas rise, oil and condensed water are removed through the lower well. The sweep efficiency of this process is high, creating recovery factors up to 60%. The minimum zone thickness (net pay thickness) necessary is about 15 m for exceptionally good reservoirs with high permeability (> 2 Darcy), high bitumen saturation ($S_o > 0.80$), and few shale streaks (Dusseault 2005). One can anticipate that due to the high recovery ratios possible, SAGD will probably displace pressure-driven thermal processes in all cases where the reservoir is reasonable thick. Nevertheless, there are certain challenges for SAGD: The crude bitumen has to be upgraded (as in any other production method), the high energy demand for steam production (1500 MW for 100,000 bopd), and the related CO_2-emissions (1 ton CO_2 per ton synthetic crude oil) (Cupcic 2003).

Both, the bitumen from the extraction plant (open pit mining) as well as that produced via in-situ methods have to be upgraded into a synthetic crude oil (SCO) through thermal cracking, hydrocracking and/or deasphalting the crude bitumen. For pipeline transportation to the upgrader, the bitumen has to be diluted, e.g. using condensate or light oil (up to 40%). Because of the foreseeable limits on diluent availability, new transport blends – e. g. mixtures of raw bitumen with SCO – will have to be developed for existing refineries in the USA, where most of the oil is sent. Typical residues of the upgrading process are petcoke, asphalts, and sulphur. Stockpiling of these residues is avoided by e.g. using sulphur for the production of gypsum and fertilizers whereas the organic substance could be combusted or gasified in order to generate steam.

Until the end of 2004, about 724 Mt of bitumen have been produced in Canada. The annual production rose from 48.1 Mt (2002) to 55.7 Mt in 2003, and about 58 Mt in 2004. Since the development of new open pit mining plants is significantly faster than the development of new in-situ production facilities, the bitumen production from open pit mining is supposed to be in the year 2012 about double as much as from in-situ production (85.8 Mt/a vs. 44.9 Mt/a).

Extra heavy oil

Extra heavy oil is a natural product similar to the bitumen in tar sands, but with lower viscosity (< 10,000 mPas.s) under reservoir conditions. Deposits are known from 21 countries, the most important ones are located in Venezuela, in the CIS (e.g. Melekess, Olenek, Siligir), Canada (Lloydminster), and Madagaskar. The largest deposit occurs in Faja del Orinoco in Venezuela. 7.5 Gt from total 7.7 Gt reserves occurring worldwide do exist in Venezuela (Meyer & Attanasi 2004), in an area of roughly 54,000 km^2. Miocene sandstones, 500-1000 m deep, are the reservoir rocks. 'Elevated' reservoir temperatures of about 55°C allow a 'cold production' from horizontal wells. Production as high as 2000-2500 b/d have been achieved in single wells where sediments with permeabilities in excess of 5-6 Darcy are exploited. Unfortunately, this technology can only achieve 10-12% recovery, because lower permeable zones that contain 40% of the resource are totally ignored at the moment. In order to increase the recovery ratio, SAGD is evaluated to be used in Venezuela as well.

28.8 Mt of crude oil have been produced in 2002 – the annual oil production is estimated to increase to 70 Mt in 2025 (EIA 2004). At the surface, the crude is diluted prior to pipeline transportation (up to 200 km) to the upgrader. The crude oil (e. g. 8.5° API) is partly refined into a typical light oil (e. g. 32° API), partly mixed with water resulting in a product named Orimulsion® (70% crude oil, 30% water) which is usually shipped overseas where it is burnt in power plants.

Oil shales

Oil shales contain a vast amount of energy – the worldwide resources are estimated to be 184 Gt. The term 'oil shale' is misleading since it does not contain oil. Oil shales are defined as fine-grained brown or black sedimentary rocks containing a significant proportion of solid organic matter that will yield liquid or gaseous hydrocarbons upon heating and distillation. Only those oil shales are of economic interest that yield more than 40 L of oil per tonne shale (Sæter 2004) – this is equivalent to a TOC-content of 8%. Giant resources of oil shale exist in the western part of the United States, namely in form of the Tertiary Green River oil shales. Besides, other large deposits are the Tertiary Stuart oil shales in Queensland, Australia, the Paleozoic deposits on Scandinavia (Alum Shale) and Estonia (Kukkersite), and the Cretaceous El-Lajjun deposit in Jordan. Large scale mining of oil shale started already before 1900 in Scotland (oil production), followed by activities in Estonia, Russia, China, and Brazil. Production peaked in 1980 when more than 46 million metric tons of oil shale per year was mined, with roughly 30 Mt in Estonia. The following decline was mostly due to the gradual downsizing of the Estonian oil shale industry (production of electricity).

The decline was mainly due to the fact that – using current technology – oil shale could not compete economically with conventional petroleum as an energy resource. Three major reasons are to be named:

– The retorting of oil shale can either be done in situ or after mining and crushing, and subsequent treatment in a processing plant. The energy consumed during these processes is at leat 40% of the outcome. Both processes also use considerable amounts of water.
– Retorting of oil shale is accompanied by large releases of CO_2, NO_x and SO_2 as well as by huge particulate emissions (enriched with a variety of metals, organics, etc.).
– The spent shale occupies 20-30% greater volume after processing than raw shale due to a popcorn effect.

Nevertheless, oil shales can be considered as a strategic reserve. The future development and expansion of the oil shale industry will be governed by the price of crude oil, the possibilities to reduce greenhouse gas emissions, and the implementation of favourable remediation strategies.

Non-conventional natural gas

Four different types of non-conventional gases can be differentiated. These are, ordered accordingly to their economic relevance: gas from almost tight reservoirs (so-called 'tight gas'), coal gas occurring either in coal seams or in coal mines, gas hydrates from marine sediments of the continental margins or continental polar permafrost regions, and aquifer gas dissolved almost ubiquitous at low concentration in each deeply buried aquifer.

'Tight gas'

So-called 'tight gas' is defined as natural gas from reservoirs having an extremely low permeability below 0.1 mD (MilliDarcy). Such reservoirs usually exist in great depths, the geological/geochemical situation is complex and often poorly understood. The economic production of these gases usually requires large stimulation, e. g. fraccing the reservoir. Worldwide reserves are estimated to be rather low (1 $T.m^3$), whereas the resources are estimated to amount to 80 $T.m^3$ (BGR 2003). Tight gas reservoirs have been developed in the USA, in Canada, China, Australia, the Middle East, in Egypt, and in Germany.

In northern Germany, 85 prospects and leads of tight gas reservoirs have been identified in Rotliegend and Carboniferous sediments (Liermann & Jentsch 2003). Their natural gas content is estimated to be around 300 $G.m^3$ – 30-50% of this gas is expected to be recoverable. This would prolongate the static lifetime of the domestic gas production by another 7-8 years. Core questions regarding the commercial development of these gases include the predictability of reservoir quality, detailed knowledge about the stress regime (recent and paleo), the understanding of frac propagation, and reliable possibilities of production forecasts. However, on top of this are the economic factors: development costs of German tight gas reservoirs are 3-4 times higher than those of conventional boreholes (Fig. 2).

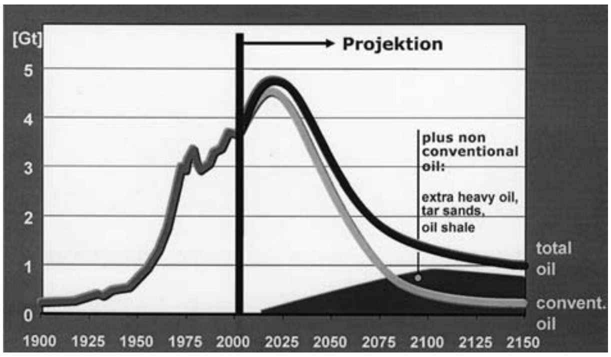

Fig. 2. The development of tight gas in northern Germany is 3-4 times more expensive than the costs of conventional gas (source: Liermann & Jentsch 2003)

Coal gas

Three different gas types are hidden behind this term: coalbed methane (a gas mixture containing 90-95% CH_4) which occurs in un-touched seams, coalseam methane (mixed gas with 25-60% CH_4 and 7-17% O_2) degassing in active coal mines during mining activities into the galleries, and coalmine gas (mixed gas with 60-80% CH_4, but no oxygen) from abandoned mines. Generally, coal gas can be generated in or degas from coal seams having reached or exceeding the rank 'high volatile bituminous B coal' (which corresponds to 0.7% vitrinite reflectance). Coal gas is reported to occur in 52 states (BGR 2003), 16 of those – namely the USA, Canada, Mexico, Australia, China, Japan, Germany, Great Britain, Poland, France, the Czech Republic, Bulgaria, Russia, Ukraine, Kazakhstan, and South Africa – recover this type of gas. Highest total resources (= recoverable reserves + in situ resources) are reported to be in Russia (50 $T.m^3$[5]), followed by China (31 $T.m^3$), Canada (12.5 $T.m^3$), USA (10.7 $T.m^3$), Australia (9.3 $T.m^3$), Ukraine (7 $T.m^3$), Indonesia (6 $T.m^3$), Germany (3 $T.m^3$), Great Britain (2.5 $T.m^3$), and Poland (1.3 $T.m^3$). The mean worldwide coal gas potential is estimated to be about 143.2 $T.m^3$. 1.1 $T.m^3$ from these can be characterized as reserves, meaning they can be economically extracted at present with existing technologies. Highest reserves are reported from the USA (> 400 $G.m^3$), reserves of more than 100 $G.m^3$ exist in Russia, Canada, and China. These elevated amounts are the result of extensive exploration programs, which – vice versa – allow the conclusion that the worldwide increase of exploration on coal gas will lead to a reserve growth between two and five times.

An interesting German development should be mentioned at this point: Stimulated by the EEG (Renewable Energy Law) and based on a monthly production 6-7 $M.m^3$[6] mine gas, more than 40 CHP (combined heat and power plant) have been installed since 1998 on shafts of abandoned coal mines using the emanating coalmine gas for a monthly generation of > 4 GWh heat and around 10 GWh power (values of 2004) (Fig. 3).

[5] *$T.m^3$ = trillion m^3 = 10^{12} m^3*
[6] *$M.m^3$ = million m^3 = 10^6 m^3*

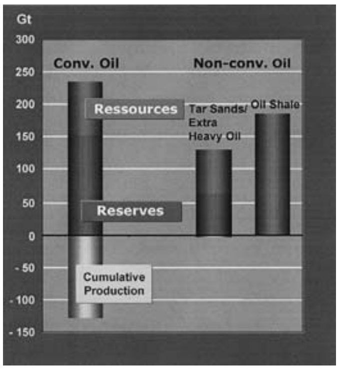

Fig. 3. Utilization of mine gas in Germany since 1988 (courtesy of T. Thielemann, BGR)

Gas hydrates

Gas hydrates are ice-like solids that form rigid cage structures under specific conditions of pressure, temperature, and gas and water concentrations. Marine gas hydrates are stable in pore spaces of sediments in water depths larger than about 300 m beneath the slopes of continental margins. The lower limit of hydrate occurrences is determined by the geothermal gradient, so that the zone of hydrate stability generally is within the first few hundred meters of sediment. Continental hydrates occur in polar permafrost regions in the Arctic and Siberia. Most of the hydrates which have been investigated so far contain methane of microbial origin. Thermogenic hydrocarbons – catched in different hydrate structures – have been detected only at specific locations like the Golf of Mexico or the Caspian Sea where neotectonics allow these hydrocarbons to migrate from deep below into the sediments where gas hydrates are built.

Seven major international research programs are underway to characterize the resource potential, to test exploration methods and play concepts, and to develop production technologies. Perhaps 250 million US$/year are currently spent on R&D by the leading national programs of Japan, China, Korea, Taiwan, USA, India, and Canada. Greatest efforts are made by Japan, which have a drilling program of 17 wells in the Nankai trough, off shore.

Although there are still a lot of uncertainties about the production potential, a few facts seem to be generally occurring: gas hydrates are widespread in the marine environment, but at low concentrations (2-20 vol% of sediment). In contrast, continental hydrate occurrences are by far smaller, but concentrated up to 80%. Beside these differences in gas concentrations, future production technologies will have to deal with the fact that offshore sediments containing hydrates will probably become weak after destabilizing the hydrates (and migration pathways may just collapse) where in permafrost regions may remain stable due to the permafrost. Considering all this, the worldwide resource estimate of 500 T.m^3 given by BGR (2003) is most probably by far too high.

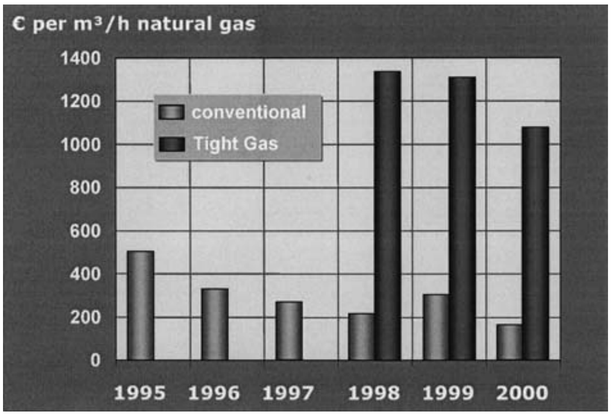

Fig. 4. Historical development and projection of future oil production: conventional oil vs. total oil, including non-conventional oils.

Aquifer gas

Pore space and fractures of sediments in the earth's crust are usually filled with water. Large volumes of natural gas can be dissolved in this 'ground water' – the term 'aquifer gas' has been created for this type of gas. Gas solubility in water depends on several factors, e. g. pressure, temperature, salinity, and the solubility of other gases. Generally, solubility increases with depth. Under hydrostatic pressure, the solubility of methane in groundwater can exceed 5 m^3 per cubic meter of water – under lithostatic pressure even 10 m^3/m^3. Higher gas concentrations (up to 90 m^3/m^3) are known from great depths or overpressured zones. The latter have been an exploration target in the USA.

Aquifer gas can only be produced by pumping water. The productivity of a reservoir depends on the water quality, and especially on porosity and permeability of the sediment. According to calculation given by BGR (2003) the world's aquifer gas resources are estimated to be between 24 and 1,500 T.m^3. Due to high production costs this type of gas is currently – and for the next decades – beyond economic interest.

Conclusions

Non-conventional hydrocarbons have a large potential and will play a growing role in the world's future energy supply. The relevant oil and gas industry will only be able to produce these if sufficient capital will be invested, sufficiently skilled human resource are available, and technological progress is continuously made. Especially technological improvements – and possibly in a faster way than before – are necessary to increase recovery rates from already known fields, and to develop new, more challenging prospects. Often, non-conventional hydrocarbons are situated in rather remote, sensible environments, or/and can only be exploited with the currently existing technology while emitting harmful substances. Thus, environmentally sensitive technologies for exploration, drilling, production and transportation have to be developed or used.

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COBY VAN DER LINDE

What drives the oil price?

There are as many oil price forecasts as there are oil price fluctuations and unfortunately all those forecasts share the same quality: they are way off. Depending on exactly why one needs to know the future oil price level, for instance for investments, determining production costs in consuming industries, etc., the uncertainties with regard to oil price forecasting can be overcome by approaching future oil prices differently. The approach we employ is to take account of the fundamentals in supply and demand and in additions take account of the upward and downward pressures on the current oil prices in order to determine which direction oil prices will move. For our type of analysis it would be great if we could exactly predict market outcomes, but we can live with less precise outcomes as long as we understand the direction of price movements and why.

Our approach is to make an assessment of both the international political and economic pressures on the oil price and relate these to the current oil market circumstances. The volatility of oil prices in the last decade is a reflection of both the maturity of the international oil market (expressed in relatively low yearly average world growth compared to other industries) and the political and economic uncertainties about demand and supply. The surprising surge in Chinese oil demand in 2004 and the inability to accommodate this increasing demand at relatively stable market prices is an excellent example of both short term changes in the market balance and the inability of the market to prepare for such fluctuations. The lack of idle capacity in the market, which can be partly seen as a reflection of past oil price expectations, amplified price fluctuations. Oil prices are a reflection of both long and short term factors, national and international developments, political and economical changes, and fundamental and psychological movements in the market. For our analysis we look, among other things, at:

Economic factors:
– Demand and supply (f.i. strong demand growth U.S., China in 2004)
– Transport chokepoints
– (Lack of) Investments
– (Uncertainties) Reserves
– Production/refining capacity constraints
– Monetary developments

Geopolitical factors:
– Concentration of reserves in few (Middle East) countries

– Political unstable producer countries
– Import dependence of consuming countries
– Competition between consumer states
– Security: infrastructure vulnerable to terrorism

Demand and supply

The year 2004 was a memorable year for oil prices both in terms of the nominal level of oil prices (over $50 a barrel) and the speed at which prices increased. Both developments indicated that demand and supply were very tight. This tight market can be explained by the unexpected surge in demand of China and the robust recovery of oil demand in other Asian economies and the US. The surge in demand very quickly pressured OPEC countries to abandon the production restrictions. After June 2004, world production was approaching its peak capacity. Also OPEC countries had only very limited idle capacity left at their disposal. It was clear that increasing demand had not been flowed by a steady increase in supply, at least not in the OPEC countries. Non-OPEC supply has increased substantially in the past 25 years but growth has levelled off. Given the distribution of reserves the 2004 oil market made it very clear that future increases in production have to come from OPEC countries. OPEC's role of residual or swing supplier of the world market and manager of oil prices requires sufficient spare capacity to fulfil this role. However, investing in spare capacity is very costly and very likely the costs cannot be recouped in the market. The fact that Saudi Arabia had to keep up this capacity for use within 3 months for a very long period of time can become a burden when competing domestic expenditures begin to take preference. Although OPEC countries attach great importance to their role as swing producer, both the ability and the solidarity to carry these costs as a group has been low. Most of these costs were carried by Saudi Arabia, United Arab Emirates and in the past Kuwait. The other OPEC members have had economic and political difficulties to keep up production and expenditures in the oil industry without this additional burden.

In 2004 the oil market was so tight that every barrel of lost production had an immediate upward effect on the oil price. The fact that commercial oil stocks were low meant that price increases could not be cushioned in consumer markets. Notable disruptions of supply in 2004 came from the domestic political unrest in Venezuela and Nigeria, strikes in Norway, the highly unstable security situation in Iraq, storms in the Gulf of Mexico and the problems of surrounding Yukos. Since every barrel counted, supply disruptions, even minor ones, pushed prices upward. In the second half of 2004, the thirst for oil was so large that consuming countries engaged more actively in competition for future oil flows.

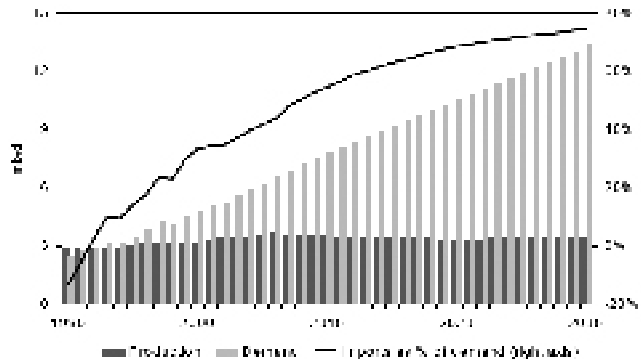

Fig. 1. Chinese oil demand outlook to 2020 (left-scale: mbd), source: IEA

Given the upward prediction of world demand and the time-lag to increase production to meet these new demand levels, it is likely that prices will be substantially higher than the oil price band that OPEC ($22-28 per barrel) employed between 2000 and 2004. According to the IEA World Energy Outlook, the world is expected to consume 125 million barrels per day (mbd) in 2030, compered to 80 mbd in 2004. The main drivers behind future demand growth continue to be China and India, whose economies grow some 2-3 times faster than the developed Western economies. Although China and India have only a modest energy consumption per capita compared to Western countries – China uses only 0.75 litres of oil per capita, while this is eleven litres in the U.S. – its energy intensity (energy input per unit of GDP) is actually four times higher than Western economies. This means that every percentage of growth of the Chinese GDP will be accompanied by an energy input that is four times higher than that of the U.S. and 5-6 times more than that of the E.U.

Production and investments

The challenge for the world is both to meet new oil demand and, crucially, at the same time replace the production capacity in mature oil fields that cover current demand levels. Large investments are required to meet this double challenge. Although many experts claim that the amount of required investments should not pose a problem, the shift in these market from predominantly investments in OECD countries to less secure energy investment markets in the Persian Gulf, Caspian Sea region and Russia, may pose a problem to securely employ this capital. Particularly when international oil companies with deep investment pockets of their own, cannot participate in these projects, banks will demand additional securities to express the higher level of risk. This problem is connected to limited access for foreign direct investments in a large number of OPEC countries and the fact that national oil companies hold a monopoly on exploration and production. The IEA calculated that only 35% of the current proven oil reserves are accessible to foreign investors. The remaining share belongs to national oil companies. Furthermore, countries that have opened up for foreign direct investments and have a potential for capacity enlargement, like Russia, are still considered to have an unstable investment climate. Legal stability and owner-

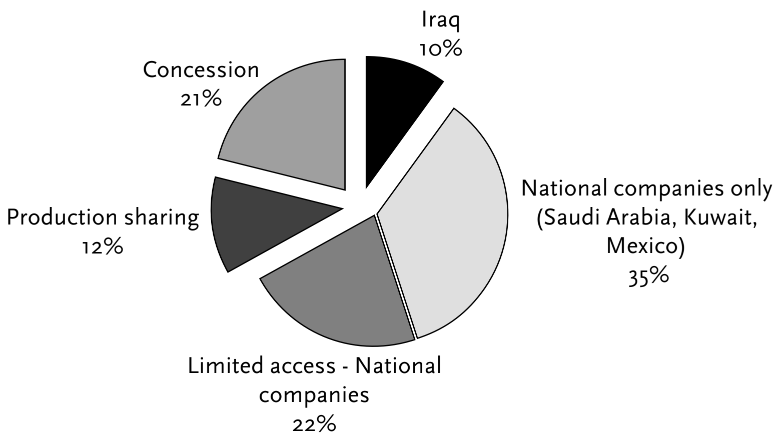

Fig. 2. Foreign investment possibilities (source: IEA 2004)

ship rights are poorly developed, as the Yukos affair has demonstrated. In West-Africa, political unrest forms a barrier for investment.

Choke points

Infrastructural problems may occur in the future. Already a few major chokepoints in trade routes exist and traffic is still increasing. Already some 15 mbd of oil passes through the Straits of Hormuz and some 3 mbd passes through the Bosporus. There inevitably comes a point that these seaways can either not handle more traffic or the energy traffic becomes more vulnerable to criminal or terrorist attacks: particularly if we bear the expansion of gas trade in the form of Liquified Natural Gas (LNG) in mind and that these LNG-ships will have to use the same sea routes (Strait of Hormuz, Suez canal). Therefore a variety of investments have to be made to accommodate future shipping of oil and gas.

The distribution of proven world reserves of oil is heavily biased towards the Persian Gulf. Since 1974, the production share of the Persian Gulf countries has decreased due to the particular role of some countries in OPEC and the devastation to production capacity due to war in the region (Iran, Iraq, Kuwait). The oil crisis of 1973/1974 was followed by intensified exploration and production activities outside the OPEC countries. The market share of Non-OPEC oil increased substantially to the detriment of OPEC's share in world trade and production. It is clear, however, that in the future a greater call on OPEC, and in particular on the Persian Gulf oil, must be made to satisfy growing demand. Some important Non-OPEC oil regions are reaching maturity and despite intense investments, growth of Non-OPEC supply will be modest compared to the need of new supplies.

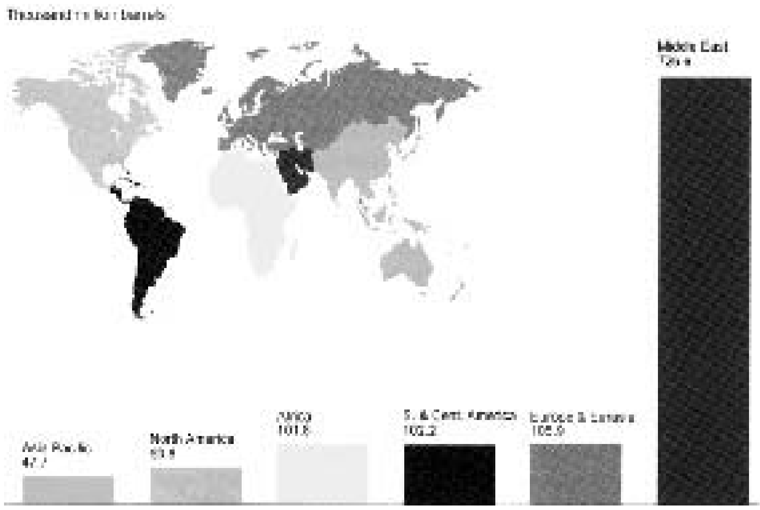

Fig. 3. Proven world oil reserves according to BP (source: BP statistical review of energy 2004)

Given the fact that the lion's share of the remaining proven oil reserves in the world are found in the countries around the Persian Gulf, their share in world production must increase. In 2004 uncertainty with regard of the size Persian Gulf reserves appeared. The fact that reserves remained unchanged for years and little transparency is offered about the quality of mature fields, raised doubts about the potential for production capacity expansion. Also reserve figures are used to determine the distribution of production quota in OPEC and could have led in the past to reserve inflation. Nevertheless, even with uncertainties about reserves, it is clear that the bulk of the reserves reside under the countries of the Persian Gulf.

Security of supply

The distribution of future demand and supply leads to one conclusion: the import dependency of major consuming countries/regions is not only set to increase but will also be concentrated on but a few suppliers. This will heighten concerns about security of supply. It is seen as both politically and economically undesirable to import oil from only a few suppliers. Security of supply concerns are further sharpen because consumer countries must increasingly compete for supplies. The buyers market of the 1980s and 1990s has switched to a seller market. Given the political tension in the world, politics matter again and oil flows could again become politically determined. For countries that had banked on purchasing oil in the international market place, where oil had been stripped of its nationality, this might be a crucial change in international oil relations.

The expected dependence on OPEC oil makes the consumer countries also more vulnerable to political and economic fluctuations in producer countries. The OPEC production policies have become more and more income driven when government budgets needed to be financed. Most OPEC countries have a relatively young population and the pressure on government to create jobs is very large. Furthermore, the

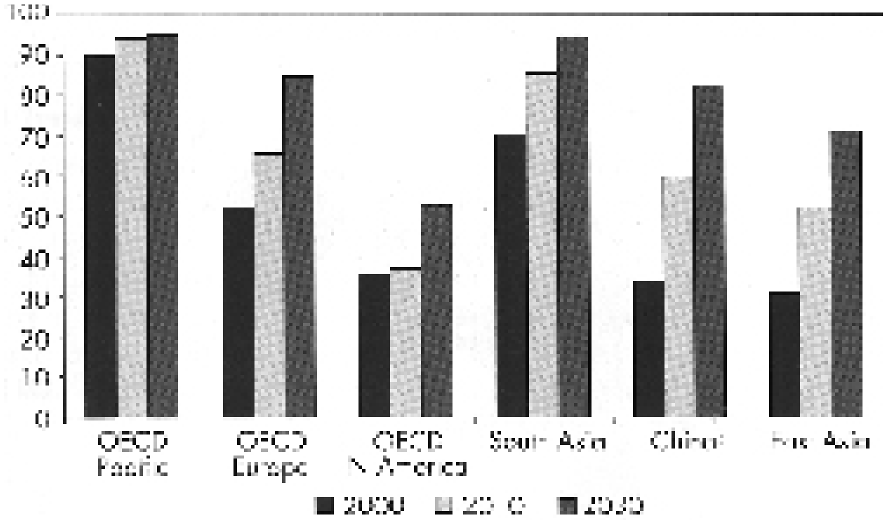

Fig. 4. Import dependency of selected major importing regions (source: IEA 2004)

Persian Gulf countries have seen their security budgets increase substantially in the past few years. Based on these domestic spending needs, many OPEC countries (also Saudi Arabia) need at least a real oil price of about $25 to balance their budget. The depreciation of the dollar, therefore, created additional pressure on the oil price because OPEC countries wanted to compensate for the loss of purchasing power.

Currently, the EU imports about 55% of its oil consumption, compared to 35% in North America and China and 90% for Pacific Asia. By 2030 these figures will have dramatically changed. The EU will import about 85% of consumption, North America about 55%, China 80% and Pacific Asia 95%. Although the North American figure of 55% seems relatively modest compared to the other consumer regions/countries, in absolute volumes the imports will increase to 18-20 mbd (depending on demand growth), by far the largest volume of all countries.

The policy response for consumer countries could be to diversify to other fuels, such as gas. Gas reserves are substantial, although also relatively far removed from the market, and the emission of CO_2 is lower than oil. Although coal reserves are abundant, environmental policies steer demand away from coal. In the future, under the pressure of security of supply problems in oil and gas and environmental needs, clean coal technologies could become an important instrument to address security of supply problems. Renewable and nuclear energy could to a certain extent help manage the import dependency. At the moment, the high rate of dependency of the transportation sector implies that oil will remain an important fuel in our economies for some time to come. The driving forces of the oil market will therefore require our full attention in the next decades!

HOWARD CHASE

Energy geopolitics and investment

Introduction

What are the recent events that are shaping our thinking on energy security? As we all know, the price of oil on the international market rose sharply over the last year from $28 to a peak of over $50/bbl before falling back to under $40/bbl today (Dec. 2004). To understand the reasons for these shifts you have to look back at the events of the last five years.

What has changed and what are the consequences of those changes?

Back at the end of the 1990s we were all accustomed to an oil price which averaged a reasonably stable $18 a barrel with only occasional excursions beyond $20 per barrel, and one brief fall at the end of the 1990s to $10. That was the picture for a decade, from the end of the first Gulf war onwards. Throughout the 1990s technological advances extended the range of economic production. Advances in seismic technology reduced the risks and costs of exploration. Advances in deep water technology opened up new areas for exploration and development. Advances in reservoir management technology pushed up recovery factors. And political change also opened new doors. International companies were able to invest in areas previously closed to them – including Russia, the Caspian, Central Asia and China. These developments created a situation in which costs were falling and in which prices were moderate and seemed more likely to decline than increase. The factor which changed the outcome was the decision in April 2000 by the OPEC member states to use their market power to set a price framework for oil at around $25 a barrel – varying up or down from that level by no more than $3 a barrel. That was a major step, and OPEC's successful management of their production kept prices at those levels throughout the period from 2000 to the end of 2003.

The next fundamental change came on the demand side. The growth in demand for oil in 2003 and 2004 has been so strong that - for the first time in 30 years - the rate of oil demand growth worldwide has almost matched the growth of GDP. That is the context in which we have seen the sharp price movements of the last twelve months. That rise in global demand has been led by China, which remarkably has increased its imports of oil by 400% in just four years. Other developing economies have also contributed to the overall demand growth.

For most of the last two decades the market has operated with around 3 million barrels per day of spare capacity. This year that spare capacity fell at times to around 1 million barrels per day – which is less than production from a number of areas where continuity of supply has been threatened by disruptions – including Iraq, Nigeria and Venezuela. There has been no shortage but there has been a fear that a shortage would develop. Fortunately the market has responded in a very effective way. Partly in response to this increased price, the private sector part of the industry began to increase its spending on exploration and production. The top 30 quoted companies have increased their investment in exploration and production by more than 15% a year during the last five years. They are now investing between them almost $100 bn a year. This investment is already producing significant new sources of supply.

A whole series of major new fields are coming on stream over the next three years – including in the Caspian, in Angola, and in the deep water of the Gulf of Mexico. Those new developments should help to restore stability to the market. So will the parallel growth in OPEC capacity. If, as can be reasonably expected, demand growth resumes its normal path of around 1.5% per annum, surplus capacity should be restored over the next three years to a more comfortable level of around 3 million barrels per day. In the absence of any further major disruption to supplies, that should remove some of the speculative concern which has driven prices up over the last year, even if there is no additional production from Iraq.

In these circumstances it seems realistic to expect that prices might fall back towards the levels set by OPEC production discipline from 2000 to 2003. That is a reasonable level which will reward investment by the private sector and generate sufficient revenue for the producing states - but which will not do major damage to the global economy or to those who depend on oil imports. Such an outcome, however, is not the end of the story. None of the developments here described should be taken to mean that the medium and longer term issues of energy security have been resolved.

Supply and demand

There are four substantive issues, each of which poses challenges for energy security. The first is supply and demand. The demand for energy continues to grow, with the growth underpinned by the global increase in population and the gradual spread of prosperity. More and more of the world's population can afford the energy they want to buy. The spread of prosperity, especially in China, India, and parts of Latin America, adds to effective demand on a daily basis. The result is tens of millions of new consumers of commercial energy every year. The current projection from the International Energy Agency is that global demand for all forms of commercial energy will rise from the current level of around 190 million barrels of oil equivalent per day to some 240 million barrels of oil equivalent per day by 2015. This is a rise of almost 30%.

How can that demand be met?

Renweables and alternative forms of energy supply will make a growing contribution, including from wind, waves and solar panels. In BP for example we are investing heavily in photovoltaics – the technology which supports solar power – as well as in other forms of alternative energy supply. In the future one or more of those new sources will provide a significant proportion of global energy demand. But the current proportion of renewables in the world energy mix is low – perhaps 2.5% including biomass – and the time scales to achieve major market penetration are still long term. Meanwhile nuclear energy also seems unlikely to provide an increasing proportion of world energy supply for some time to come. And that leaves hydrocarbons – coal, oil and gas – to meet the balance for many years into the future. The IEA figures estimates that over the next ten years, global oil demand could increase by 20 % from today's level and natural gas demand could rise by 45% in the same period.

Can the oil and gas industry meet that demand?
In physical terms the answer is clearly yes. The resources are there. The world currently holds some 1,000 billion barrels of oil which has been found but not yet produced, and some 5,500 trillion cubic feet of natural gas also found but not yet produced. At current consumption rates that is the equivalent of 40 years of oil supply and 60 years of gas. In addition the US Geological Service estimates that some 800 billion barrels of oil and 4,500 trillion cubic feet of natural gas are yet to be found. So in terms of physical resources, energy security is within reach. There is no fundamental physical reason why there should be a shortage in the next two decades or beyond. The challenge for energy security is that supply is not collocated with demand.

The environmental challenge
The second key strategic element is the environmental challenge associated with the growth in hydrocarbon consumption. In part this is about local pollution caused particularly in the cities as hydrocarbons are burnt. In part, and potentially more seriously, it is about the impact of increasing emissions of greenhouse gases on the earth's atmosphere – the issue of climate change or global warming. The detailed science of climate change is still provisional. There are many things we do not know. But – on the basis of the available evidence about climate change – the clear judgment must be that there is a powerful case for precautionary action. The best current estimate is that precautionary action should be designed to limit any increase in the world's temperature to around 2 degrees Celsius. This translates into a stabilisation of greenhouse gases in the atmosphere at around 500 to 550 parts per million. As knowledge advances, this estimate could of course be adjusted and refined.

So can stabilisation at this level be achieved?
In our view the answer is firmly yes. It would mean putting ourselves on a trajectory to the point where – in 2050 – 50% of global needs for energy would be met by conventional fossil fuels and the other 50% would come from fuels with lower or zero emissions. Each of those two halves would be about the size of today's energy industry. We believe this is achievable. Some of the most interesting work in this area has been done at Princeton University in the US. This has identified a range of technologies which could each contribute to meeting the overall challenge. None of these technologies requires a material advance on currently available techniques – and all have already been demonstrated at scale. The requirement is simply for a continued reduction of the engineering cost curve, comparable to the gains the oil and gas industry has achieved over time in areas such as arctic and deep water oil production or the transport of liquefied natural gas.

Some of these possible 'wedges' of carbon saving involve advances in efficiency – such as raising the mileage per gallon of vehicles from 30 to 60 or eliminating the flaring of natural gas produced in association with oil. Others involve changing the fuel mix – for instance from coal to natural gas for fuelling power stations rather than coal. And others involve the use of existing technologies to capture and store carbon dioxide so that it never reaches the atmosphere. In Algeria, BP has developed a huge project to strip the carbon dioxide out of gas bound for Europe and re-inject it into the reservoir from which it originated. That large scale test will reduce emissions by the equivalent of taking more than 200,000 cars off the road.

These technologies are in essence available. The key is to have an agreed long term target supported by a trading system which allows effective and efficient allocation of resources. The European Emissions Trading System, due to come into operation on 1st January 2005, is a critically important step in this direction. In our view it can and should be seen as the starting point for a long term global mechanism for investment and trading in carbon reduction.

The structure of the energy industry

The third strategic element is the structure of the energy industry. The whole of the private sector of the world oil business represents only about 30% of the total global industry, and rather less than that in terms of future reserves and production. For the last thirty years the private sector has historically been concentrated in the OECD areas such as the United States and the North Sea. Those areas are now mature and production is at peak or declining. Other major new areas of private investment coming on stream – such as the Caspian and Angola – are extending this capacity.

However, perhaps as much as 75% of the total remaining reserves of oil and gas in the world, lie in areas where there is little or no private investment in the natural resources sector. This may increasingly pose a challenge in terms of securing the resources needed for timely and efficient development of oil and gas reserves.

Trade in energy

The final strategic factor is trade in energy. For the next decades, four regions will account for the bulk of the import side of the energy trade equation – the US, Europe, Japan and China. Even allowing for maximum economic development of indigenous and alternative resources, these regions will still need substantial and growing volumes of imported oil and gas. At the same time the export side of the equation will display an even more powerful concentration of activity.

By 2015 three areas will account for almost 80% of all the oil traded in the world each day. The three are Russia, West Africa and the Gulf States of the Middle East. By 2015, according to IEA estimates, Saudi Arabia alone will be required to export some 15 to 16 million barrels of oil every day to balance the world market – and that assumes that both Iran and Iraq are by then producing and exporting at something close to their full capacity. That is the issue at the heart of global energy security. The question then is how to structure market relationships in order to ensure the required flow of finance, technology and expertise into the key production areas – and how to safeguard the trade of energy into the key regional markets.

Part of the answer clearly lies in the development of new and innovative forms of partnership involving both the private and publicly owned sectors of the global industry. The widespread use of production sharing and similar forms of contract around the world already provides a strong basis of experience in this area. New forms of joint venture structure may also provide effective vehicles for major production and infrastructure development.

Secondly the legal structures and investment environment provided under national law for all investors – whether private or public – are critical in establishing investor confidence and willingness to participate in major energy projects. Where governments have developed a track record of adherence to agreed contract terms, the outcome has invariably been a sustained flow of investment into the national economy.

And finally the various mechanisms of international dialogue and cooperation can and do play an important role in representing both sovereign and investor concerns and building a framework of investor confidence. In this area the work of the European Union – for example through the EU/Russia energy dialogue and the Energy Charter Treaty – has proved to be of particular value. Like much achieved by Europe, these processes may not spectacular but they do work and they deserve continued support on all sides of government and industry.

ROB VAN DORLAND

Climate change – an overview

Introduction

The science of climate change tries to find answers on three main issues. The first issue is the detection of climate change from instrumental records as well as from proxy data, such as tree rings, sediments and ice cores. Since 1979 the climate system has been monitored using satellite information, which are in principle radiation measurements in various frequency bands from which relevant climate parameters can be retrieved. The attribution of observed climate change to potential causes is the second key issue in climate research. Over the past century it concerns the ability to separate the climate effects due to human activities from the natural variability. By its various activities mankind inadvertently is changing the composition of the earth's atmosphere. The steady increase of a number of trace gases since pre industrial times is warming our planet. This is the so-called enhanced greenhouse effect. The third issue is projection. Given the insights in the climate system, i.e. knowledge of physical (feedback) mechanisms, and given the observed climate parameters, climate models can be used to compute the future climate. State-of-the-art information on detection, attribution and projection can be found in the Working Group I assessment reports of the Intergovernmental Panel on Climate Change (IPCC). These reports are updated every five or six years.

The climate system

The Earth's climate is a complex system. It consists of the atmosphere, ocean, cryosphere (snow and ice), land surface and the biosphere. It includes many physical, chemical and biological processes with a large variation on timescales as well as special scales. As compared to our neighbour planets, Venus and Mars, the earth's system is unique with respect to hydrological, biological and carbon cycles. The temperature of the earth's surface and atmosphere allows for the coexistence of all water phases. Oceans cover about 70% of our planet. Evaporation processes from ocean and land surfaces result in a transport of water vapour into the atmosphere. Due to transports of water vapor against a general decrease of temperature with height in our atmosphere, water vapor condensates into tiny water droplets and freezes higher up, thereby forming a large variety of clouds in our atmosphere. Cloud freezing and coagulation processes result in precipitation

Climate change

All through the geologic past and human history climate and atmospheric composition have been changing. Changes occur at practically all time scales from years to thousands of years. A well-known example of the latter is the occurrence of ice ages. During the last one, which had its maximum some 18,000 years ago, global average temperature most probably was in the order of 5 K lower than at present, while the CO_2 concentration of the air amounted to only 60% of the present value [Figure 1]. There are strong indications that the alternation of ice-ages and interglacials are triggered by periodic changes of earth's orbital parameters, namely the precession of the equinoxes, the axial precession and the precession of the ellipse, on timescales of 20,000 to 100,000 years. These are the so-called Milankovitch orbital effects. After the last ice age global temperatures reached present levels at about 12,000 years before present. Since then variations were numerous but their amplitude has generally been smaller than 2 K on a world average basis.

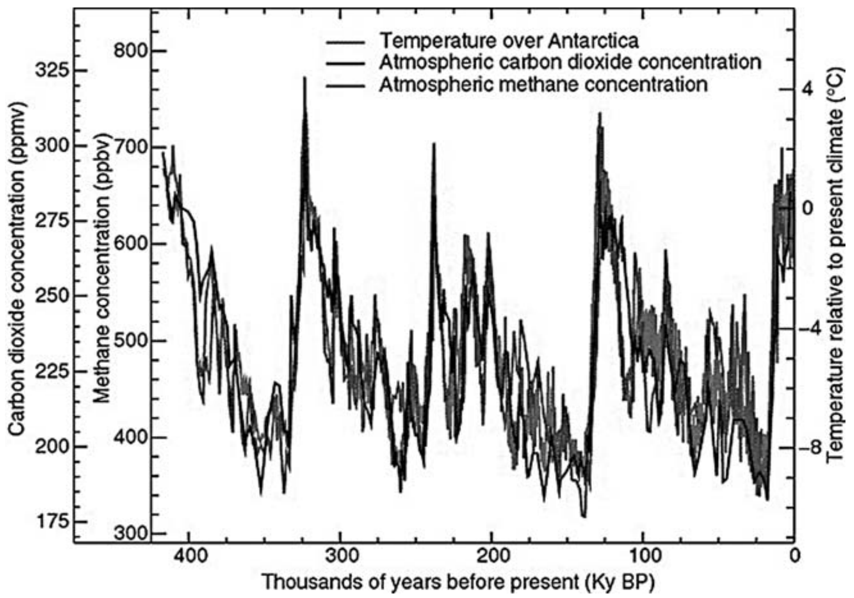

Fig. 1. Variations of temperature, methane and atmospheric carbon dioxide concentrations derived from air trapped within ice cores from Antarctica [source: IPCC 2001]

The changes we observe at present in earth's climate show a general tendency for warming, i.e. an increase of the global average near surface air temperature of about 0.4-0.8 K over the past century (Figure 2) and a retreat of mountain glaciers all over the world. Related to this, a sea level rise of 10 to 20 cm over the past century is observed. Climate changes of this extent, however, are not an unusual phenomenon. Regional changes of climate are larger and even more common than changes in a global average sense. In fact, it may happen that climate is changing almost everywhere without a net global average change of e.g. temperature and precipitation. Alternatively, changes of global average temperature may be very unequally distributed over the globe. This means that regional changes of climate are far less predictable than global average changes. The central question in climate research is how much of the warming trend in the observed global mean temperature can be attributed to the human influence.

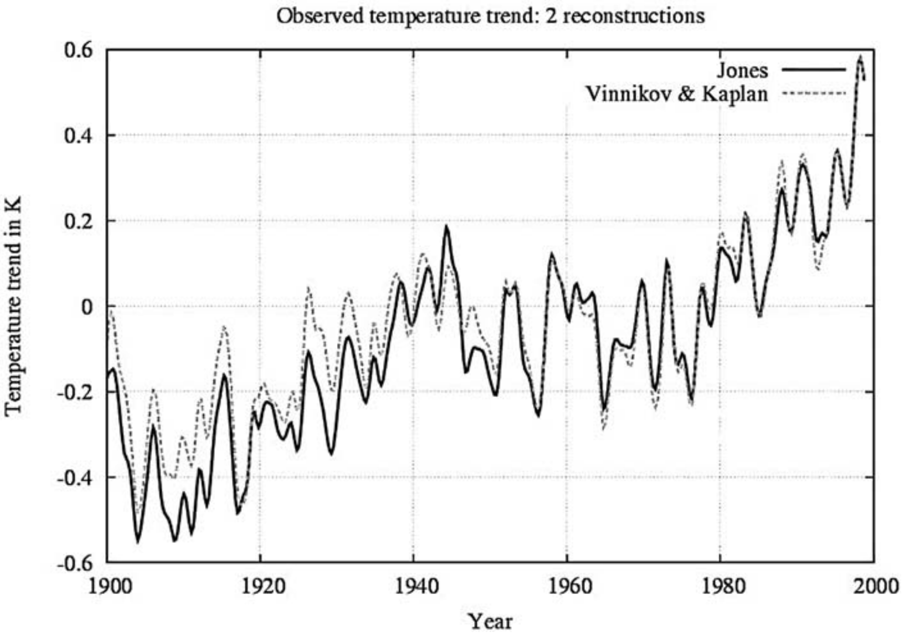

Fig. 2. Observed global mean near surface temperature trend in the twentieth century relative to the average temperature in the period 1961-1990. 1: Jones (dark line), 2. Vinnikov and Kaplan (light line).

Global energy balance and radiative forcing
Atmospheric radiative transfer is one of the most important features in the climate system, because the only interaction with outer space in terms of energy exchange takes place via radiation. The sun is the primary source of energy for the earth's climate system. According to the latest measurements, the solar flux at the mean sun-earth distance has a value of 1370 Wm^{-2}, known as the solar constant. On average, the globe is illuminated effectively by the solar constant times 1/4, being the ratio between the cross section of the earth, perpendicular to the solar insolation, and the earth's total surface. The shortwave radiation, originating from the sun is either absorbed, scattered or reflected in the atmosphere or at the surface of the earth. The ratio between reflected and incident irradiance at the top of the atmosphere, the so-called planetary albedo, has been measured by satellites to be around 0.3. Therefore, the true global and annual mean solar input to the earth-atmosphere system is approximately 240+/-5 Wm^{-2}. Most of the shortwave radiation reaches the earth's surface and is absorbed by the oceans and land-masses; about 30% is absorbed in the atmosphere by ozone, water vapor, clouds and aerosols.

The present global and annual mean temperature of the earth's surface is approximately 289 K. Due to the fact that the atmospheric temperature decreases with height, the thermal emission towards the surface is larger than that escaping to space. About 90% of the counterradiation at the earth's surface is caused by greenhouse gases, while clouds are responsible for the remaining 10%. Part of the total radiative energy input to the soil is returned to the atmosphere by infrared emission. The emission of longwave radiation does not fully compensate for the solar flux and infrared counterradiation from the sky into the surface. The deficit is compensated by transports of latent heat due evaporation of water at the earth's surface and condensation in the atmosphere, and sensible heat. At least in the long term mean the total exchange of energy at the top of atmosphere has to be balanced. If this did not happen, the constant loss or gain would cause climatic change.

On a global scale, perturbations of the radiation balance, either in the longwave or in the shortwave part of the spectrum, result in a climate change, since the energy balance at the top of the atmosphere has to be restored by changing the temperature of the earth's surface and the atmosphere. In reality, perturbations of the radiation balance, e.g. due to steady increases of greenhouse gases, and the subsequent climate response in terms of temperature adjustments, elapse gradually. However, the new climate equilibrium, i.e. the restored balance at the top of atmosphere, is independent of the time evolution of a radiative perturbation under the condition that the climate feedbacks behave linearly. This is at least valid for relatively small perturbations, as compared to the background radiative fluxes For example, doubling the CO_2 content of the atmosphere results in an imbalance of about 4 Wm^{-2}, which is about 2% of the total outgoing longwave radiation at the top of atmosphere. Therefore, we may couple equilibrium climate change to instantaneous perturbations of the radiation balance. The best link between surface temperature change and radiative perturbations on a global scale is given by the net radiative flux change at the tropopause (on average at 13 km altitude) after allowing the stratospheric temperatures to adjust to a new radiative equilibrium. This net flux change at the tropopause is also known as radiative forcing.

Changes in atmospheric composition and in radiative forcing

Over ages, human communities have had little or no effect on the composition of the global atmosphere. In the last one-and-a-half century the rapid growth of the world's population and the development of technology caused an immense increase of energy use. Most of this energy was and still is produced by burning fossil fuels. The direct consequence has been an increase of the atmospheric CO_2 level by about 30% since 1850, the beginning of the industrial era. Routine measurements of the concentration of atmospheric CO_2, which started in 1958, clearly show an average increase of about 0.4% per year. The CO_2 concentration has reached a level of 379 ppmv (parts per million by volume) in 2004. Isotopic analysis suggests that this increase is largely due to human activity. Anthropogenic emissions of CO_2 are partly absorbed by the oceans (35-40%) and the biosphere (5-10%). The remanent fraction of CO_2 in the atmosphere, at present 50-60%, is dependent on temperature and biotic content of the oceans as well as on the changes in the amount and type of vegetation. The concentrations of other naturally occurring greenhouse gases, such as CH_4 and N_2O, are increasing rapidly by human activities such as the combustion of fossil fuels, urbanization, agriculture and deforestation. Also the level of purely anthropogenic trace gases, like chlorofluorocarbons (CFCs), has increased. Besides the fact that CFCs are strong greenhouse gases, they chemically destroy the ozone layer in the upper atmosphere. It is due to the latter effect that international agreements have been made on a production stop. Since 1992, increases of CFC-concentrations are slowing down. The radiative forcing due to changes of the aforementioned well-mixed greenhouse gases is known within the relatively small uncertainty limit of about 10%. CO_2 contributes most to this forcing with about 60%.

In addition to these uniformly mixed greenhouse gases, various short-lived radiatively active atmospheric constituents have changed due to industrial activities. Emissions of NO_x and CO, together with the already mentioned greenhouse gas CH_4, lead via a number of complex chemical reactions to the production of tropospheric ozone. In the stratosphere, increases of CFCs cause a depletion of ozone. In the vicinity of the tropopause, aircraft emissions result in ozone increases. The radiative effects of tropospheric increases and stratospheric decreases of ozone are quite uncertain due to the fact that patterns of change are highly variable in space and time. Moreover, the radiative forcing is strongly dependent on the altitude at which ozone changes occur.

Changes in the tropospheric sulfate aerosol content exhibit even larger uncertainties in the radiative forcing. Anthropogenic sulfur emissions lead to the formation of sulfate aerosols, which act to cool the climate by virtue of their ability to scatter shortwave radiation back to space, known as the direct effect. The radiative forcing due to the indirect effects of aerosols, i.e. the changes the optical properties and lifetimes of clouds, has a very low confidence level. Due to the large uncertainties in the direct as well as indirect cooling effects of sulfate aerosols, the total radiative forcing of greenhouse gases and aerosols from human activities is poorly known, ranging from +0.5 Wm^{-2} to +2.5 Wm^{-2}.

Climate sensitivity

The coupling between radiative forcing and equilibrium temperature response is called the climate sensitivity, expressed in K/Wm^{-2}. For the present generation of 3D climate models, this climate sensitivity parameter is ranging from 0.5 to 1.1 K/Wm^{-2}. This range is mainly the result of uncertainties in the climate feedbacks induced by temperature dependent processes in the climate system. The response to perturbations of the radiation balance can either be amplified or damped as the result of these feedback mechanisms. Most pronounced is the positive water vapor feedback: if the temperature increases, e.g. due to increases of the atmospheric CO_2 level, the air will contain more water vapor. This is based on the observation that in our present climate the relative humidity especially over the oceans is quite constant. Since water vapor is an important greenhouse gas, increases herein result in an amplification of the global warming. The feedbacks related to changes in cloud properties are highly uncertain and are therefore largely responsible for the uncertainties in climate sensitivity.

Role of the oceans

The partition between the heat storage in the oceans and the directly rendered energy into the atmosphere through either longwave radiation or latent and sensible heat flows, is largely dependent on the thermal and salinity structure of the oceans, thereby regulating the heat diffusion as well as the upwelling processes. Since the climate system acts as a low pass filter due to the large heat capacity of these oceans, the partition is also dependent on the period of the climate perturbation. Moreover, it is very difficult to evaluate this partition of heat with observational data. Although the mechanisms of the human influence on the radiation balance are physically well understood, accumulation of uncertainties due to the total anthropogenic radiative forcing, the climate sensitivity and due to the partition of energy, results in poor estimates of subsequent global mean temperature changes.

Attribution

Global mean temperatures show a broad spectrum of variability, ranging from interannual fluctuations to a long-term warming trend over the past century [Figure 2]. Attribution of observed temperature variations to specific causes requires specifications of both the response due to the radiative forcings and the dynamic state of the climate system. A prominent example of variations in the dynamic state is the El Niño-Southern Oscillation (ENSO). ENSO has a broad spectrum of variability with most of its variance on interannual to decadal time scales. Important sources of radiative forcings are major volcanic eruptions, variations in solar activity and anthropogenic emissions of greenhouse gases and aerosols.

When we correct the global mean temperature for the best estimates of these natural factors [Figure 3], we are left with a residual signal that shows a striking rise during the second half of the twentieth century of about 0.5 K [Figure 4]. This temperature rise in form and timing strongly resembles the results of the climate models in connection with human influences. For example, the CO_2 concentration in this period rose sharply from 311 ppm in 1950 to 368 ppm in 2000. Before the industrial revolution, about two centuries ago, the concentration fluctuated around 280 ppm. On the basis of comparing sign and amplitude of natural and anthropogenic forcings, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations.

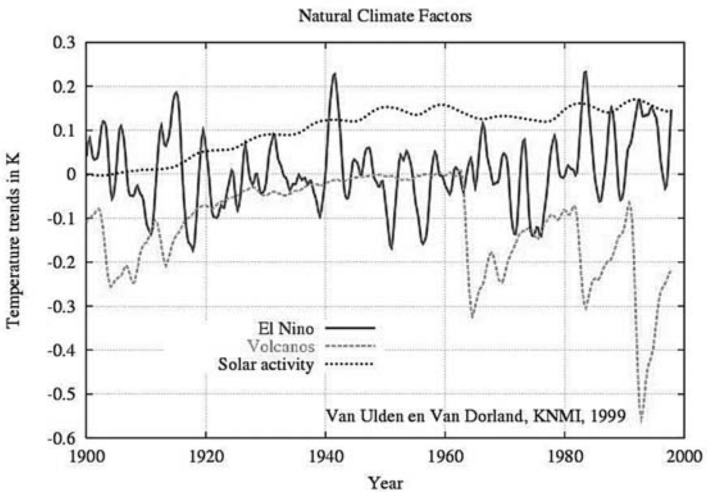

Fig. 3. Best estimate of the temperature signals due to natural climate factors: volcanic (light line), solar activity (dotted line) and ENSO (dark line)

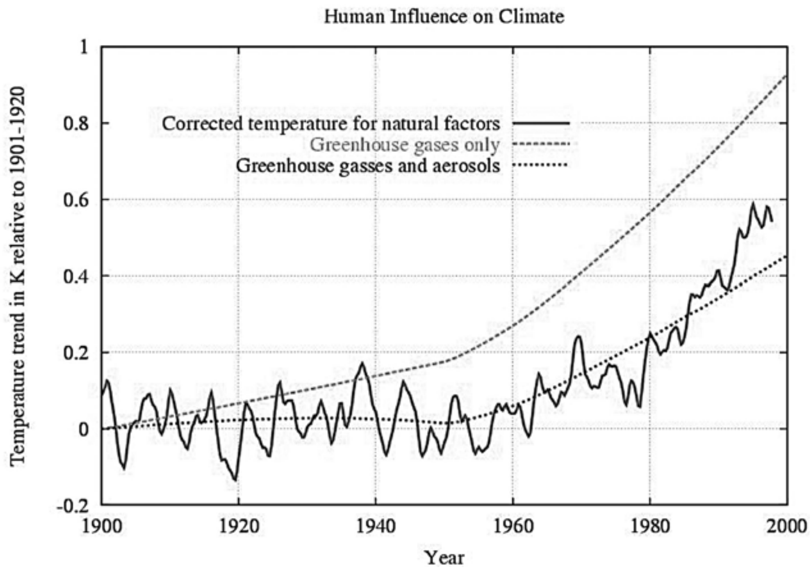

Fig. 4. Residual temperature signal as computed by subtracting the sum of the natural signals from the observed temperature trend of Jones (dark line). This signal is consistent with the computed anthropogenic influence due to greenhouse gases and aerosols using middle estimates of radiative forcing and climate sensitivity (dark dotted line). Also, the computed temperature signal of greenhouse gases only is shown (light line)

Climate projections for the 21st century

In order to predict developments in the 21st century it is necessary to form a general picture of greenhouse gas emissions and dust particle concentrations in the future. For this purpose the IPCC has developed scenarios which were scientifically computed using climate models. It is almost certain that during the next century the development of the concentration of CO_2 in the atmosphere will be determined by the burning of fossil fuels. As the amount of CO_2 increases, the ability of oceans and land to absorb it will diminish. At the end of the 21st century a CO_2 concentration of 1.5 to 2.6 times the current values is to be expected. In all scenario's the relative contribution of CO_2 to the net greenhouse effect during the present century will expand. The cooling effect of dust particles is estimated to be substantially smaller.

Computer simulations based on the above mentioned scenario's show that the increase in the 21st century will lead to an increase in the global mean temperature of 1.4 to 5.8 K relative to 1990 [Figure 5]. Such a warming will continue for centuries, and eventually, on a time scale of 1,000 years, a sea level rise of several metres is to be expected. Apart from the projected temperature increase, sea level will rise due to thermal expansion of the world oceans and melting of ice caps. Also the hydrological cycle will intensify, on average resulting in more precipitation. Unless society is able to lessen the output of greenhouse gases substantilly, the expected increase in the global mean temperature, in the short period of time of one century, is comparable with the natural processes from the last ice-age until the present day.

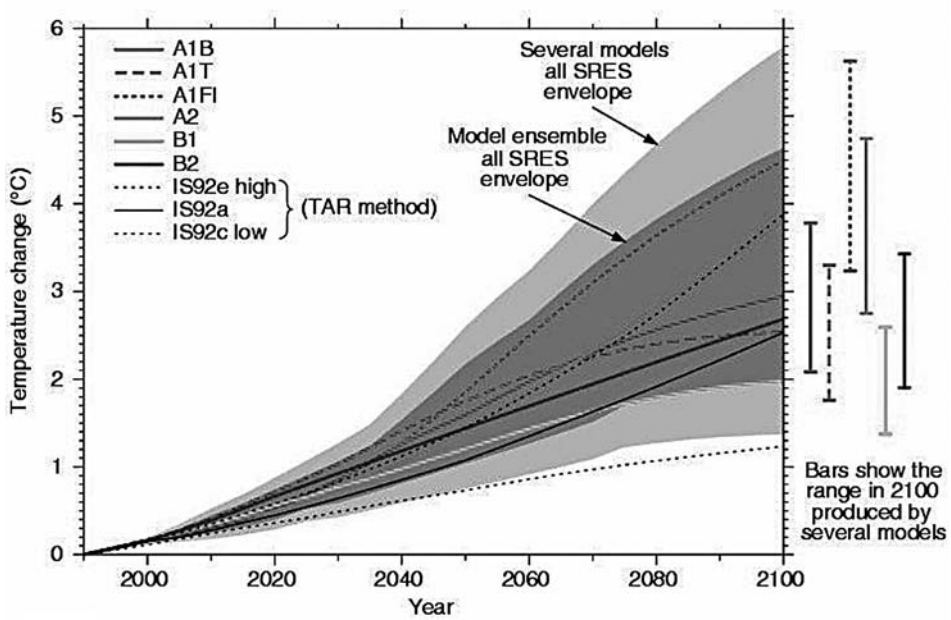

Fig. 5. Temperature projections due to the six illustrative SRES scenarios for the 21st century with the full range of climate sensitivities

HEIN DE BAAR

Role of the oceans in the high- CO_2 world

Atmospheric CO_2 is expected to be doubling to ~700 10^{-6} atm in about 2050 A.D. This is only 46 years ahead and our children and grandchildren living today will witness this double CO_2 world. This transient increase of anthropogenic CO_2 in atmosphere and oceans may well cause other changes of the globe. Climate change has been predicted, with global warming which may already be taking place. Moreover, by the invasion of ~40% of anthropogenic CO_2 into the sea, the chemistry of seawater is changing, the ocean becomes more acidic. Major shifts of marine ecosystems, including coral reefs, will take place soon, if not already going on right now.

Introduction

In 1957 Dave (Charles David) Keeling from Scripps Institute of Oceanography started the now world-famous time series of atmospheric CO_2 measurements at Mauna Loa, Hawaii, far away from local industrial sources. The first values of about 315 10^{-6} atm were rapidly rising at a rate of ~2 10^{-6} atm/y. At first this was met with scepticism about errors or local pollution. However, soon it was widely accepted the increase was real and attributable to the burning of fossil fuels by mankind. Nowadays in 2005 the values are approaching 380 10^{-6} atm and continue to rise.

In order to know what the natural CO_2 was in the atmosphere before the onset of the Industrial Revolution, many efforts and approaches to reconstruct the past CO_2 failed. It was not until the drilling of ice-cores at Greenland and Antarctica that well-preserved, marvelous, records of CO_2 in air bubbles enclosed within the ice were obtained. Ice cores collected in regions with high precipitation (snow which in the upper ~0.5 metre rapidly converts to ice with gas bubble enclosures) have proven that over the preceding ~1000 years, and ~10,000 years, of the Holocene, the CO_2 in air was quite constant at ~280$\pm$3 10^{-6} atm, then from 1780 A.D. onwards increasing rapidly, and from 1957 onwards perfectly overlapping with the Anthropocene atmospheric record of Keeling. Moreover, by deep ice drilling at central Antarctica where is very little precipitation, ice cores with lower resolution but very long records were obtained, first over the past ~160,000y, next over the past ~420,000y and recently over the past 740,000y. The first cores showed regular oscillation of atmospheric CO_2 over the well-known 100,000y glacial/interglacial cycle, with minima and maxima of ~190 and 290 10^{-6} atm. For the recent 740,000y ice core eight complete glacial/interglacial cycles were shown. Its air bubbles record has not yet been completely analyzed, but preliminary CO_2 results thus far confirm the oscillations and minima/maxima of the previous cores. The regular CO_2 oscillations are correlating with the temperature record as derived from stable isotope signals in the ice. This shows a minimum local temperature at the Vostok drilling site which is ~6-7 °C below the interglacial or 'warm' periods like the modern Holocene interglacial era.

Atmospheric carbon dioxide and global temperature

Summarizing the above, the atmospheric CO_2 value of today (~375 10^{-6} atm) is ~100 10^{-6} atm higher than the past 10,000y Holocene. This rise is the same magnitude (~100 10^{-6} atm), but beyond, the regular oscillation between 190 and 290 10^{-6} atm over the past >420,000y. Latter oscillation co-varying with a ~6-7 °C warming and cooling, there is concern that the current 100 10^{-6} atm excess CO_2 will give rise to an excessive global warming of similar magnitude. However, this simple extrapolation is not necessarily valid. Mankind and the planet have risen well outside the CO_2 versus temperature 'calibration' of past >420,000y, i.e. the CO_2-temperature correlation of the past is, on its own, not necessarily valid for the future.

One century before, in 1896, Svante Arrhenius had already proposed lower atmospheric CO_2 as an explanation of the preceding last ice age (Last Glacial Maximum): 'In order to get the temperature of the ice-age, the carbonic acid in the air should sink to 55-62% of its present value (lowering of temperature 4°-5°C)'. Taking the 'present' value as 296 10^{-6} atm in year 1896 from the now available ice core record, Arrhenius thus hypothesized ~162-183 10^{-6} atm (i.e. 55-62%) during an ice age, remarkably close to the ~190 10^{-6} atm minimum now observed in the ice cores.

Recently the IPCC (2001) reported an observed global warming over the past century. While recognizing the complexity of the climate system, the most straighforward, hence most acceptable, explanation of this observed warming is due to the rise of CO_2 in the atmosphere. This is consistent with the most recent climate models, which, when taking into account all other variations (solar cycle, volcanism, etc.), cannot reproduce the observed warming trend, unless also taking into account the anthropogenic enhancement of the natural CO_2-greenhouse mechanism by the rising CO_2 in the atmosphere.

Moreover, climate models predict the most rapid global warming at high latitudes, notably in the Arctic. The recent Arctic Climate Impact Assessment (ACIA) predicts a temperature rise of ~5-7 °C in 2100 in the Arctic, when the CO_2 would have risen well over 800 10^{-6} atm. This was also foreseen by Arrhenius: 'A simple calculation shows that the temperature in the arctic regions would rise about 8° to 9° C., if the carbonic acid increased to 2.5 or 3 times its present value.' Again using latter 'present' value of 296 10^{-6} atm in 1896, one arrives at ~740-880 10^{-6} atm to achieve the 8-9 °C Arctic warming. Thus, tedious hand-calculations in 1896 are consistent with modern climate simulation modeling with powerful computers. Obviously both Arrhenius and ACIA merely give predictions, yet when eventually our grandchildren would find these true, it would be too late to remedy. Recently World Wildlife Fund has cautioned for extinction of polar bears, animals which WWF is concerned that our grandchildren will only know from history.

Ocean carbon cycle

Towards curing a high fever or any other disease, medical science relies on fundamental understanding of the healthy human body. Towards unraveling the fate of the excess or anthropogenic (man-made) CO_2 and related global warming, we first need to know the natural global carbon cycle (Table 1). The atmosphere, that we are

Reservoir	PgC=10^{15} gC	relative to all biomass	Turnover Rate PgC y^{-1}	Residence Time year
Atmosphere	-700	~1	~3.5	(fossil fuel increase)
Seawater DIC	~42,000	~75	~42	~1000 y
				(mixing time deep waters)
Sediments: $CaCO_3$	~60,000,000	~109,100	~0.06	~10^9 y = billion
Organic C store	~15,000,000	~26,800	~0.03	~500 10^6 y
Recoverable Fossil Fuels	~4,000	~7	6.6	~600 y
Humus in soils	~3,000	~5.4		
All living organisms (plants and animals)	~720	1		
All mankind (6 billion people)	0.056	0.00008		

Table 1. Relevant reservoirs of carbon in the biosphere in units of PgC as well as relative versus biomass of all living organisms. In terms of biomass mankind is modest. Only the reservoirs most relevant are shown, i.e. with focus on marine reservoirs. The PgC unit is equal to the GtC (gigatonnes carbon) unit in older literature, both amounting to 10^{15} gram C. Ocean deep waters on average reach the surface (i.e. contact with the atmosphere) only once every 1000 years, this also applies for the Dissolved Inorganic Carbon (DIC) in the seawater. The annual burial of organic carbon in marine sediments is modest (0.03 PgC y^{-1}) but over long geological time scale (~500 10^6 y) of ocean basins a large organic C store has accumulated. Of this only a very small fraction is recoverable as petroleum and natural gas. Together with the burning of coal the overall mining and combustion of fossil fuels now is ~6.6 PgC y^{-1}. Every year the average person is burning about 100-fold his own body content of carbon as fossil fuels.

concerned about for the CO_2-greenhouse effect, is only a small reservoir compared to the Dissolved Inorganic Carbon (DIC) in seawater of the ~4,000 metres deep ocean. The sediment reservoirs of both limestone ($CaCO_3$) and the organic C store are enormous. Both huge reservoirs are biogenic, i.e. have been produced by marine plankton organisms, shelled animals and coral reefs. The recoverable C store is relatively small. It also has accumulated over ~10-100 millions of years, and now is recovered and burned within only a few centuries.

The CO_2 gas is not a simple dissolved gas in seawater, but reacts with the water to form carbonic acid, which further dissociates. In order to understand the role of the oceans, we have to look more closely at the Dissolved Inorganic Carbon (DIC) pool in seawater. This consists largely (~90%) of bicarbonate ion $[HCO_3]^-$, also there is quite some (~10%) carbonate ion $[CO_3]^{2-}$ but only very little, about 1% of all DIC, of the true $[CO_2]_{dissolved}$ form. These three chemical forms together constitute the DIC pool:

$$DIC = [CO_2]_{diss} + [HCO_3]^- + [CO_3]^{2-} \quad (1)$$

and react with each other according to the following equilibria:

$$CO_{2(gas)} \Leftrightarrow [CO_2]_{diss} + H_2O \Leftrightarrow [H]^+ + [HCO_3]^- \Leftrightarrow 2[H]^+ + [CO_3]^{2-} \quad (2)$$

These equilibria also are the natural buffer for the acidity or pH ($-{}^{10}\log[H+]$) of seawater which is very stable at pH~8.1 in surface waters.
During photosynthesis by algae in the upper ~50m surface waters of the oceans where light penetrates, the CO_2 is combined with nitrogen and phosphorus into organic matter, and oxygen is produced:

$$106\ CO_2 + 16\ N + P + \text{solar energy} \xrightarrow{\text{photosynthesis}} (C_{106}N_{16}P_1)_{organic} + O_2 \quad (3)$$

The algae produce organic matter with very uniform proportions of C and N and P in the ratio C:N:P = 106:16:1. Due to the CO_2 uptake from seawater, all reactions in above (1) shift to the left to replenish the $[CO2]_{diss}$ pool again. Moreover some extra CO_2(gas) enters from the atmosphere, i.e. the atmospheric CO_2 tends to decrease. Part of algal organic matter sinks out into the deep dark ocean, where it is used by bacteria and animals as food (energy supply) in respiration:

$$(C_{106}N_{16}P_1)_{organic} + O_2 \xrightarrow{\text{respiration}} 106\ CO_2 + 16\ N + 1\ P + \text{energy} \quad (4)$$

This is exactly the opposite of photosynthesis and extra CO_2, and N, and P dissolves in the deep seawater. The combination of uptake from surface seawater by photosynthesis in the upper 50 metres, and dissolution into deep seawater by respiration, is the reason why Dissolved Inorganic Carbon (DIC) and N (as nitrate) and P (as phosphate) are much higher in deep ocean waters than in surface waters.

Moreover when shells or corals are formed or dissolving again, there is the following equilibrium of the solid limestone of shells, and corals, with the DIC pool in the seawater:

$$CaCO_3\ (\text{solid}) \longleftrightarrow [Ca^{2+}] + [CO_3^{2-}] \quad (5)$$

By the uptake or dissolution of $[CO_3^{2-}]$ this also affects the chemical equilibria (2) of the DIC pool.

Global anthropogenic CO_2 budgets and uptake by the oceans

The increase of atmospheric CO_2 accurately measured by Keeling and others, is much less than the annual emissions from fossil fuel burning. These emissions also are known accurately from the annual production statistics of the petroleum and natural gas companies, and coal mining. Roger Revelle and Dave Keeling at Scripps immediately realized the oceans are taking up vast amounts of excess CO_2, but how to quantify this ? The above chemistry of CO_2 in seawater is quite complicated but its principles very well known. For example, already in the 1950s Revelle had worked out that at increasing CO_2 in the atmosphere, from the above equilibria you can predict that the abiotic uptake capacity of surface seawater will decrease in the future.

Henk Postma of the Royal Netherlands Institute for Sea Research (NIOZ), member of the KNAW, while staying for a while at Scripps, in 1964 wrote an article in which the chemical equilibria were worked out, and he showed that, in principle, the increase of CO_2 in the oceans was directly detectable (Postma, 1964). Deep water DIC values could be corrected for respiration using above (4) with measured concentrations of Nitrate, Phosphate and Oxygen, similarly for dissolution of shells with above (5), and the corrected DIC value after some more corrections would give the excess dissolved CO_2 from fossil fuels. However, at the time the oceanic CO_2 data was not accurate enough to do this. It was not until the extensive and reasonably high-quality data set for DIC was collected during the GEOSECS expeditions of the 1970's, that the potential of such an approach was recognized and formalized.

	CO_2 Sources and Sinks [Pg C] = [Petagram C] = [10^{15} gram Carbon]	**1800 to 1994** [Pg C]	**1980 to 1999** [Pg C]
	Constrained sources and sinks		
(1)	Emissions from fossil fuel and cement production	244 ± 20	117 ± 5
(2)	Storage in the atmosphere	-165 ± 4	-65 ± 1
(3)	Uptake and storage in the oceans	-118 ± 19	-37 ± 8
	Inferred net terrestrial balance		
(4)	Net terrestrial balance = [-(1) - (2) - (3)]	39 ± 28	-15 ± 9

Table 2. Anthropogenic CO_2 budget for the Anthropocene (1800 to 1994) and its most recent decades 1980-1999. See further Sabine et al (2004).

My then promotor Peter Brewer [1978] and Chen and Millero [1979] independently published formal approaches to extracting the small excess (anthropogenic) component from the large and strongly varying natural background DIC concentration. However, it took until the 1990s before the ocean measurements of DIC and CO_2 were accurate enough to do this well. Nicki Gruber [1996] developed a sophisticated correction method. Chris Sabine and friends applied this method to the accurate JGOFS/WOCE Ocean CO_2 Survey of the 1990s, to calculate the anthropogenic CO_2 inventory of the world oceans (Table 2). Since the onset of the industrial revolution (~1800) until ~1994 the oceans have accumulated an estimated, 48% of CO_2 emissions from fossil fuel burning and cement production. Over the final 20 years of the century this ocean uptake was a third of the previous 200 years, but relatively less at 31% of the emissions. By absorbing 31-48% of fossil fuel emissions, the oceans have slowed down the atmospheric CO_2 increase accordingly; however, at a price being paid by marine ecosystems.

Pumping CO_2 down into the deep ocean

This net uptake of anthropogenic CO_2 takes place via three mechanisms or routes: the so-called 'physical pump', the 'biological pump, and the 'continental shelf pump'.

Physical pump

Seawater is expanding a very little when heated, and contracting upon cooling. In the high North Atlantic seas north of Iceland, the surface water is cooling very much in winter (February). As a result it contracts somewhat, its density increases, and once the density is higher than that of the deeper water layers, the surface water sinks to great depths. When sinking it takes along all its dissolved substances, thus dissolved CO_2, and also dissolved freons (CFCs), artificial gases introduced by mankind into the atmosphere. Latter freons are a perfect tracer for physical transport of anthropogenic substances into the sea. From the high Nordic Seas, the deep water slowly travels southward towards Antarctica. There in the Weddell Sea in austral winter (July-August) the same process happens and extra water sinks to great depths, also taking along CO_2 and freons. The process of deep water formation has taken place for a very long time, and the deep water has entered into the deep Indian and Pacific Oceans, where it arrives ~1000 years or more after it has left the surface in Arctic or Antarctic winter long time ago. However, the youngest deep water, less than 200 years 'old' age, also carries the extra fossil fuel CO_2 into the deep ocean, and the water younger than about 70 years also carries the signal of the anthropogenic freons (CFCs). Indeed in the deep North Atlantic and around Antarctica, the calculated signal of anthropogenic CO_2 nicely coincides with the high concentrations of CFCs.

Biological pump

The natural biological pump was described above, in essence with the equations (3) and (4). Before the Industrial Revolution this presumably was in balance, i.e. when averaging out this biological pump over all seasons (i.e. one year) and all ocean regions, the net exchange of CO_2 with the atmosphere due to the natural biological pump is assumed to be zero. With rising CO_2 levels, or by iron fertilization, perhaps this biological pump can be stimulated, i.e. the overall biological pump gets stronger, and the net increase would be the 'extra' biological pump bringing down 'extra' CO_2 into the deep sea. Until recently it has been assumed this has not yet happened, i.e. the biological pump has remained constant. Yet recently we have realized that the below feedbacks of the extra CO_2 may also affect the biological pump, getting either weaker or stronger.

C*ontinental shelf pump (a case study in the North Sea)*

The dissolved CO_2 fixed by algae in the North Sea is partly replenished by an influx of CO_2 from the atmosphere. Upon demise of the bloom, the algal debris settles into deeper waters of the North Sea. There the organic debris is respired by bacteria, this leading to extra CO_2 within the deep water layer. Next this deep water layer comprising the extra CO_2 is exported by a subsurface current into the deep Atlantic Ocean. The overall 'continental shelf pump' takes up anthropogenic CO_2 from the atmosphere. Four cruises of NIOZ ship Pelagia during one month each, in 4 seasons, each occupied 92 stations and collected ~22,000 pCO_2 data underway in the entire North Sea. Overall a net uptake of CO_2 by the North Sea was found and recently reported in *Science* (Thomas et al., 2004). When extrapolating, all coastal seas worldwide would take up ~20% of oceanic CO_2 uptake. The summer situation has been assessed in detail by Yann Bozec (2005).

Feedbacks of elevated CO_2 on marine ecosystems

Until recently the biological pump in climate prediction scenario's has, by sheer ignorance, been assumed to remain constant over decade to century time ranges into the future. In fact, by the CO_2 invasion into the sea, the pH is dropping and ecosystems respond. The rates of both general photosynthesis, and calcification by corals and various calcareous plankton, already are and will be severely affected by the high CO_2 world. Thus by burning their fossil ancestors we now are harming the modern plankton. The calcifiers get into trouble; shells and corals so characteristic of the sea are at peril. The heavy calcite shells act as ballast for bringing down organic debris, i.e. organic carbon, into the deep sea. Future shifts in production of ballast calcite will shift the efficiency of the biological pump, hence the CO_2 uptake capacity of the oceans.

Changing Chemistry of CO_2 in Seawater

Upon invasion of fossil fuel CO_2 into the oceans, the resulting shifts of above complicated chemical equilibria (2) of the DIC pool can be summarized as follows:

$$[CO_2]_{\text{fossil fuel}} + [CO_3]^{2-} + H_2O \text{ -----> } 2\,[HCO_3^-] \qquad (6)$$

The $[CO_3]^{2-}$ concentration will decrease strongly. For example, when doubling the atmospheric CO_2, the $[CO_3]^{2-}$ concentration will become about half of its present value. Also the pH will decrease and ocean surface waters become more acidic.

Biological Responses

Surface waters of the oceans nowadays are ~6-fold oversaturated for limestone ($CaCO_3$), i.e. the product of dissolved $[Ca]^{2+}$ and dissolved $[CO_3]^{2-}$ is ~6-fold larger than the solubility product

$$K_{s.p.} = [Ca]^{2+} \times [CO_3]^{2-} \qquad (7)$$

and the plankton organisms and corals can happily make their shells and reefs. When the $[CO_3]^{2-}$ concentration becomes half due to reaction (6) with fossil fuel CO_2, the surface waters still would be ~3-fold oversaturated, and the shells and coral reefs could still be produced by the biota. Therefore ocean scientists until recently were not very concerned about this, at least for the near future.

However, recently it was realized the $[CO_3]^{2-}$ concentration directly influences the rate of calcification by the biota. Briefly when the $[CO_3]^{2-}$ concentration is half, the rate of biocalcification would be half of what it is today. This decrease of bio-calcification has been shown in experiments with coral reefs by Langdon (2000). My past student Ingrid Zondervan has shown the same decrease of biocalcification for calcifying single cell algae in context of her PhD thesis work with Ulf Riebesell. This is more or less understandable as briefly explained here. However, unexpected surprises were seen by Tortell and colleagues when subjecting a complete plankton community, collected in the equatorial Pacific, to the high-CO_2 concentrations of the future. Similarly Dave Hutchins observed surprising responses to high CO_2 for a plankton community in the Bering Sea. Both the more or less understandable decrease of bio-calcification, and the surprises found by Tortell and Hutchins, now are reasons for major concern about imminent major shifts in ocean ecosystems.

Engineering the oceans at large scale

(*Why it does not work*)

Several ingenious schemes for by-passing the surface ocean by capturing CO_2 and directly pumping it down into the oceans, as well as fertilization to stimulate the biological pump, have been proposed and are investigated. Feasibility is hampered by technology, economics, and environmental, legal and ethical questions.

Deep Sequestration

Capturing the CO_2 emissions from point sources (power plants, refineries) and pumping this down to 3000m into the deep oceans is seriously investigated. In principle this is technically feasible for point sources, which, however, represent only a minor portion of all CO_2 emissions. The large part of emissions is due to traffic, shipping and airlines. This, in principle, may be improved by implementing a hydrogen economy for traffic, i.e. producing hydrogen fuel at a large power plants which function as point sources of CO_2 emission. However, the cost of deep sequestration is not economical, both in financial terms as well as due to the fact that a significant part (>20%) of the produced energy is dedicated to the deep sequestration alone. The impact on ocean ecosystems would be a shift from surface waters to deep waters, of the above described acidification and decreasing [CO_3^{2-}] concentration. In the most extreme case when routing 100% of fossil fuel CO_2 directly into the deep oceans, both the increase of atmospheric CO_2 and the impact on upper ocean ecosystems would vanish, however, at high financial costs, at the expense of >20% of energy produced, as well as causing the devastation of large parts of deep ocean ecosystems.

Mankind has explored the moon and other planets, but the discovery of ecosystems and biodiversity in the deep oceans of our own planet has barely begun. Deep CO_2 sequestration, in combination with major damage due to increasing deep sea fisheries, would destroy ecosystems which have hardly been discovered yet. Having such poor knowledge still about deep sea ecosystems and their biodiversity, at time of writing it is impossible to fully assess the ecological impact of the deep sequestration option versus the alternative, i.e. the current rapid increase of atmospheric CO_2 and imminent ecological impact on upper ocean ecosystems.

Iron Fertilization

At the end of the 20th century oceanographers discovered that photosynthesis in large parts of the oceans, e.g. 40% of the entire Pacific basin, is limited due to lack of essential trace element iron (Fe). The Southern Ocean is by far the largest such Fe-limited region. Moreover in the ice core record the low CO_2 glacial periods coincide with significant 6-16 fold increases of atmospheric dust input from adjacent continents (South America, South Africa, Australia). This continental dust is rich in iron, and it has been suggested the natural Fe fertilization of the Southern Ocean is a major cause of the low CO_2, hence the low temperature, during glacial periods.

Immediately it was suggested that Fe fertilization might be the solution to the CO_2 greenhouse problem. The extra Fe would stimulate the above described 'biological pump' and all fossil fuel CO_2 would be transported down into the deep ocean via the conduite of algae to sinking organic matter to respired CO_2 in deep waters. Initial laboratory experiments with algae suggested only 1 atom of Fe was adequate to fix some 100,000 to even 500,000 molecules of CO_2 into organic matter. The equivalent of Fe of half a supertanker per year (not the cargo but the tanker itself !) presumably would be adequate to absorb the complete annual fossil fuel emission (6.6 PgC y^{-1}) into the oceans. However, very strong winds also play a role, notably in the Southern Ocean which is notorious with all sailors. By deep wind-driven mixing of the upper Southern Ocean down to depths well exceeding 100 metres, the algae more often than not, find themselves in deep dark waters. There, due to lack of light, they cannot or hardly photosynthesize.

Over the 1993-2002 period this Fe limitation hypothesis has been investigated by 9 *in situ* Fe fertilization experiments. Areas as large as 50 km^2 or even 225 km^2 have been fertilized with dissolved iron. The concentration of dissolved Fe was ~100-fold higher than in ambient, pristine, surface waters. Comparison of the iron experiments shows that maximum Chl *a*, the maximum CO_2 removal and the overall Carbon/Iron (C/Fe) efficiency all scale inversely with depth of the Wind Mixed Layer defining the light environment. In other words, under perfect weather conditions, no wind and a calm flat sea, somewhere in the North Pacific near Japan, the added Fe was most effective in stimulating the blooming of algae, and their uptake of CO_2 from seawater.

Nevertheless, even in such optimal weather conditions, the C/Fe efficiency was only 16,000/1, far less than the initial suggestions of efficiency as high as C/Fe ~100,000-500,000. Moreover, we know that within plankton ecosystems almost all biomass of the algae is consumed again by bacteria and zooplankton. At most 10% of the algal matter sinks out into the deep oceans. Using this 10% for sake of argument, the optimal C/Fe efficiency would accordingly be only C/Fe = 1,600. This still is an optimal efficiency, because the weather was very calm, so the algae nicely remained in the surface layers where they received plenty light for photosynthesis.

For reasons of deep ocean circulation, the Fe fertilization scenario would only lead to long term CO_2 storage when done in the Southern Ocean. However, the Southern Ocean also happens to be the place where strong winds are unfavorable for photosynthesis. For the Fe fertilization experiments done in the Southern Ocean, the C/Fe efficiency was worse due to deep down mixing of the algae largely preventing photosynthesis. The initial CO_2 uptake during 3 Southern Ocean experiments had a C/Fe efficiency of only ~4,300. Again assuming that only 10% of that would eventually sink out into the deep ocean, the overall efficiency for removing CO_2 from the atmosphere would only be C/Fe ~430. During the Last Glacial Maximum, when the natural Fe input into the whole Southern Ocean was 6-16 fold higher, this would still have had a stimulating effect on the net uptake of CO_2 by the Southern Ocean, i.e. could explain at least part of the lowering of atmospheric CO_2 during ice ages. Over the whole region this would actually be very much extra Fe input by massive dust storms. Achieving a similar very high Fe input by large scale artificial fertilization is impossible and far from economical. In other words, at an efficiency of only C/Fe ~430 instead of the first optimistic ~100,000-500,000 one would need some 100-500 instead of just half a supertanker per year to solve the fossil fuel CO_2 problem. Just forget it.

Closing remarks

The invasion of anthropogenic CO_2 into the oceans is 31-48% of fossil fuel CO_2 emissions, slowing down the increase of atmospheric CO_2 and global warming, yet at the same time causing major impact on marine ecosystems of the upper ocean. The continental shelf pump accounts for some 20% of this ocean uptake, i.e. ~8% of fossil fuel CO_2 emissions. Sequestration of CO_2 into the deep ocean only would shift latter ecosystem impact from surface waters to deep waters, but admittedly would slow down or stop the increase of atmospheric CO_2 and global warming. However, it is not economical. Large scale iron fertilization has much lower C/Fe efficiency than initially assumed, hence is impossible.

Last but not least, the science of CO_2 and climate has a long tradition of more than one century. This equals fundamental chemistry which after all was founded in the late 19th century by the same Svante Arrhenius and contemporaries like Van 't Hoff, as recognized with Nobel prizes in 1903 and 1901, respectively. Royal NIOZ has more than 40 years expertise on the oceans in the CO_2-climate problem. The state-of-the-art of the worldwide ocean carbon cycle expert community is merely summarized here. Undoubtedly, mankind has entered the unique future of the 'Anthropocene' era (Crutzen, first Nobel prize in recognition of environmental chemistry, jointly with Molina and Rowland).

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Symposium on The Ocean in a High-CO_2 World at 10-12 May 2004 in Paris, France
Co-sponsored by Scientific Committee on Oceanic Research (SCOR) and Intergovernmental Oceanographic Commission (IOC-UNESCO):
http://ioc.unesco.org/iocweb/CO2panel/HighOceanCO2.htm

– Caldeira, Ken, *Global model predictions of ocean chemistry changes for scenarios of atmospheric CO_2 emissions, atmospheric CO_2 stabilization, and ocean CO_2 injection.*
– Hoegh-Guldberg, Ove, C*hemical and biological effects on corals in a high-CO_2 world.*
– Riebesell, Ulf, *Phytoplankton in a high-CO_2 world: Biological responses and their biogeochemical implications.*
– Baar, Hein de, *Summary of iron-enrichment experiments.*

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Clean fossil fuels

Summary

Energy consumption in the world amounts to 325 EJ in 2000 and is expected to grow with 1.5% per year in the coming decades (IEA, 2000). Fossil fuels, hydrocarbons and coal, are forming 80% of the primary energy consumed. In total 24 Gton of CO_2 and huge quantities of thermal heat are emitted each year into the atmosphere (WEA, 2000) causing the worldwide rise of CO_2 concentration and temperature. A variety of climate policy measures are taken by governments in order to stimulate the reduction the emissions of CO_2 and heat into the atmosphere. In order of priority: transition to renewable or nuclear energy resources, improving energy efficiency and CO_2 capture and storage. CO_2 capture and storage, also known as clean fossil fuels, is considered to be very important in the transition period in the future towards a sustainable energy mix, mainly consisting of renewable energy resources. Major reductions of CO_2 emissions up to 40% can be achieved at large scale energy consuming sites (power stations, cement and steel industry). Distributed CO_2 emissions from fossil fuels (cars, heating) can only be avoided by centrally converting fossil fuels to hydrogen with CO_2 capture. Worldwide and European storage capacity inventories (PEACS, GESTCO) have indicated that geological CO_2 storage is the best option for cost effectively storing the large volumes of CO_2 produced each year. Current CO_2 storage sites (Sleipner, Weyburn, K12-B, Katowice) indicate that CO_2 storage is safe and that geologically stored CO_2 can be monitored. When emission trading will be further endorsed and accepted in Europe the development of geological storage facilities might become a booming business as for storing 5% of worldwide emitted CO_2 requires 1000 Sleipner field facilities. In the coming decades the Netherlands could become an important player in CO_2 capture, transport and storage due to its favorable geological and energy infrastructural position.

Introduction

Energy consumption in the world amounts to 325 EJ in 2000 and is expected to grow with 1.5% a year in the coming decades (IEA, 2000). Fossil fuels, mainly hydrocarbons and coal, are forming more than 80% of the primary energy consumed. Although oil and coal consumption is expected to stabilize gas consumption is growing at more than 3% a year.

In total 24 Gton of CO_2 and huge quantities of thermal heat are emitted each year into the atmosphere (WEA, 2000) causing the worldwide rise of CO_2 concentration in and temperature of the atmosphere (climate change). In the Netherlands alone 200 Mton of CO_2 is emitted. It is held responsible for growing risks of flooding of coastal areas not well protected and flooding of rivers due to the enlarged amount and variability of rainfall. At the same time other areas are expected to suffer from droughts due to a diminishing amount of rainfall. The rising temperature also effects ocean temperature and shrinking icecaps (Figure 1, NASA).

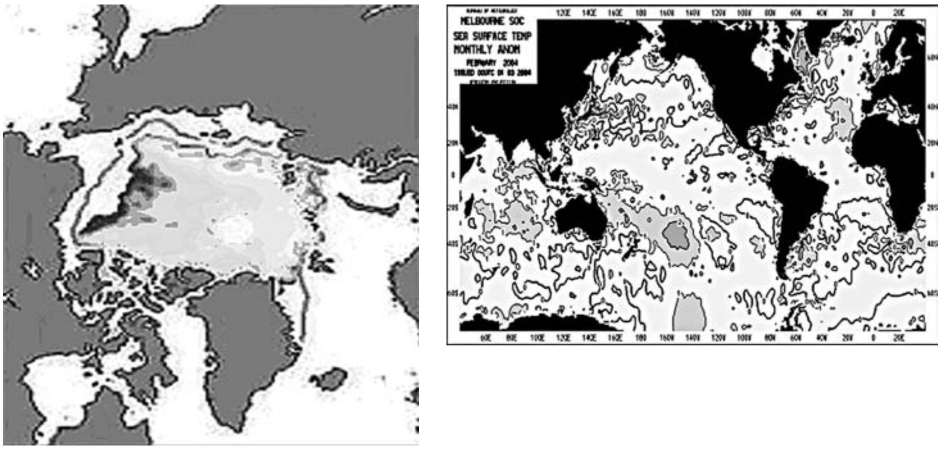

Fig. 1. Shrinking icecap (a), map of raised monthly ocean temperature (b) (NASA)

Concerning the CO_2 emissions an increasing amount of CO_2 is dissolved in ocean waters which can have a negative impact on marine life (Figure 2, Caldera and Wicket, 2003).

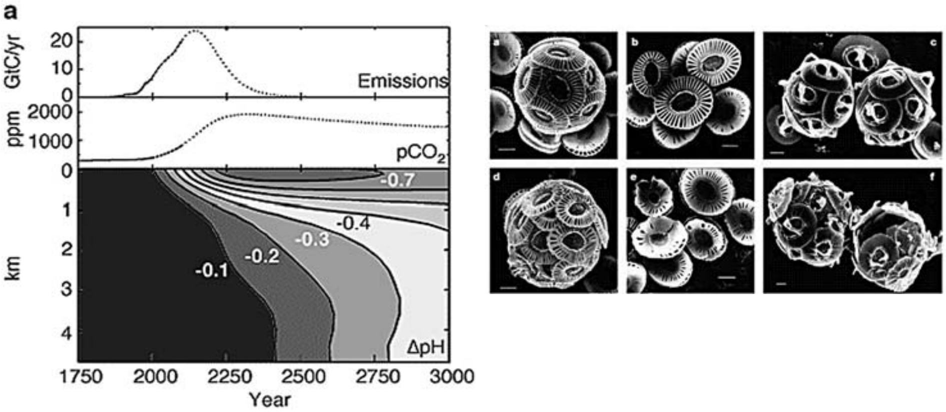

Fig. 2. CO_2 concentrations (a) and impact on marine life (Caldera and Wicket, 2003 and Ribersell et al., 2000).

Clean fossil energy policy

Worldwide many governments are convinced (Kyoto protocol) that sustainable energy policies are needed. Apart from policies aimed at avoiding unnecessary energy consumption or increasing nuclear energy resources energy policies are targeted at: energy efficiency (not wasting energy), renewable energy use (energy from natural fluxes) and making fossil fuels cleaner (avoiding CO_2 and heat emissions into the air). Energy efficiency is focused at reducing or reusing energy losses (heat). Examples are district heating systems using waste heat from industry and power plants or reducing electricity consumption by electrical devices. Renewable energy systems are capturing energy from natural fluxes: wind from air fluxes in the atmosphere, water from water fluxes in rivers or tides and solar and geothermal energy from radiation and heat fluxes.

This paper focuses on the technical and socio-economical aspects of CO_2 capture and storage, also known as the clean fossil fuels policy. This policy is connected to power and hydrogen production.

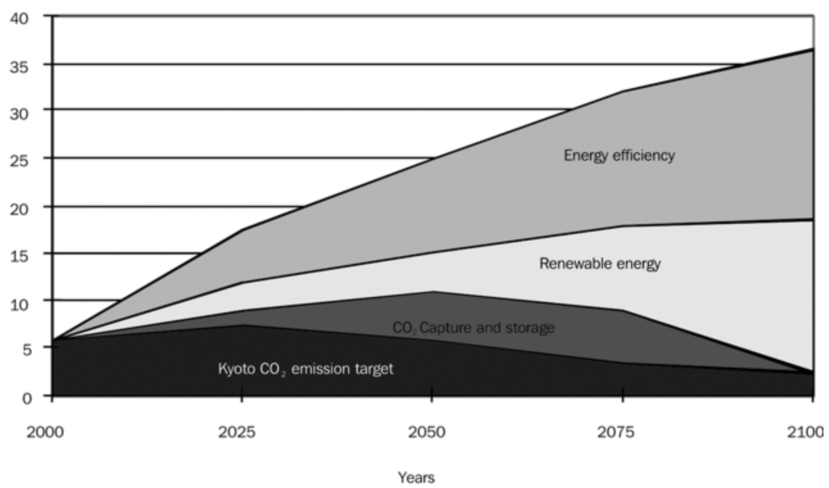

Fig. 3. CO_2 emission reduction policies (after Turkenburg, 2002).

CO_2 capture and storage techniques

According to IEA-GHG (2000) CO_2 is emitted in large quantities at local point sources, such as power plants and the steel, cement and chemical industries. These emissions are responsible for more than 40% of all CO_2 emissions. The rest of the CO_2 emissions are diffuse, coming from car, boat and airplane transportation systems (25%) and heating and cooling of building (25%) and small industries and agriculture (10%). CO_2 can be captured before it is emitted into the atmosphere. The capture process is the most economical at point sources, such as in electricity generation in power plants or hydrogen production by reforming fossil fuels. The diffuse CO_2 emissions could only be avoided when hydrogen would be used in the diffuse systems. The hydrogen could in that case come from renewable or nuclear energy sources but most likely for the first 50 years from hydrogen plants where it is produced together with CO_2 by reforming fossil fuels.

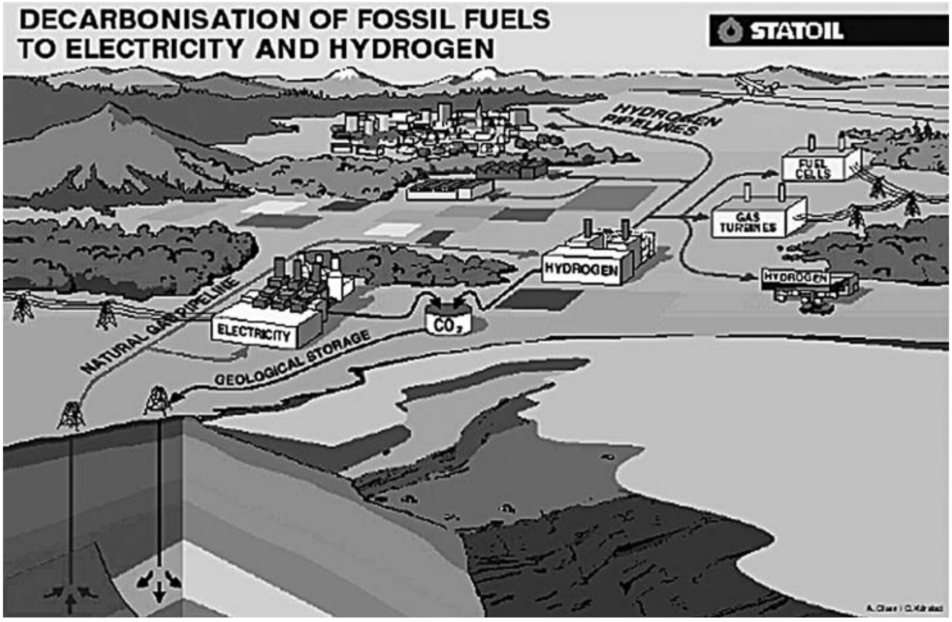

Fig. 4. CO_2 capture and storage infrastructure for decarbonised fossil fuel use for clean energy carriers, such as electricity and hydrogen.

The three basic capture techniques in electricity generation are: firstly post combustion capture, where CO_2 is removed from flue gases also including N_2 and other gases, secondly pre-combustion capture, where fuels are converted into hydrogen to be combusted resulting in H_2O and thirdly oxy-fuel, where air is converted into pure oxygen to be used in the combustion processes, resulting in a stream of pure CO_2. Several techniques are known, but not designed for capturing large quantities of CO_2 and therefore expensive (ca. 25-100 euro/ton CO_2 avoided). Summarizing it can be stated that major reductions of CO_2 emissions up to 40% can be achieved at large scale energy consuming sites (power stations, cement and steel industry). Distributed CO_2 emissions from fossil fuels (cars, heating) can only be avoided by centrally converting fossil fuels to hydrogen with CO_2 capture.

The captured CO_2 has to be stored completely, safely and without any negative effects to the environment. It can be either stored into the oceans or in the subsurface. The most attractive option is geological storage as it is safe and environmentally the safest. The geological storage options include: empty oil and gas fields or aquifers and coal beds. Storing it in oil and gas fields may even create a benefit from the enhanced production of oil or gas which can be achieved. Storage in aquifers offers large volumetric potential and no interference with hydrocarbon production. Storage in or under coal beds has the additional advantage that CO_2 is preferently adsorbed to the coal and therefore decreasing leakage potential. Current CO_2 storage sites (Sleipner, Weyburn, K12-B, Katowice) indicate that CO_2 storage is safe and that geologically stored CO_2 can be monitored. The costs for geological storage may vary from 2-50 euro per ton CO_2 avoided.

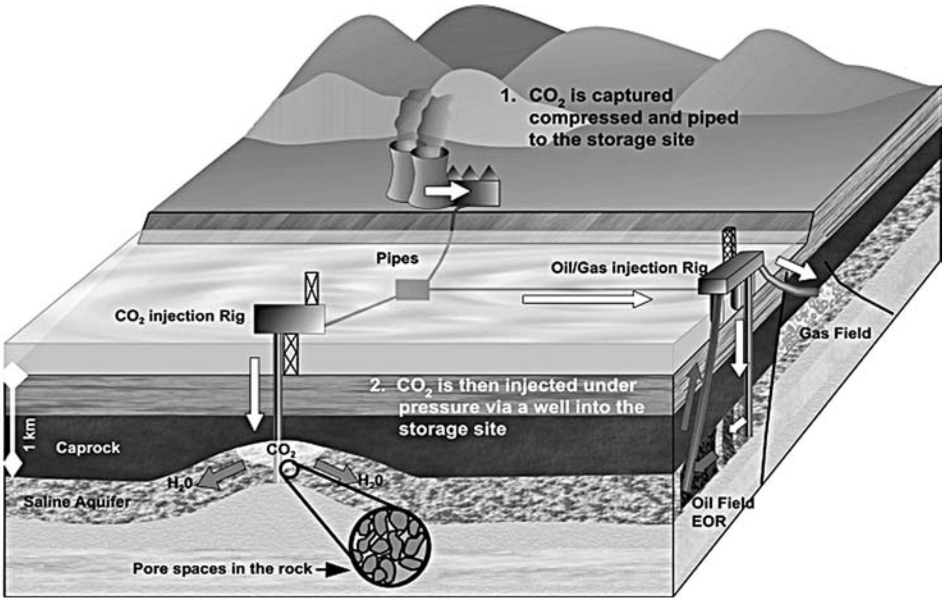

Fig. 5. Geological CO_2 storage options (Benson, 2004).

Transport of CO_2 from the capture facilities to the geological storage facilities depend very much on the distance and existing infrastructures. The cost for transport rage in the order of 3-10 euro per ton CO_2 transported over 100 km.

CO_2 capture and storage capacity worldwide and in the Netherlands

CO_2 capture and storage only makes sense when sufficient storage potential is present. Worldwide and European storage capacity inventories, Peacs project (IEA GHG, 2003, van Bergen, 2004) and GESTCO project (Christensen, 2004), have indicated that geological CO_2 storage capacity is sufficiently available (worldwide 100-10.000 Gton CO_2) for storing all CO_2 produced each year worldwide. This means that storage resources are sufficient for more than a hundred years of 50% of all worldwide CO_2 emissions. The largest contribution for storage capacity comes from aquifers pore space even though the volumetric estimates for aquifer storage still vary widely (> factor 10). This uncertainty is due to lack of information on aquifer systems. The second largest capacity is the sum of emptied gas fields. The capacity for gas fields is huge, but due to the fact that CO_2 molecules are larger than methane molecules, more space is needed to store CO_2 created by gas produced. Oil fields volumes and coal beds are smaller but attractive as oil recovery could be increased by injecting CO_2.

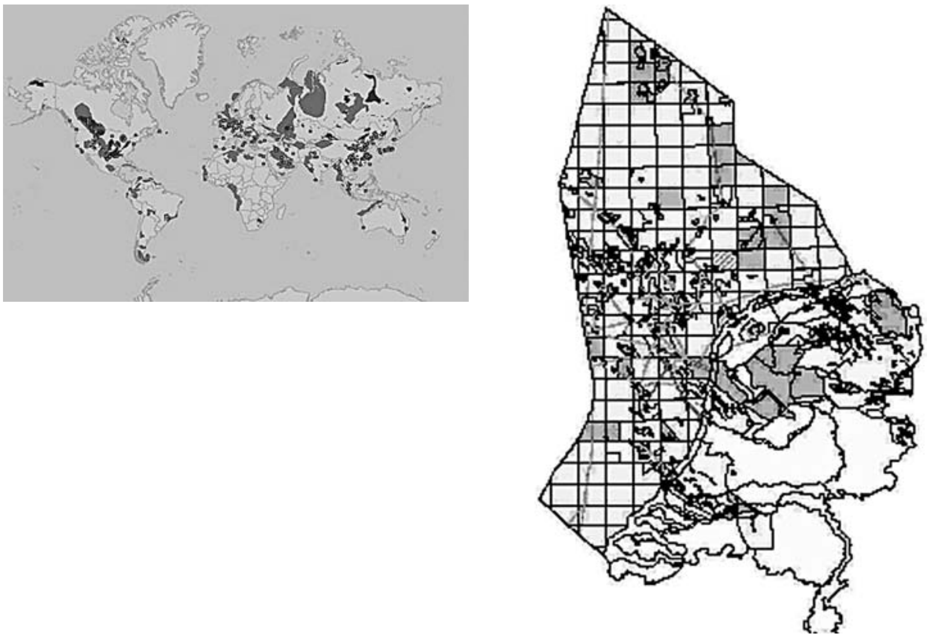

Fig. 6. Areas suitable for geological CO_2 storage: (a) worldwide (van Bergen, 2002) and (b) gas fields in the Netherlands (Ministry of Economic Affairs, 2004).

The geological storage capacity in the subsurface of the Netherlands is relatively large (ca. 8-15 Gton). The most interesting option from both a technical and economical point of view for the Netherlands is storing CO_2 in the (empty) gas fields. The storage capacity for the Groningen gas field could be ca. 6 Gton of CO_2; the storage capacity for the smaller, non Groningen, gas fields is estimated to be 1-2 Gton. In figure 7 it is shown that many smaller fields and their infrastructure become available for CO_2 storage starting in 2005 being able to store 0,1 Gton of CO_2 per year, which equals 50% of all CO_2 emitted in the Netherlands.

Reserves of CO_2 storage capacity

It is important to realize that storage capacities referred to are defined without socio-economic criteria. The reserves of storage capacity are defined as the capacities available to economically store CO_2 with currently low CO_2 storage prices. These prices vary in time and place depending on CO_2 tax regimes and CO_2 emission trading schemes. Currently CO_2 prices vary between 0-10 euro per ton CO_2 avoided. At the moment CO_2 storage prices outweighs their costs in only a few occasions.

The total cost for avoided CO_2 is determined by sum of capture, transportation and storage costs. Typically capture costs vary, 25-75 euro for power plants. Early opportunities to get CO_2 exist where pure CO_2 streams are present, such as existing CO_2 separation facilities at gas production sites, refineries and fertilizer plants. In those cases no capture costs occur. Transportation costs are very much dependent on the transportation distance. Typically the costs for transporting a ton of CO_2 over a distance of 100 km are estimated at 1 euro. The storage costs vary, 1-4 euro per ton, assuming that the geological storage facilities required, such as wells, are applied to store a minimum of 0.5 Mton.

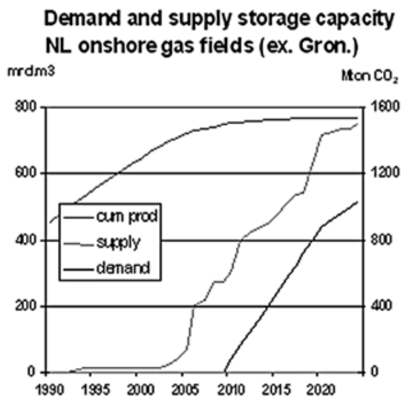

Fig. 7. CO_2 storage capacity of empty gas field becoming available in the coming decades (Breunese, 2004).

There exists an enormous business opportunity for the Netherlands to become a hub in a possible future CO_2 capture, transport and storage network. The country has large storage potential both on and off shore, a large gas transportation infrastructure, as well as many CO_2 emissions inside and relatively close to the Netherlands. Rotterdam could be the main European transfer station for bringing onshore produced CO_2 (from the Netherlands, Germany, Belgium, France) to offshore oil and gas fields in the North Sea. In addition there is a large knowledge base for gas treatment and transportation. It will all depend on the price of CO_2, but it is wise to be prepared for this scenario. When emission trading will be further endorsed and accepted in Europe the development of geological storage facilities might become a booming business, as for storing 5% of worldwide emitted CO_2 requires 1000 Sleipner fields and their facilities.

Performance, safety and environmental aspects

The performance and safety of CCS infrastructure, CO_2 capture, transport and storage facilities, must be assured during the use and operation of these facilities. The fate of CO_2 stored in the subsurface is another issue, where long term environmental risks have to be managed. Many regulations exist to manage performance as well as risks of CO_2 leakage at facilities processing and transporting pure CO_2. They are operational at numerous refinery and fertilizer plants. In the USA 2500 km of pipelines are operational for many years without any significant accidents. Typically it can be stated that the performance and safety risks associated to CO_2 infrastructures are comparable or smaller than those of gas infrastructures. Similar verification and inspection procedures, adapted to CCS, can be applied.

Assessing the long term behavior and associated environmental risks of CO_2 in the subsurface, for a period of 1.000-10,000 years, is a more complex issue. Typically all risks have to be assessed in advanced, be monitored and mitigation actions defined during the whole operational life cycle as well as way beyond that period.

Various risk assessment exist. Typically an extensive qualitative risk assessment is carried out as a first step including the identification of all known risks, the expected environmental (and safety) impact and assessment of the probability of occurrence of each or a combination of risks for the complete subsurface system (wells, reservoir, overburden, fresh water aquifers, soil, water and atmosphere). The most likely risks are quantitatively modeled using comprehensive modeling techniques capable of making quantitative predictions of subsurface CO_2 concentrations and fluxes over periods of 1.000-10.000 years for subsurface formations and at the ground surface.

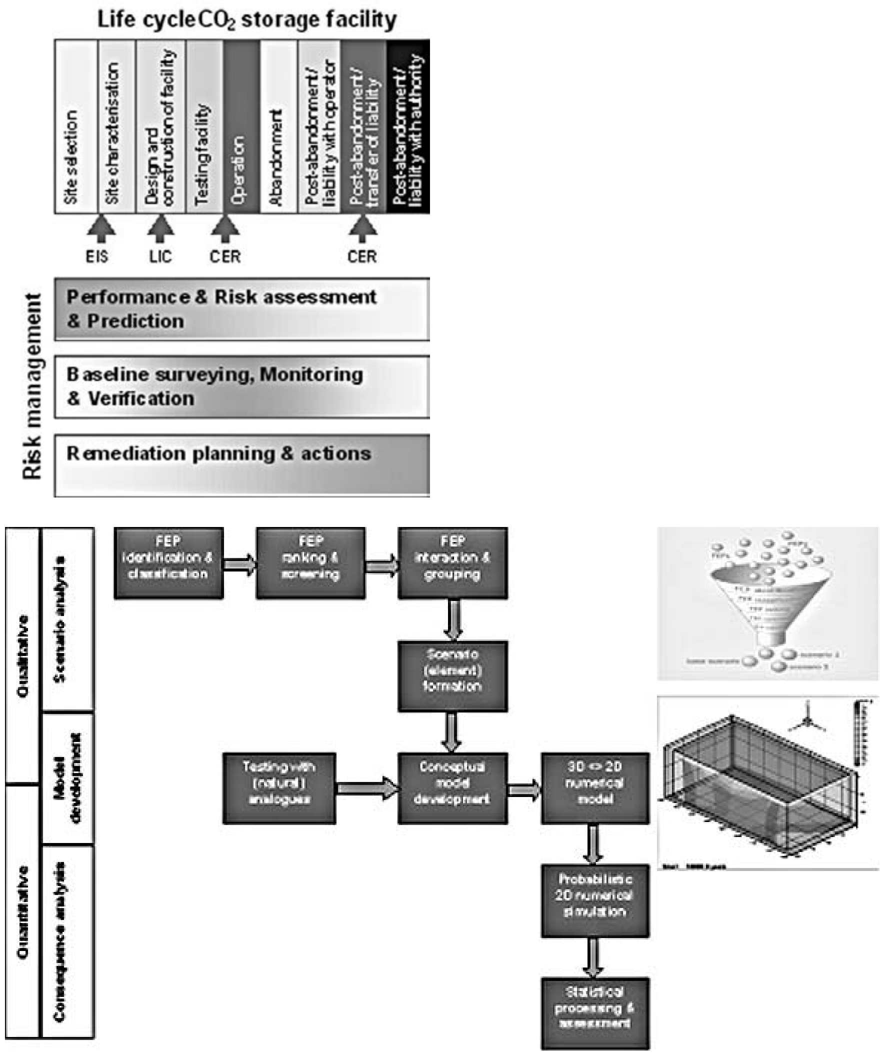

Fig. 8. Risk management: (a) scheme of risk management processes in lifecycle of CO_2 storage site, (b) risk assessment methods.

Based on the most likely migration routes monitoring systems can be designed for checking any leakage at those routes. Main risks occur near the well trajectory, possible faults or leaking sealing formations. Monitoring focuses therefore at the well using various logging techniques, seismic imaging capable of seeing CO_2 migration at large depth either through a seal or along wells or faults. As a reserve option shallow subsurface or surface monitoring techniques can be applied.

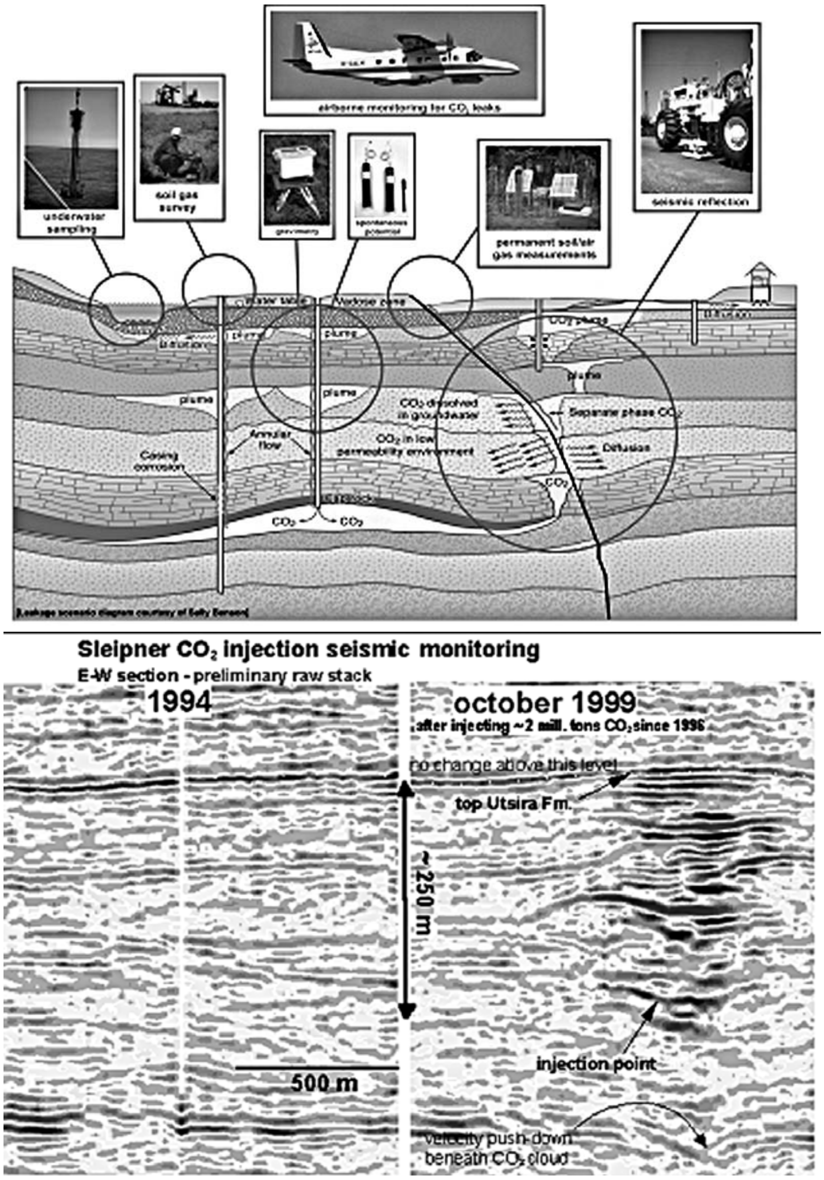

Fig. 9. Monitoring: (a) schematic overview of monitoring targets and methods, (b) monitoring methods.

Despite the fact that all CO_2 storage sites have not shown any leakage risk assessment, monitoring and mitigation is continuously being improved in order to be able to more accurate and cheaper in predicting and controlling any CO_2 leakages. Responsibilities and liabilities concerning the handover of a CO_2 storage sites from an operator company to a governmental agency are not yet clearly defined. This depends also the perception of remaining risks after abandonment of the facilities and on the question of how often monitoring should happen over 100 year time periods.

Emission of heat

A separate remark has to be made about heat emissions. The author believes that avoiding CO_2 emissions by capture and geological will not completely solve the climate effects for 100% as also direct heating effects will remains in the clean fossil fuel scenario's. It is therefore important to also reduced heat emissions. The brief explanation is that we assume that 50% of all energy consumed (160 EJ) ends up in heat the available heat is accumulated over the last 150 years is 8000 EJ. This amount of energy is sufficient for directly heating the atmosphere, hydrosphere and geosphere with 0.1-0.3 degree.

Conclusions

Fossil fuel energy can be made cleaner by CO_2 Capture, transport and geologically Storage (CCS). There are no technical, safety or verification obstacles. One of the remaining issues is to further build confidence in geological storage by establishing environmental monitoring and mitigation procedures and by transparently sharing experiences from existing geological storage sites.

The main remaining issue for CCS is the business model, as the extra costs have to be incorporated in the consumer price for fossil energy. This is waiting on public acceptance and the development of a CO_2 marker driven by the emission trading system or other eco-tax systems. When this scenario evolves the Netherlands and especially Rotterdam might become an important hub in the future CO_2 infrastructure, creating new economic activity in the energy sector.

Acknowledgements

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I am also grateful for the many sponsors of the executed work: national funds of the ministries of economic affairs and spatial planning and environment, the EU DG Research and industry, especially Statoil, Shell, Gaz de France and BP.

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BERT DE VRIES

Wind, solar and biomass: Their role in a sustainable future

Introduction

Since the 1970s numerous assessments have been made of the potential of renewable energy sources wind, solar and biomass-derived fuels. Assessment methods and coverage have been improved. Recent work at Utrecht University and MNP-RIVM has used the spatial data of the IMAGE-model and other data bases to construct a global assessment of the technical, geographical and economic potential of renewable sources (wind, electricity from solar photovoltaics – PV, and fuels and electricity from biomass).

To this purpose a generalized methodology has been set up. First, the technical potential is calculated and constrained by (competing) land use considerations to give the geographical potential. Next, a long-term supply cost curve is constructed for a generalized set of techno-economic parameters. For electricity from wind and solar-PV, a tentative calculation is made of the additional costs due to transport and supply-demand mismatch. For biomass the costs of conversion into automotive fuel or electricity are estimated. The results give a fairly solid impression of the role which renewable energy sources can play in the world energy system and of their potential contribution to the reduction in [the growth of] greenhousegas emissions.

The definition of potential is based upon the introduction of constraining factors. The geographical potential indicates the land availability and suitability – onshore only as offshore areas are not considered. Estimating the fraction which can technically be produced in the form of on-site electricity or biomass yields the technical potential. Including various factors which influence the cost at which energy can be produced on-site and/or at the conversion or demand site, such as plant size, interest rate, conversion rates and distance from load centers, gives the economic potential in the form of a long-term supply cost curve. Finally, one can explore the various social and cultural constraints in order to establish the implementation potential. The four potentials are not fully independent. Moreover, they change over time due to the dynamic influences of, for instance, technological breakthroughs and learning-by-doing and changing land use patterns and prices.

The results for windpower indicate that the technical potential easily exceeds the present world electricity use. However, there are large uncertainties. Some of these can be estimated from stylized facts, such as the variety in wind regimes and the role of scale effects. Others, however, are highly dependent on the larger societal developments, such as the actual availability/suitability of land area for windturbines or biomass plantations and the density with which windturbines or solar PV panels can be placed. Figure 1 shows the extent to which these two parameters alone influence the worldwide economic supply cost curve c.q. potential. Similar estimates have been made for electricity from PV which is at present still much more expensive.

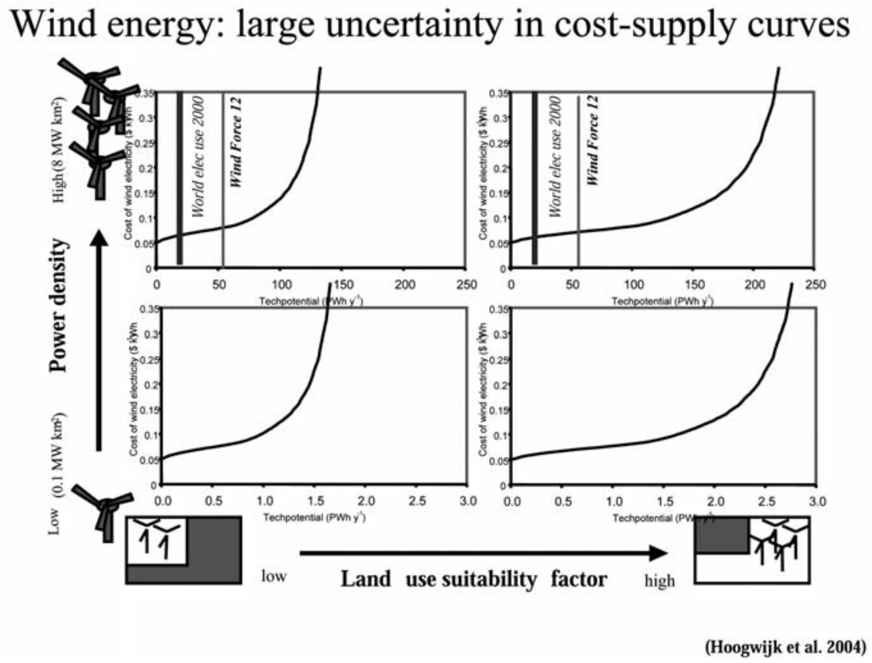

Fig. 1. The global supply cost curve for electricity from wind for four extremes regarding the land use suitability and the accepted turbine density. Note the difference in horizontal scale (Pwh/yr = 10^{12} kWh/yr).

For the potential role of energy from biomass, either as electricity or transport fuel, we have used the greenhousegas emission scenarios constructed with the IMAGE-model, the so-called SRES-IPCC scenarios. From these, the amount of land no longer used for agriculture ('abandoned land') due to intensification and the amount of low-productive and restland. For these areas, different for each of the four SRES-scenarios, the worldwide technical potential for 'energy crops' is calculated on the basis of yields (in ton/ha) as derived for the 0.5° x 0.5° grid cells in the IMAGE-model. In this way, the trade-off with land-for-food is implicitly taken into consideration.

Estimation of the capital and labour costs allows the calculation of the average biomass production costs as shown in Figure 2. The data have also been converted into regional supply cost curves. One of the conclusions suggested by these results is that one of the more interesting options for Europe to reduce its (growth in) greenhouse-gas emissions is to import (crude or processed) biomass from Eastern Europe and the former USSR as well as from South America and Africa. This option is particularly promising in a world with open markets, stabilizing world population and carbon emission ceilings.

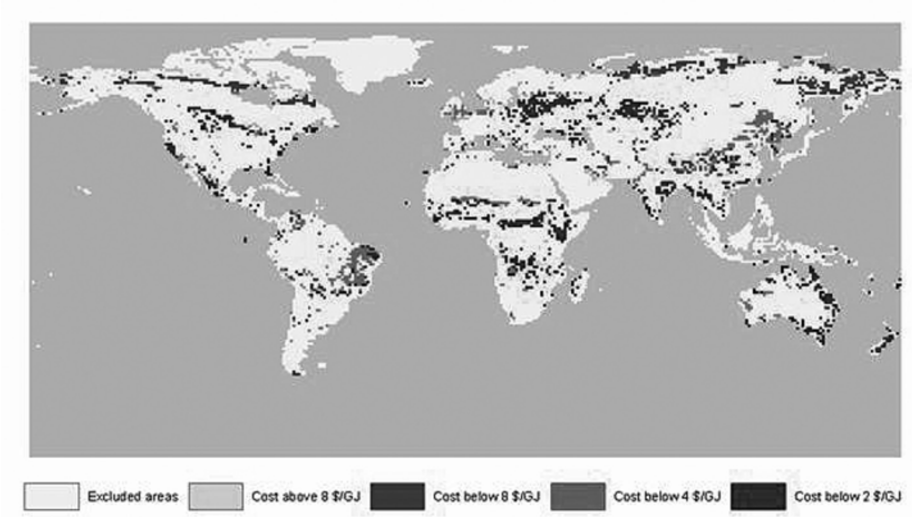

Fig. 2. The places in the world where biomass ('energy crops') could be produced and the average cost with which it might be produced assuming no learning effects.

A proper assessment of the role of energy from wind, PV and biomass requires the implementation of the supply cost curves into an integrated assessment (energy) model such as IMAGE/TIMER (De Vries et al. 2001) or POLES (www.upmf-grenoble.fr/iepe/). Even then, however, there remain major uncertainties. In essence these concern three aspects:

- Energy supply security: what will be the availability and cost of the dominant energy carriers of the present i.e. oil and gas?
- Climate change: how serious will climate change and its impacts be and how and when climate-related policy will start to influence energy supply?
- Population and economic growth: which role employment, consumer habits, market deregulation and technological innovations will play?

These developments are hard or impossible to predict. However, they will have a large influence on societal acceptance of renewable energy sources and their alternatives (such as nuclear power) and on their cost (innovations, subsidies).

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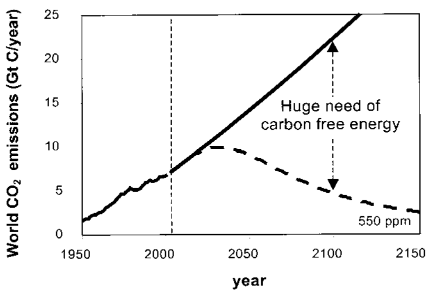
MARC BEURSKENS

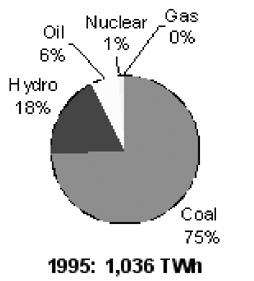
The future of fission and fusion

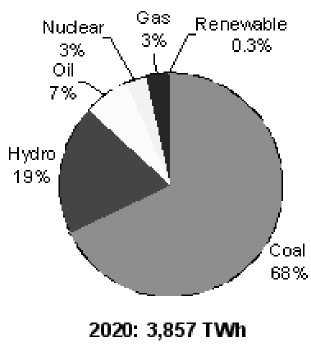
Introduction

The energy problem is urgent and complex. *Security of supply* in Europe is decreasing rapidly. Currently European dependence on imports of fossil fuels is 50%, whereas in 2030 this dependence will have increased to 70%. World oil production is expected to peak between 2010 and 2035. In addition reserves can be found only in limited areas of the world, which increases political tensions (EU, ASPO, USGS).



Climate change requires immediate action. On the short term it involves a mere change in trend, reflected in the targets represented by the Kyoto protocol. On the longer term, however, drastic changes in the energy system are required. Stabilization of greenhouse gas concentration in 2100 at 550 ppm requires emissions to roll over around 2030 and to steadily decrease afterwards (IPCC). Industrialized countries will have to reduce their annual greenhouse gas emissions by over 50% in 2050.





Despite economic growth in development countries *energy poverty* is not decreasing. In 2030 the number of people without electricity is estimated at 1.4 billion compared to 1.6 billion now. The number of people dependent on traditional biomass will have increased from 2.4 billion now to 2.6 billion in 2030 (IEA, energy and poverty 2002).

Currently 80% of world energy consumption is based on coal, gas and oil. Moreover, world energy consumption is expected to double by 2050 and to triple or quadruple by 2100. Especially in fast developing countries like China and India the increase in energy demand in very rapid. For China it is expected that the demand for energy will double and the demand for electricity almost quadruple in the period between 1995 and 2020. The pie charts to the right show the worrying fact that the fuel mix that is to sustain this growth will hardly change. However, China is currently the second largest CO_2 producing country. If its energy structure does not change, the CO_2 emission of China will increase by a factor of two within the next 20 years. This will certainly have a big impact on the global environment.

There is no single sustainable energy source that can presently take over the role of fossil fuels. Energy scenarios foresee a mix of many different energy sources, with different characteristics. Energy saving programs and the implementation of renewable energy need to be stimulated strongly, but may not be able to cover the full demand. Clean coal technology combined with carbon sequestration technology could fill in the gap until truly clean energy technologies have been developed. Nuclear energy can also provide carbon free electricity and enhance security of supply. The possible role of nuclear fission and fusion will be described in this paper.

Nuclear fission

Currently nuclear fission covers roughly 6% of the world's energy demand, and this number has not increased over the past decades. After the glory years of fission in the sixties and seventies the growth has stagnated because public acceptance of this energy source decreased. The lack of public acceptance is tied closely to three specific issues of 1) safety, 2) nuclear waste and 3) weapons proliferation. A fourth issue that is often mentioned as a cause of slowdown in fission plants construction is the economics of large scale 0.5-1GW capital intensive power plants.

The current global growth rate of fission plants is of the order of 5-10 new plants per year[1]. However, to cover only the annual growth in global energy demand, at least a hundred new fission plants should be build every year. Clearly at the current growth rate the share of fission power in the world energy production will steadily decline.

All four issues above are related to public acceptance and will have to be dealt with to boost the fission plant production rate. Currently a large international research enterprise is under way that is called the Generation IV initiative[2] that is trying to do just that. The aim is that Generation IV nuclear power plants are inherent safe, have reduced their nuclear waste lifetime from hundreds of thousand of years to 300-1000 years, are proliferation resistant and are smaller scale and highly competitive. It seems that technically it is possible to create small-scale (100 MW) inherent safe plants that produce relatively short-lived waste (<1000 years), although it may be hard to achieve. However, because these types of plants will require enriching and breeding of nuclear fuels, the illicit distribution of nuclear materials will be hard to control and proliferation will remain a problem.

Fusion

Fusion powers the sun and the stars. In the fusion process, two light nuclei fuse together to form a heavier one, and during this process a lot of energy is released. The

[1] Source: Tim Van der Hagen, IRI, Delft

[2] The Generation-IV Initiative is a collaboration of the following countries: Argentina, Brazil, Canada, France, Japan, Republic of South Africa, Republic of Korea, Switzerland, United Kingdom, the US and the EU

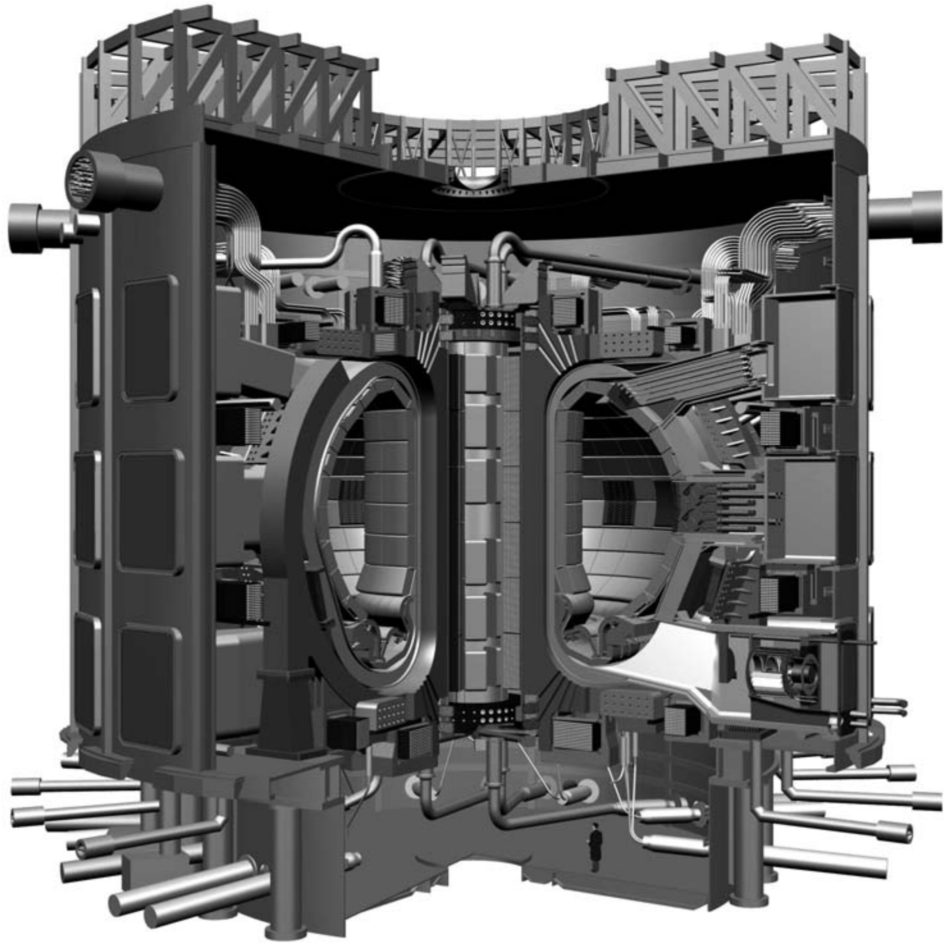
heat can be used to power a fusion power station with a typical size of 1000 MWe, or be used to produce hydrogen. Fusion has the potential to play a key role in long term, base-load electricity production. Fusion fuels are cheap and evenly distributed on the Earth, and there are no significant constraints on resource availability even for an extensive use of fusion energy over centuries. The reaction that runs best here on earth is the reaction between two isotopes of hydrogen: deuterium and tritium. This reaction runs at a temperature of 150 Million °C.

Fusion is inherently safe: in a future fusion power plant there is no possibility of uncontrolled power runaway since inherent physical processes limit power excursions of the plasma. Moreover, the plasma vessel of a fusion reactor will only contain enough fuel for a relatively short burning time – a couple of minutes at most. As fusion is not a chain reaction, the process just stops if no more fuel is added. Even in the case of a total loss of active cooling, melting of the reactor structures is excluded due to the low density of decay heat of the materials present in the reactor. The safety and environmental friendliness of fusion are largely based on the passive and inherent features of the design, rather than on highly reliable safety systems. Even in the worst possible in-plant driven accident scenario, the risk to the general public would be below the level at which evacuation would be required.

The fusion fuel cycle does not involve any input of radioactive material and there is no radioactive waste associated with spent fuel. Radioactivity is present in the intermediate fuel, tritium, which is produced inside the power plant from lithium. Therefore there is no radioactive fuel cycle outside the power station. The radiotoxicity of the activated materials generated by fusion reactors during their lifetime will only last for approximately one hundred years, after which it is comparable to the radiotoxicity of the ash from coal power stations. Unlike nuclear fission, therefore, fusion waste would not constitute a permanent burden for future generations.

The R&D strategy of the European Fusion Programme has been successfully based on work with a single, large, central facility, complemented by a number of specialized small and medium-sized devices run by more than 20, also non-EU, individual member states. The central facility is the Joint European Torus (JET), a tokamak experiment approved in the 1970s, began operations in 1983 and is currently planned to continue until 2006, and operation is most likely extended until 2010.

JET has produced significant fusion power in deuterium/tritium plasmas for up to 16 MW for a few seconds. However, the input power required to achieve these conditions was 25 MW. In these experiments JET has demonstrated that fusion devices can be operated safely with radioactive tritium fuel and that radioactive structures can be maintained and modified using remote handling techniques. The reason why JET cannot produce net energy output is simply because the device is too small. The energy confinement of JET is not good enough to confine the heat of the fusion plasma long enough in order to have sufficient fusion reactions. A simple solution to this problem is to construct a device that is bigger. Namely, the heat loss scales with linear dimensions of the reactor, whereas the energy confinement scales with the third power of these dimensions.



ITER

The world fusion community is now ready to take the 'Next Step' of constructing a twice as large device, which will produce burning plasmas under reactor conditions of high power gain and provide a reliable basis for proceeding to a demonstration reactor, capable of producing electricity. The design of a 'Next Step' is being carried out within the framework of the ITER collaboration between the EU, Japan, Russia, China, South Korea and the United States. The current design is a cost-effective tokamak, which could allow the study of burning plasmas under physics conditions that can be extrapolated to a power plant. Important reactor technologies are integrated in ITER. The ITER participants now have to approve the construction of the machine and select the site where this international project will be constructed. Both the EU and Japan want to host this new experiment, and final discussions on site selection are underway.

In parallel to the realisation of ITER, technological progress is required in several areas, especially in the development of plasma-facing materials sustaining high heat loads and of low activation structural materials, the latter to reduce the quantity of radioactive waste from a fusion reactor. There are still numerous challenges ahead if fusion is to become an energy source of the future. For instance, after ITER, in which the conversion of fusion produced heat to electrical power will not be addressed, an additional step (DEMO) will be needed to demonstrate that an efficient production of electricity from fusion is both practicable and compatible with a low environmental impact. If politicians give their backing and take the necessary decisions at the appropriate time, DEMO, the first electricity generating fusion power plant, will be ready in about 35 years from now.

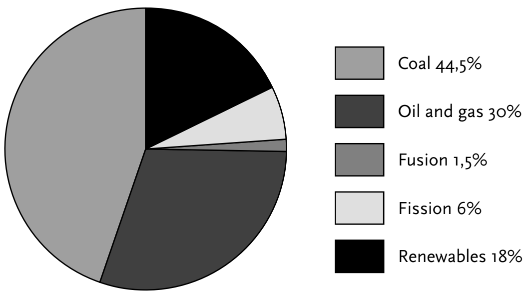
The role of fission and fusion

Will fission and fusion play a role in the future energy mix? Both technologies have the great advantage that they do not emit greenhouse gasses. Additionally they could contribute to the diversification of a future energy system and enhance security of supply. Both technologies are complex and will therefore be mainly suited in developed countries. A nuclear power plant will not be the most obvious solution in rural Africa to reduce energy poverty. However, the largest growing economies in the world like China and India already have a very high standard of education and a well-developed knowledge base.

Nuclear fission suffers from low public acceptance. Nuclear waste reduction, operational safety, proliferation mitigation and plant economy will have to improve significantly for the technology to be acceptable in future energy systems. The Generation IV research program is aiming at improving all of these four factors. Acceptance of new safer types of reactors will depend on the level of progress made on these issues. However, it is also very well possible that public opinion will change in favour of nuclear fission plants because of growing awareness of climate change threats and the need for alternatives to decreasing reserves of fossil fuels. In any case it is true that the current production rate of 5-10 fission plants per year is too low. The production rate of fission plants needs to increase by a factor of 10 for fission to significantly contribute to the future energy system.

Fusion solves many of the problems that fission has regarding safety, waste and proliferation. A fusion power plant will be a capital-intensive power plant with a minimum power output of 1 GW of electricity. Therefore fusion is very suitable for centralised base-load power production. Cost analysis of future fusion power plants show that a fusion reactor will produce electricity at a similar price as that of most renewables. Fossil fuels, and especially coal, will always remain cheaper. However, if the cost of greenhouse gas emissions is included in the price of fossil fuel electricity then future fusion power plants and renewables can compete. For fusion and other renewables to be successful in future energy markets it is therefore essential that a price is attached to carbon dioxide emissions.

However, fusion power plants do not exist yet. An extensive research program is needed to work towards future fusion power stations. ITER will cost €5 billion to build, spread out over a period of ten years and over the six partners. If ITER will be built in Europe, then the cost for Europe will be approximately €2.5 billion over ten years, i.e. €250 million per year. This may seem like a lot of money, but in terms of European energy budgets for research and subsidies it is not a lot. Currently the EU-15 countries together spend €30 Billion annually on energy R&D and subsidies. The entire European fusion budget currently takes up only 1.5% of that. In order to keep the current Fusion programme running and to built ITER over the next ten years, the European fusion research budget should rise to 2.2% of the total budget for European energy support.



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