A global clean fossil scenario
discussion paper

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Publication date:
1997

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Kuemmel, B. (1997). *A global clean fossil scenario: discussion paper*. Roskilde Universitet. Tekster fra IMFUFA No. 342 http://milne.ruc.dk/ImfufaTekster/

TEKST NR 342 1997

A global clean fossil scenario

DISCUSSION PAPER

prepared by Bernd Kuemmel
for the project

LONG-TERM SCENARIOS FOR GLOBAL ENERGY DEMAND AND SUPPLY

financed by the EFP-96 project 1753/96-0002
of the Danish Energy Agency,
project leader: Bent Sørensen

OCTOBER 1997

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TEKSTER fra
IMFUFA
ROSKILDE UNIVERSITETSCENTER
INSTITUT FOR STUDIET AF MATEMATIK OG FYSIK SAMT DERES
FUNKTIONER I UNDERVISNING, FORSKNING OG ANVENDELSER

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OCTOBER 1997

A GLOBAL CLEAN FOSSIL SCENARIO, DISCUSSION PAPER

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IMFUFA text 342, 169 pp ISSN 0106 6242

Abstract:

This discussion paper contains a preliminary sketch of a global *clean fossil scenario* for year 2050, meaning a scenario using fossil fuels without contributing to greenhouse warming, achieved by removing the carbon either from the fuels or from the flue gases.

The scenario is produced as part of a project performed for the Danish Energy Agency, in which four scenarios dealing with greenhouse mitigation options are under consideration. The other three are a *safe nuclear* and a centralised or decentralised *renewable energy* scenario.

The project is scheduled to finish by the end of 1998, so by disseminating the present fossil scenario sketch as a discussion paper we hope to attract comments and suggestions, that may assist us in selecting the final features of the scenario.

Preface

The scope of the project *Long-term scenarios for global demand and supply* performed for the Danish Energy Agency under its energy research programme EFP-96 has been outlined in two published papers:

Bent Sørensen: Scenarios for greenhouse warming mitigation, ***Energy Conversion & Management****, vol. 37, pp. 693-698 (1966),* also available as **IMFUFA Tekst** 300/95.
Bent Sørensen: Economic and Environmental choices for achieving stable greenhouse gas concentrations, in ***Renewable Energy, Energy Efficiency and the Environment****, (A. Sayigh, ed.), vol. 2, pp. 1061-1066, Pergamon Press, London (1966).*

Bernd Kuemmel has been employed on this project during the Spring 1997, and has produced the following sketch of one of the scenarios in the project, based on advanced fossil technologies with removal of carbon dioxide and deposition of it at sites considered safe from the point of view of greenhouse warming. The other scenarios consider renewable and nuclear options and are currently being investigated by Peter Meibom and Bent Sørensen.

The project runs until the end of 1998, where final scenarios will have been selected. We therefore invite discussion of the present preliminary work, before it is given its final form. Some of the questions that have occurred to us in connection with the preliminary fossil scenario are the following ones:

Demand assumptions
The scenario of Bernd Kuemmel deviates somewhat from the outline papers in its choice of demand projections for the scenario year, which is 2050. Where the outline papers used a basic needs approach to determine primary energy demands and demands derived from fulfillment of secondary needs (explained in an appendix in the book ***Life-cycle analysis of energy systems*** by B. Kuemmel, S. Krüger Nielsen and Bent Sørensen, Roskilde University Press, 1997), and then measured development in terms of how close the countries were to these goals, the preliminary fossil scenario adds a differentiation based upon economic activity in individual countries. The basis for this is the belief, that energy intensive production will take place in intermediate economies and not in the fully developed economies (due to too high salary levels) and not in the poorest countries (due to lack of skills). This assumption leads to energy use, which is higher in the former Soviet Union countries, in China and in India, than it is in Western Europe, Australia and the United States. In contrast, the outline papers mentioned above assumes a fairly equal distribution of manufacture over all but the least developed countries. The rationale behind this assumption was a belief, that increasing amounts of automation will characterize future industrial manufacture, so that robot technology will provide a "backstop" option taking over when costs exceed a certain level. The mentioned intermediate countries are in the scenario enjoying a high standard towards the end of the period, and thus it may be argued, that by 2050 they have no salary advantage that will warrant transferring manufacture to these regions. Only Africa may be considered for low-salary work with the assumptions made, but this option is not used in the preliminary scenario. It is thus a pressing question whether the basic manufacture should be assumed evenly distributed or as in the preliminary scenario unevenly distributed.

Conversion system
In matching the supply and demand in the clean fossil scenario, Bernd Kuemmel finds

problems that causes him to suggest long-distance transmission of electricity as a way to optimize the system. The reason for this kind of problem, which is often found in connection with intermittent energy supply sources but is rarely of concern for fossil energy sources because of their easy storability, lies in the extensive use of co-production of heat and electricity, through combined power plants and fuel cells. The assumed stiffness in the heat to power ratio is the cause of the problem. In reality, there are many ways of avoiding the problem: use of heat pumps to convert excess electricity to heat (this method was used in the outline scenarios), use of the more flexible heat-to-power ratio in extraction-type plants, and access to local heat stores and/or pure heating boilers. While it is true, that heat pumps may not be appropriate for the coldest regions (e.g. Northern Siberia) because of lack of suitable environmental heat reservoirs, the bulk of load centers will be amenable for heat pump usage. Many of the high population centers have a low heat requirement, anyway. The exceptions may most simply be treated by adding pure heat-producing plants, which will not greatly affect the whole system, as population densities in the affected regions are necessarily low.

Overall system aspects.
Compared with the outline clean fossil scenario, Bernd Kuemmels has twice the use of CPH plants (of the IGCC type), half the use of fuel cells and 30% less use of hydrogen as a fuel. This makes the bulk of carbon removal take place by stack cleaning rather than by fuel conversion. The present technology outlook (see e.g. Appendix B in Kuemmel, Nielsen and Sørensen, 1997, op. cit.) does not favour this balance, because of the energy input required for stack cleaning techniques (and furthermore, this energy seems not yet to be included in the scenario balances) and because currently, only partial carbon dioxide removal is possible using these techniques. In the overview scenario, the bulk of carbon removal were handled by hydrogen production. The preliminary scenario presented in this paper includes a sketch of the economic implications, but it is not clear, exactly how carbon disposal costs were included. The final scenario will have to look at this issue on a regional basis, and try to determine the best disposal options at hand, for each region.

In most of the issues brought forward above, there are arguments both in favour and in disfavour of the construction used in the attached fossil scenario. It therefore constitutes an interesting point of departure for further discussion, and a good input to the process of reaching eventually a consistent and possibly attractive fossil scenario.

Bent Sørensen

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A global clean fossil scenario

DISCUSSION PAPER

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SEPTEMBER 1997

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A GLOBAL CLEAN FOSSIL SCENARIO

CONTENTS:

1. Authors' Introduction:

In the following work we shall present an overview of the present global energy system and try to elaborate a possible scenario that should lead to drastically reduced greenhouse gas emissions from the energy sector compared to scenarios based on a simple extrapolation of the present development in the World's energy demand. We will investigate the scenario by different means of analysis, try to establish the necessary developments for its realisation, and interpret the results and conditions necessary for those developments.

The original very rough scenario description for this task has been given by Sørensen (1996), who has proposed this kind of clean fossil scenario as a means to reduce atmospheric CO_2 emissions and thereby to stabilise global climate in a long-term perspective. Here the technologies are investigated somewhat more detailed and a cost overview has been given.

Our means to do the analysis work is by choosing a series of technologies that we think will be applied in the future to provide for the energy-based services necessary in a modern society. The number of technologies will be smaller than will be found in any conceivable reality. This simplification process leads to a description of how the future energy system's main features might be and not how it will look like in detail.

An argument for the points stated above is the limited amount of time available for such studies and that it would be futile to try to detail too much. The latter argument is based on the realisation that we anyway would not be able to provide a feasible description of the future with all its vagaries and insecurities. The reader should only try to read descriptions of the past that describe other authors' thoughts of how the future should turn out to look like. It will become clear within a few paragraphs that our present state is very different from the "future" described by our ancestors.

If we keep in mind the foregoing arguments, we can acknowledge the fact that our work will only be a rough sketch of any future global energy system. And this is the only thing we can do. We can only try to describe possible alternatives. The scenario chosen in this work will probably not be the real answer to the question of how we are going to provide energy to serve our needs in the future and at the same time be gentle to Earth's climate. Still, what we do, by presenting those scenarios, is to give the reader an idea of how one can solve this question, and what technical means we already can see today, that are - or will likely become - available to humanity in the next decades.

In a way the scenario we have chosen is an extreme description of a possible future. We have a range of alternatives available[1], and we believe reality will turn out to lie somewhere in between this scenario and others – unless, of course, some surprises or unforeseen development change our opinion base[2]. But if we for the moment disregard this possibility, our study does indeed present one of the edges between which we have to assume our future to lie.

The scenario as such is based on preliminary work presented in the literature before, but the more elaborate investigation here will shed light on some aspects not yet treated sufficiently by Sørensen (1996).

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[1] Acknowledged also in Shell (1996) where fossil energy carriers seem to be phased out during the next century.

[2] This might in fact be the most probable development in the future as experience has shown us.

2. SUMMARY

Current Global Energy System

An overview has been generated on the current global energy system, based on available country-wide data. Currently energy demand is satisfied by fossil fuels to a very high degree. The global primary energy input is about 340,000 PJ, of which 306,000 PJ are from fossils and about 20,000 PJ from wood and waste; average global end-use intensity is about 1.4 kW per capita; global energy imports amount to bills of about 140 billion Euro per year.

Fossil Resources

In all scenarios the question of energy resources or potentials[3] occurs. This question has to be answered, and we start the work with a presentation of the presently known resources and an investigation of any possible future changes. Energy resources are by no means easily established, as will become clear in the investigation. Still, we need to have an idea of what energy resources we can rely on in the future, and this point is valid both for fossil and the other scenarios.

As will become clear in the section on resources, we cannot give a simple value for the fossil resources that will play a large role in the fossil and a minor role in the renewable[4] scenarios. What can be said without doubt is that the economic conditions play a large role in a proper resource estimation of fossil energy carriers[5]. A big problem with fossil energy resources is our imperfect knowledge of the physical upper limits, which is caused by our imperfect knowledge of the composition of the Earth's crust and limits to measuring and identifying possible new resources.

In order for a fossil scenario, covering the middle of the next century, to be plausible we have to make sure that resource exhaustion will not argue against it. Our investigation has shown that there indeed is no reason to assume that fossil fuels are in danger of immediate exhaustion, and that we therefore have to look at such a solution. If fossil fuels were not available to such a high degree, as they are now, then our choice would be immediately to argue for other kinds of scenarios, possibly ones that build on renewables in a high degree.

The Clean Fossil Scenario

The scenario presented here is the Clean Fossil Scenario(CFS), whereas other scenarios are thinkable. This scenario is based on fossils, but only clean technologies are chosen. The scenario is clean, because emissions to the environment especially of CO_2, are being reduced drastically compared to today's average applied technologies. It is fossil, as its primary energy nearly exclusively is being provided by fossil energy carriers. It is a scenario, in that it is a description of a possible future state of the global energy system. With respect to the latter, it should have become clear that it is not a deterministic forecast, and this was also not the intent of this paper. Such a scenario would be a prolongation of the current reliance of the World's energy system on fossil fuels, but it would mitigate the emissions of CO_2, and other greenhouse gases of course, so that the current rise of the greenhouse effect (GHE) would stop.

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[3] The latter word is normally used with renewable energy carriers.

[4] As feedstock for the chemical industry.

[5] Energy carriers are the physical conveyors of energy. For example coal is a carrier of chemical energy, which can be exploited in power stations to produce electricity. Energy defines an ability to do work. Energy itself can not be destroyed but only be converted. If engineers (and we too!) speak about energy losses, then they mean that a part of the energy from *e.g.* the coal can not be exploited in the conversion process, but is lost – in most cases as heat. This energy form cannot be recuperated and so cannot do work.

Demand Determining Factors

The most important parameter when the energy demand has to be determined is the living standard. In this project we have assumed further development leading to improved living conditions for most people in the World. We might expect that this development decreases the differences between the industrial and the developing regions of today, although this could be a too optimistic assumption. It is, however, supported by the difference in growth rates between ICs and industrialising or developing countries over the last decades. Increasing urbanisation will also influence the provision of energy services such as entertainment or chilled food storage. Therefore we have to assume that those kinds of services will increase in importance in the future – and necessarily their share of the final energy consumption.
Another important factor is technological development that leads to improved efficiencies compared to today's average employed technologies. Population size is determining the total energy demand of a society, but economical arguments are weighing most.

Energy Sector Technologies

The fossil scenario will rely on technologies that are more advanced than today both on the production and on the end-use sides. It is shown that the technologies should allow the realisation of the scenario targets, that energy costs *per se* will rise to about double the current values, but that reduced end-use intensity will compensate for this.

Societal Developments

As has been noted before, various scenarios can necessitate societal changes to varying degrees. These changes will be described shortly during a description of the scenario, they are not the main point of our investigation and are only given as a rough reference of how society can be expected to change, or how it should change.

Economics of the CFS

The CFS will necessitate global investments of about 700 billion Euro yearly (assuming the future Euro to be similar in value to the current ECU) to keep the capital stock unchanged. This will probably put some strain on the global financial markets, unless new effective methods can be found to transfer means to the poorer regions.

Climate Change Challenges

Normally the convolution of energy and climate is understood to mean the various energy systems' impacts on the climate system of the Earth. This matters have been discussed for some time. Although first actions have been realised to try to mitigate climate change, for example by the UN *Framework Convention on Climate Change* (FCCC) (UNEP 1992), they are restricted to an emission target for the industrialised countries in the year 2000 only (Ruijgrok 1996, 752).
If one then realises that a long period will be required to fulfil the targets set out in our scenario, or in similar ones based *e.g.* on renewables, it might become obvious that some further increase in the concentrations of major *greenhouse gases* (GHGs) might not be avoided. And the long atmospheric life times of the GHGs virtually ensures that the climate system will experience further forcing, resulting in some unavoidable climate change.
This knowledge should actually be used again to scrutinise, whether the scenarios are lacking a certain precaution in their resource choices. How will biomass be impacted from the unavoidable part of the climate change, for example? Unfortunately it has not been the scope of this study to investigate this matter, but it might be leading to necessary questions to look at those problems. Especially when scenarios cover a long period over many decades, such questions should be addressed.

3. CURRENT GLOBAL ENERGY SYSTEM

Introduction

In this section we shall give an overview of the current energy system with respect to the energy supply, conversion, transmission and the end-use[1] patterns. Energy supply will not be treated in detail, this will normally be the primary energy extraction of the before mentioned energy carriers[2], and we concentrate on the energy that is provided to the different countries' energy systems. The conversion and transmission steps will be described in some detail, and we also will present an overview of the end-use energy patterns.

As very likely known to the reader, the current global energy system is based to a very high degree on fossil energy carriers, like coal, oil or natural gas, but also with some contributions from renewable energy sources or biomass, the latter especially in poor countries, where fuelwood, and to a certain degree, charcoal play a role in providing energy for the population's needs.

We have aggregated the data for energy carriers to present some regional overview, and we will also analyse a few countries' consumption patterns in more detail. The regionalisation is the starting point for further investigations for potential future global energy systems, that will be presented later on. Depending on the aggregation that is deemed useful for that work, we shall try to describe the differences and parallelities between those two cases.

The data we present stem from few sources, in fact the major source for them is an electronic database, prepared by the US American Energy Information Administration (EIA), a subdivision of the US Department of Energy, that we gained access to via the internet[3] and that we completed via other, more traditional, data sources. We start with a presentation of the data material that we have used and the way we have treated it. Afterwards we will analyse and aggregate the data to present some more general overview. This is necessary, as it would be very difficult to treat in detail all the more than 200 countries that are given in the EIA-database.

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1 End-Use means the final conversion of energy into an energy service. This step is taking place at the final consumer of the energy, *e.g.* the households and service sectors, the traffic sector or industry.

2 We also have to acknowledge geothermal, hydro, tidal, wind, solar-thermal and solar-electric energy extraction. These energy forms will be treated in detail in the section on electricity.

3 An aggregation of computers that handle requests between each other and that allows you to communicate with other machines and gain access to the data that is available on those via a common "language". What we mean with *Internet* is actually the most prominent part of it, the so-called *World Wide Web*, abbreviated as WWW.

Data Material Used

Our investigation of the current global energy system relies on our knowledge of the production, conversion and consumption of different energy carriers. It is of some advantage to have a more detailed database, down to a country level, or in some cases, for large countries, to a certain regionalisation. The latter is somewhat more problematic to do and necessitates a high degree of work effort, and therefore we concentrate on the country base.

Our main database for doing this work has been gained via the internet from the US *Energy Information Administration* (EIA), (Internet Resource no. 5). This database is rather extensive, as can be seen in the example given in the Appendix on the petroleum products. It contains a *World Energy Overview* and information on *World Energy Consumption* and *Production*, and also more detailed data on the following energy carriers: *Petroleum, Natural Gas, Coal, Electricity, Energy Prices, Energy Reserves* and *Appendices*.

Despite its obvious information plenitude, this database is not sufficient for a complete description of the current energy system. For example no data can be found on non-commercial energy carriers, like fuelwood or charcoal in developing countries, and the data on electricity generation are aggregated, so that only hydropower and nuclear generation can be sensed specifically. It is not possible to gain knowledge of the wind, solar or geothermal generation, as those have been aggregated. This, however, is common practice and also can be found in data from the *Organisation for Economic Co-Operation and Development* (OECD 1996, 1996a, 1996b) or the *United Nations* (UN 1996).

Data Homogenisation

We have selected one relatively late year, 1994, as the basic year for this investigation. This was the latest year, where we could gain information for most of the countries that we have selected data for. A reader wishing even younger data should be aware that the average time taken by the statistical units of the *United Nations* or the *Organisation for Economic Co-Operation and Development* to finish their publications typically is about two years. Even an electronic database, like the EIA database ends with 1994 as the last year, where data are described as having been provided in full.

Another matter that complicates things is that the data in our sources are not in the same units. Actually the EIA-database is worst in that respect, as coal amount is measured in short tons per year (on short ton is 0.9072 metric tonne (Global 2000, 1419)), petroleum and derivatives of it in thousand barrels per day (one barrel is 0.159 m^3 (Dong 1994, 29)) and natural gas is given as billion cubic feet per year (one cubic feet is equivalent to 0.0283 m^3 (Dong 1994, 29)). Only the data for electricity are given in billion kilowatthours per year.

With respect to the other databases, the ones from the OECD are given in thousand or millions of tonnes of oil equivalent (one toe is equivalent to 41.87 gigajoules ((Dong 1994, 31)), while the data from the United Nations are given in terajoules (one TJ are 10^{12} joules).

For the present work our data has to be merged into a common unit, this unit has to have the equivalents of energy, and it has to be related to the *System Internationale*, which means that it has to be based on the joule. For practical reasons a multitude of this unit has been chosen that seems to be appropriate to apply for all countries in the World, and this is the petajoule (PJ). One PJ is equivalent to 10^{15} joule. This is about 0.278 TWh, 0.948 TBtu[4], 0.024 Mtoe, or 0.239 Pcal[5].

Recalculation of Supply Data

The supply data presented in the following cover the energy supply after any conversion losses. So for example when we have data on the oil supply in a country this is a sum of the net production after losses during production, *e.g.* from the amount of crude or natural gas that is used at a production platform to fuel the generators for the platform's own energy demand plus imports minus exports. This is especially important to note with natural gas, due to losses to *natural gas liquids* (NGL), and with products from crude oil.

As has become clear it was necessary to recalculate the data given in the other databases to ensure that the same units could be applied, and in order to make possible comparisons between the different energy carriers and services. We present shortly the means we have employed.

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4 One British Thermal Unit is equivalent to 1055 joule.

5 One calorie is equivalent to 0.239 joule.

For coal products no figures were given for the total coal consumption for each country, and so we had to calculate the figures for the energy supply from the production, trade and stock change data (in Btu) for the different coal types, like lignite, bituminous or anthracite coal.
For crude oil and for petroleum products the EIA database did offer figures on the respective countries' production and for crude oil also the average energy density (in Btu per barrel), but not for the petroleum products. The latter is not very important, those products are standardised all over the World, and so using one factor for each of the products suffices. We have found the relevant information from UN (1997) and OECD (1997). The barrels per day were being converted to a yearly supply by multiplying with 365 flat[6].
Although the EIA database did offer total figures of the energy supply from oil products in the different countries, we have chosen not to use this value, as it proved not be consistent with other data that we have on the countries' petroleum product supply. Also we have noted that the bunkers consumption has not been excluded from the total supply, so that the domestic supply is the difference between total oil provision and bunkers.
For natural gas figures were given for the energy equivalents, in Btu, of the countries' final consumption, so we chose those values after scaling them to PJ. The quality of this data is better than for the oil supply.
For solid biomass, *i.e.* wood, we have used data from the Food and Agricultural Organisation (SOFA 1996; look in "electronic databases" in the sources and literature section). Those data are given in cubic metres and had to be recalculated to energy units by assuming a typical humidity of 20 to 30 per cent and an energy content of 9.76 GJ (0.333 tce; see notations in appendix) per cubic metre (UN 1996) [7].
Another solid form of biomass is charcoal, for which the original data are given in tonnes in SOFA (1996). We have recalculated to energy units by using a conversion factor of 28.90 GJ (0.986 tce) per tonne (UN 1996) [8].
Bagasse has not been considered explicitly. Its energy content is given 7.74 GJ (0.264 tce) per tonne (UN 1996).
We mention wind energy in the transport sector (sail ships) and tractive animal power which mostly would be used in transport and agriculture, and perhaps to certain degrees in industry. The databases do not cover these non-commercial energy forms, which mostly play a role in developing countries. Therefore we cannot show results for these energy forms, but we acknowledge the possibly large importance of these energy forms in certain countries.

Recalculation of Conversion Data

For electricity generation from thermal, nuclear and hydroelectric power stations, where data was given in the EIA database, we chose to use the values given in TWh[9] and not the ones given in Btu. It appeared as though the Btu-values were actually given in primary energy equivalents. This is a means by which the electricity that is generated in *e.g.* a geothermal power station is equated to the energy amount of some fossil fuel that would have to be used in a thermal power station to produce the same amount of electricity[10]. This is a current practice with other statistical energy publications, but it did not influence our data, as we chose the actual generation and not the primary energy equivalents.

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6 The error from any difference between sidereal and solar years is negligible: 0.068 per cent!

7 It is interesting to note that for the same humidity values and assuming a typical density of 0.725 tonnes per cubic metre and an energy content of 15.9 GJ (0.38 toe [WEC 1993, 14], the 0.36 toe given in WEC [1992, 139] seem to be a typo) per tonne of wood, results in 11.5 GJ per cubic metre. Furthermore, the energy content quoted in WEC (1992) is somewhat low. Both Lawson and Callaghan (1981, 86) and Kleemann and Melifß (1993, 18) give higher values, 18.3 GJ per tonne, 18.4 respectively. The higher figures are however for dry matter, and not for the humidity given in WEC (1992).

8 One Tonne Coal Equivalent according to UN (1996, XXX) is equivalent to 0.7 toe or 29.3076 GJ.

9 billion kWh.

10 One should also be aware of the fact that the power stations typical electrical efficiency is used. So for nuclear power stations, the efficiency is about 30 per cent, for geothermal power stations about 10 per cent. The latter is lower, as the temperature difference between the water pumped up and the surroundings is less than the one in typical thermal power stations.

A minor problem arises with the aggregated data for geothermal and other generation, where we would like to infer the wind, solar[11] and actual geothermal contributions, which had to be inferred from another source (OECD 1996, 239 ff.).
The data there were given in GWh (=0.0036 PJ) and only for the OECD member states. This is problematic, as some developing countries, like India for example, already have a sizeable share of *e.g.* wind converters providing energy for their electricity systems. One the other hand we do know that those energy forms still do not provide a major share of the global energy system, so that any errors from those sources likely will be small on a global scale, although they might become sizeable for the various countries.
So for the OECD member states we had reasonably sound data for those technologies. But what should we do about those other countries, where we only have the aggregated data from the EIA database? How do we distribute the generation into the different technologies?
As a first approximation we can take the EIA data, and use some other source for gaining some idea of the possible composition of the renewable share in the other countries. WRD (1994) is one example, but this database ends with the year 1991. The data in UN (1996) indicate for some countries a rapid increase. However, this seems to be caused only by wind energy, as this is a very dynamic contributor to the energy supply in the countries with a sizeable wind electricity share. This can be seen in WRD (1994). The reason for this is that the production and employment of new wind converters is going on at a high speed. On the other hand the solar share is of no importance yet, and so even if it was rising rapidly, it would normally not mean a large total contribution[12].
We may therefore assume that any rises in the aggregated group, geothermal and others, practically stems from extensions of the wind power capacity and generation[13]. Therefore we have recalculated the increase in wind power production for the countries with significant wind power capacity, as a simple difference between the 1991 data that we have from WRD and the 1994 share of "Geothermal/Other" generation. (?) (this leads to an overestimate of wind if geothermal production actually rises!)
For heat generation we have both data for final heat consumption and for production from *Combined Heat and Power*[14] (CHP) plants and heat plants from (OECD 1996 and 1996a). The data have been recalculated from the ktoe units to PJ via the normal conversion factor. For geothermal heat provision we have used data from UN (1996). These figures are already included in the CHP heat production figures of OECD (1996) and were thus excluded to prevent double counting.
While we have data for the electricity generation from thermal power and CHP stations and heat plants, we need to calculate the fuel input to these. This is done for each energy carrier by subtracting the final consumption for the energy carrier from the total delivered in that country. This will not give us the specified fuel input to the three types of fuel users. In the case that only one type occurs, the question is easy to answer. In the case that two or all types occur, the question is, how we divide the energy consumption onto the different consumers. We cannot answer this question, as it would necessitate taking more data into consideration, which we have not done, as we figured this was not essential for our work.
Likewise we cannot distribute the electricity generation between simple thermal power and CHP stations, even though we have data for this for the heat provision.

Recalculation of Final Consumption Data

The final energy consumption takes place at the final consumer. For example with respect to private transport one would place the final energy consumption at the driver of a car and not at the refinery or petrol station. One normally subdivides the consumers into the following groups: Industry, Transport, and Households and Other Consumers[15]. This is a very rough aggregation that we have followed. Its advantage is that we have been able

[11] In the OECD text those sources are not specified separately into solar-electric and PV.

[12] Although the growth rates could be enormous.

[13] Any dynamics for hydroelectricity are already included explicitly in the data.

[14] Where the exhaust heat is being used in district heating systems. This saves some primary energy, as the heat is a waste product and does not have to be produced separately.

[15] Normally agriculture is aggregated together with industry, but in the OECD publications it was aggregated with households and service sectors.

to find data, to perform it, but on the other hand this aggregation is not the optimal one, if we wanted to assess how efficient the energy system of a country or region actually is[16].

The EIA database does not contain data on final consumption. We want to subdivide the final consumption into the transport sector, industry and an aggregate of households, service sectors and agriculture, so we employed information found in OECD publications on OECD and some Non-OECD members (OECD 1996, 1996a, 1996b). As noted before, those data are given in ktoe and have been recalculated into PJ.

From those publications we also gained knowledge on the so-called *non-energy* uses of oil and natural gas[17]. This means the use of those fuels as feedstock in some chemical processes. For example acetylene is being manufactured from natural gas, or expanded polystyrene from crude oil. Those materials are not being used immediately in the energy cycles, and therefore they have to be treated differently from the other energy carriers.

One could argue that it was only important to know the physical amount of those non-energy applications, but to enable an easy comparison between the different applications of energy carriers we have kept the energy equivalents, *i.e.* PJ, of them in our database.

When we compare the data for the production of electricity minus the losses given by the EIA database with the ones of the final consumption of electricity found in the OECD publications, we realise that in most cases there is a difference, which on the global scale amounts to about 10 per cent of the total electricity provision. A finer analysis showed that although the EIA database did contain information on "transmission and distribution" (T&D) losses, the value in most cases seems to be too small so that electricity supply and final consumption do not balance[18]. This was especially noticeable with developing countries, but we also found this to be the case for the United States[19].

Interestingly the introduction of a term "own use" from OECD (1996 and 1996a) led, on a global plane, to a much better balancing between production, losses and consumption. However, this still led to unbalances on a regional or country base, now in the opposite direction. For very few countries the opposite was the case so that electricity consumption apparently surpassed the supply.

Seemingly the combination of the different data sources is a problematic issue, and there is no observable trend for the country groupings[20]. Part of the problem is due to the EIA database simply assuming the following (according to the EIA database helpfile WORLD20.HLP):

- "Generation means net generation, which excludes electricity consumed at the power plants. For hydro generation, net generation is assumed to be 1 percent less than gross generation; for nuclear and geothermal and other generation, net generation is assumed to be 5 percent less than gross; for thermal generation, net is assumed to be 6 percent less than gross."; and
- "'Losses' means transmission losses; these are usually about 7 percent of total generation.",

which leads to differences compared to the more detailed and balanced data of other sources, as transmission losses in many countries definitely are higher than those assumed in the EIA-database[21]. Also the own use share may be somewhat higher. According to OECD (1996e, 606) for the example of the United States we also have to take into consideration: electricity used for pumped storage (which has to be exempted from hydro production) and the energy sector's own consumption (which may not be included in the end-use data).

There is furthermore a problem of diverging definitions. Also according to OECD (1997e, 606) the following definitions may be found quoted widely in the literature:

Electricity generated:	which is the gross generation minus the amount used in pumped storage
Electricity Requirements:	which is the gross production plus imports minus exports
Electricity Consumed:	which is the same as electricity supplied minus transmission and distribution losses.

[16] To do this, one would need to also look at the energy quality, *e.g.* the temperature levels necessary for industrial processes to be able to assess savings from a so-called exergy analysis.

[17] We have ignored the limited application of coal in chemical industry.

[18] Globally there was about a ten per cent difference for this energy carrier.

[19] Which made up about a quarter of the global difference!

[20] With the exception of the oceanic region, where all energy consumption is zero except for fuel wood use.

[21] Or alternatively there is some illegal power extraction which is not possible to assess statistically satisfying.

Electricity Supplied: which is the same as gross electricity minus own use minus use for pump storage plus imports minus exports.

This makes calculations arduous and is prone to give differences between different publications, as the ones we have encountered.

We have solved the problem of the spurious electricity oversupply[22] very simply by introducing a term called *statistical difference* in the database to balance our data. This term also covers the 60 countries, for which we do not have any end-use data. Totally those mean about 160 PJ of unbalanced electricity. For ten countries we do neither have data on the provision nor the consumption of electricity.

There were no specific problems with the heat supply and consumption, as we had used the same database for this energy carrier. Also the extraction of the geothermal heat provision did not cause major problems. Unbalancing is only caused by rounding effects, and is of a minor significance.

With respect to the use of fuelwood and charcoal, we have to make assumptions on the allocation of those to the three sectors that we consider. It seems fair to exclude the transport sector, as we do not assume any large consumption there. But it is necessary to allocate the fuel wood consumption to the household sector. According to WEC (1992, 139) world-wide some 2 billion people rely on fuelwood as their principal source of domestic energy, this supports our assumption of a large wood share in the developing countries in the "other sectors" category[23].

Thus, for developing countries, where we do not have other data, we include the fuelwood amount in the energy statistics and add it in the "other sectors" category. However, for the OECD member states we neglect the fuelwood supply in order to avoid double counting, as this post already is included in the "wastes and others" category[24].

On the other hand if we look at charcoal, WEC (1992, 139) seems to imply that charcoal is mostly used as a domestic fuel, with Thailand and Senegal as examples. An exception is Brazil, where its major application lies in industry. We have therefore assumed that charcoal mostly is consumed domestically with the one exception that we have learned about[25].

Any consumption of charcoal in industrialised countries is very small compared to the total energy supply so that possible errors from the inclusion of charcoal as domestic consumption and any double counting are small, too.

Non-Energy Uses:

Although they are principally energy carriers, hydrocarbons and coal are, due to their chemical versatility being used in the chemical industry for various purposes, especially for the production of plastics products. Globally today the equivalent of about 7200 PJ of oil and 600 PJ of natural gas are being used for these non-energy purposes, plus some coal that we have not considered explicitly. Some of this energy is actually recuperated, when plastic wastes are being burned in heat plants. The energy of this waste should then actually be considered as fossil and not as a renewable, which waste *per definitione* is assumed to be today.

The Global Perspective

Using all the data material that we have described so far we have been able to calculate the global energy flow. On the following page the results of the database program run are shown. We see that the final conversion and the consumers is taking place after a primary energy extraction which is only about one and a half times as

[22] The basic reason for it occurring at all should be that the assumptions differ with the different authorities in how to interpret the data that they have, or how they estimate lacking data.

[23] As another example: Das and Banerjee (1995) state that a major share of fuel wood in India is being used in the residential sector for cooking. India is a developing country, and we may not assume that the situation in that respect is any different in other developing countries.

[24] This applies with the exception of Turkey, where we did not have data for the "waste and others" category, and where according to the FAO database 74.5 PJ of fuelwood are used. See the table over OECD fuelwood use in the appendix.

[25] This excludes other industrial applications like in home bird bedding or in shooting powder production. The total contribution should be minimal.

large. This is partly an underestimate stemming from the fact that we have not calculated the true primary energy equivalents of the electricity generation from hydro, nuclear, geothermal and other.
The data seemingly also show a general thermal power station efficiency of only about 20 per cent. This is modified, if we take into consideration also the heat provision by pure heat and CHP installations.
It can also be seen that for electricity the quality of the combined data could be better. As has been explained before this is an artefact of using several sources and of the underestimate of the T&D losses in one of those.

Global Energy Flow Data

23-apr-07

All figures in PJ   Year: 1994

Extracted Energy

15478	Fuelwood
745	Charcoal
3574	Waste
79092	Dry Natural Gas
96235	Coal
9404	Hydroelectric
7615	Nuclear
394	Geothermal and Other
130407	Oil
6452	Bunker

Conversion

Heat

44	Geothermal
1371	Heat Plants
12360	from CHP
13775	Total Generation
-1	Stat. Differences

Electricity

In: 148530

27981	Thermal
44034	Total Generation
3634	Own Use
-3598	Stat. Differences

Non-Energy Uses

7209	Non-Energy Oil
607	Non-Energy Gas

Transmission

1552	Transmission Losses (Heat)
3110	Transmission Losses (Electricity)

Supplied (Heat): 12223

Supplied (Electricity): 41323

To End-Uses

Coal	32291
Oil	79833
Gas	40001
Waste	3574
Elect	37726
Heat	12222
Fuelwood	15478
Charcoal	745

Final Conversion

Other Sectors

Coal	6955
Oil	20312
Gas	21469
Waste	2163
Elect	20412
Heat	6486
Fuelwood	15478
Charcoal	565
Total	93839

Industry

Coal	24596
Oil	22081
Gas	17096
Waste	1404
Elect	16511
Heat	5534
Charcoal	181
Total	87082

Transport

Coal	740
Oil	50988
Gas	1436
Waste	7
Elect	804
Heat	202
Total	62177

Regional Energy Overview

Aggregated Data

Even though we later on will present only aggregated data, for several parameters we have created a country-wide database, to have some liberty to aggregate countries appropriately.

Geographical Subdivisions

In order to be able to aggregate our data and to present them in a reasonable way, we have divided the countries of the World into 17 regions. The basic idea behind the grouping was that we would like to keep the geographical connections so that countries, which lie on the same continent, generally are grouped together.

For a few countries we have decided not to include them in a region, rather we analyse them separately. This is the case for Russia, and China. Those two countries are quite large, populous, or they stick out in other ways, so that it would be unwise to include them in the larger aggregate. South Africa is another typical example. The reason it not was put together with *e.g.* Australia, was that we then would have broken the basic continental divisions.

The following table shows, how we have aggregated the regional countries into groups:

Geographical region	Members	Symbol
NAFTA	Canada and United States	AM1
MX, BRA, ARG	Mexico, Brazil and Argentina	AM2
Latin America	Caribbean, Central and South America	AM3
Australia - N Zealand	Australia and New Zealand	AU1
Oceania	Oceania without AUS or NZ	AU2
South Africa	Republic of South Africa	AF1
Maghreb	North Africa at Mediterranean	AF2
Sub-Saharan Africa	Africa, except RSA and MAG	AF3
Western Europe	EU and Norway, Switzerland	EU1
Central Europe	Most Central European Countries, Turkey, Israel	EU2
Developing Europe	Poorer European Countries of Europe	EU3
Russia	Russia	RUS
China	China	CHI
Japan and Tigers	Japan and Hong Kong, Singapore, Taiwan, South Korea	AS1
India group	India, Pakistan , Malaysia, Philippines, Thailand, Indonesia	AS2
Oil rich countries	Middle East Oil States	AS3
Developing Asia	Asia, rest of	AS4

A complete list of the members according to their grouping is given in the appendix. We will give a short description of the arguments leading to the shown aggregation.

NAFTA

This group consists of the United States, Canada, and Greenland, which have comparable per capita income.

MX, BRA, ARG

This group comprises Mexico, Brazil and Argentine, countries which are now developing more rapidly and might become the new NICs of the near future.

Caribbean and Latin America

This is the rest of the American nations. Generally they are not the richest ones, neither the fastest developing ones.

Australia - N Zealand

This group is clear.

Oceania

Here the many island nations in the Pacific are grouped together. This group is the one with fewest inhabitants: only slightly more than 6 million people. Its global importance therefore is rather limited.

South Africa

Besides the republic of South Africa we have also included the richest African nation: the Seychelles. Currently the economic situation is different for those groups, but in the future we assume it will be more similar, as South Africa could become the new Korea of Africa.

Maghreb

This group consists of the African states with connection to the Mediteranean. The proximity to Europe should argue for a mor rapid economic development so that those countries in the future will be much richer than the rest of Africa.

Sub-Saharan Africa

In this group most of the countries are very poor. Our assumptions are, that they will still be poor in the future, although some of them might become better off and reach levels comparable to *e.g.* Romania or Bulgaria at the middle of the next century.

Western Europe

In this group many of the current EU members are included plus the richer countries like Switzerland and Norway, the creme de la creme of Europe.

Central Europe

Despite its name it also includes Portugal, Israel, the Gaza Strip and Turkey. The members of this group seem to have caught some economic development and would be reaching a rather well off niveau.

Developing Europe

Also those countries will be developing, but as their basis today is rather low, they can not be expected to end up in a high group.

Russia

This group only consists of Russia, the other members of the former Soviet Union are included in European or Asian groups.

China

Obvious!

Japan and Tigers

Here besides Japan we find the four Tigers: Taiwan, South Korea, Singapore and Hong Kong. Although the latter will probably not range as an independent state any longer by the middle of the next century it seems to be wise to include it in this region, which will be the economic leaders in the Asian region regarding per capita income[26].

India group

This country includes some already slightly richer Asian countries, or the ones, where some initial development can be perceived and where the infrastructure already is of sufficient quality to allow high-tech service industries: India, Indonesia, Malaysia, Pakistan, Philippines, and Thailand.

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[26] One could argue that it also was necessary to include separately the new booming free trade zones in Southern China. We do not object, but could not do this as relevant data sources were not available.

Oil rich countries

Deserves no further comment besides the one that only countries with major oil reserves are included.

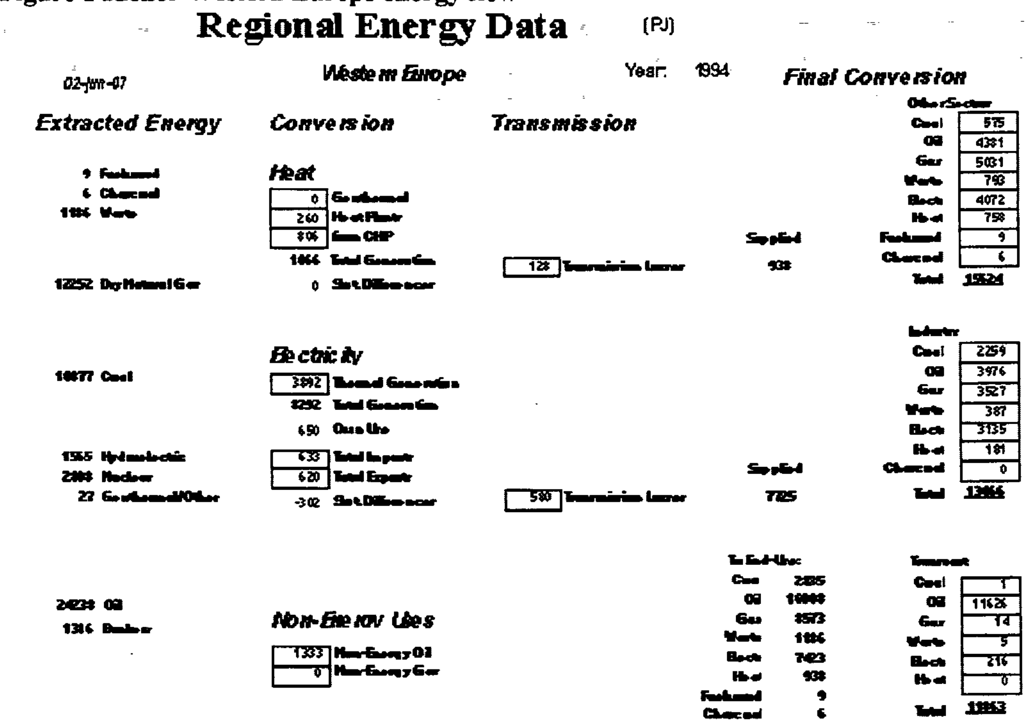
Developing Asia

This group consists of the other Asian nations. Their perspectives are not as gloomy as for the Developing Africa group, but they certainly will not become very rich.

Example of a Regional Energy Flow

We will shortly present the energy flow for the richers European region, EU1, which comprises most of the EU plus Norway and Switzerland. Other examples on the energy flows for regions we have assessed, are shown in the appendix.

Figure 1 Richer Western Europe energy flow



Source: Various sources.

If we start with the final conversion, we can see that households and the service sectors use oil, gas and electricity about equally. We may assume that oil and gas is mostly used in space heating, while electricity will fuel appliances. There is also consumption of a small amount of heat, coal and of waste, which would tend to be used in space heating[27], the same is true for the minuscule amount of fuelwood used, while the charcoal use also could be related to other purposes like food preparation (grilling) or hobby use (pet animals).
In industry coal, oil and gas will be mostly needed in providing process heat; coal and to a minor amount also natural gas or waste could also be used in the ferrous industries to make steel, though. Those fuels would also be used for providing space heating or for oil also in the transport within companies, this depends to some degree on the way the statistics handle those different aspects. Electricity can be expected to be used in appliances, for motive power and to some degree for high temperature process heat. Heat from heat plants and CHP stations would signify space heat and to some degree lower temperature process heat. Although charcoal globally also is used in industry, this is not the case in the richer part of Europe.

[27] To some degree lower temperature process heat will also be applied to households and service sectors that is used in *e.g.* food preparation or hygiene.

The transport sector is dominated by oil, which comprises various kinds of petrol, diesels and fuel oils. Waste, gas and electricity together account for only about two per cent of the liquid fuels consumption, and will be mostly used in public transport[28].

It can be seen that the electricity imports and exports for this region nearly balance, so that on average the electricity consumed in Western Europe will also be the one that is produced there. Seasonal variations do, however, occur, caused for example by climatic variability that can influence a region's affluence of hydro-power and that would necessitate balancing measures. This pattern could also be caused by some of the richer Europeans members have an ongoing electricity trade with other European countries, where the former transport the electricity via their high voltage lines to the latter.

Per capita End-Use Energy Demand

We have tried to calculate the energy end-use demand patterns of the 17 regions from the data that were at our hands. The result is shown in Table 1 for the year 1994 for all the three sectors and based on the countries for which we could find data in OECD (1996, 1996a, 1996b) or SOFA (1996).

Table 1 1994 end-use consumption in all sectors (in watts per capita)

REI	Geographical region	coal	oil	gas	el	waste	wood	total
AF1	South Africa	476	555	21	420	0	57	1528
AF2	Maghreb	19	375	96	95	0	24	609
AF3	Sub-Sahara Africa	6	52	3	12	0	291	364
AM1	North America	164	3502	1742	1369	152	2	6931
AM2	Brazil, Argentina, Mexico	84	683	164	178	38	214	1360
AM3	Caribbean & developing L. America	50	469	116	107	0	172	914
AS1	Japan and Four Tigers	486	2275	185	742	17	8	3714
AS2	India group	52	154	27	44	0	124	401
AS3	China	37	53	43	19	0	35	187
AS4	Developing Asia	1190	329	45	204	0	157	1924
AS5	Oil rich countries	12	1453	530	248	0	7	2250
AU1	Australia - N Zealand	429	2240	702	960	361	1	4693
AU2	Oceania	0	0	0	0	0	291	291
EU1	Western Europe	249	1755	753	652	104	1	3514
EU2	Central Europe, Turkey, Israel	364	758	197	269	92	41	1722
EU3	Developing Europe	295	337	532	226	0	12	1402
RUS	Russia	401	637	840	489	0	53	2420
globally	**Global average**	**194**	**605**	**240**	**226**	**21**	**97**	**1383**

Source: OECD (1996, 1996a, 1996b), SOFA (1996), IR (14), own calculations.
Notes:
el: electricity consumption;

The only aggregation of this data is possible into the three sectors: industry, transport and others; with exception to the transport sector[29] it is not possible to give data on the actual end-use energy quality, *i.e.* whether a fuel has been used to generate low, middle or high temperature process heat, space heat, or in cogeneration units to generate electricity. Electricity can *e.g.* be used for space heating, which exergetically is an unsound project[30]. It might also be used to generate high temperature heat in furnaces, that also could be fuelled with

[28] We may neglect the disappearing use in private electric vehicles. Natural gas has been successfully used in buses in Sweden, for example in Malmö. Coal will be mostly used for decorative purposes in older locomotives. Waste could also imply the use of fatty liquids instead of petroleum products.

[29] If we abstract from the fact that in some countries the industry energy data also will contain internal transport within companies.

[30] Unless, of course, heat pumps are employed for this purpose.

petroleum products, coal or natural gas. The same is true for natural gas, which in most cases would be used for process heat demand, although an ever increasing share is employed in the power sector.
Independent of this we can establish the following pattern:

- Globally end-use consumption is about 1.4 kW, however this covers over large regional differences.
- The industrialised regions tend to have by far the largest energy consumptions.
- The totals for those are surpassing 3000 watt per capita.
- Final energy consumption is about 7 to 15 times 120 times larger in the industrialised regions than in Sub-Saharan Africa or the current India group.
- The low end-use demand in Oceania is caused by lack of data for this region.
- Although natural gas supply is technically more difficult to establish than for electricity, coal or liquids, average consumption of this fuel is comparable to electricity, but liquid fuels are being used much more intensively.
- waste seems to be a veritable energy source in many of the industrialised regions, while wood[31] is the prominent fuel in many developing regions.

Industrial End-Use

As has been explained before, we can also make an aggregation of the kind shown in Table 1 for the industrial energy end-use, see Table 2.

- wood is only occuring in the Brazil, Argentine, Mexico group, as charcoal used in Brazil is assumed to be used in the metal works of that country, otherwise we could not find indications for wood or charcoal in industrial applications, although they exist.
- An investigation (not shown) has indicated that industry's share of the total end-use consumption generally is about a third. But in some regions, like South Africa, Developing Europe and Developing Asia is surpassing 40 per cent, for the latter region the ratio is 60 per cent!
- Industry's share tends to be highest in coal, gas and electricity, so that industry typically is responsible of about 70 per cent of a region's final coal and gas consumption, whereas the figure is about 50 per cent for electricity.

Table 2 Industrial end-use (in watt per capita)

REF	Geographical region	coal	oil	gas	el	waste	wood	total
AF1	South Africa	404	99	20	266	0	0	788
AF2	Maghreb	19	106	74	39	0	0	238
AF3	Sub-Sahara Africa	5	6	3	7	0	0	20
AM1	North America	155	518	687	483	78	0	1921
AM2	Brazil, Argentina, Mexico	52	161	124	95	8	22	462
AM3	Caribbean & developing L. America	30	94	97	57	0	0	278
AS1	Japan and Four Tigers	460	834	62	349	16	0	1720
AS2	India group	51	35	20	21	0	0	127
AS3	China	35	4	7	9	0	0	56
AS4	Developing Asia	852	120	33	140	0	0	1145
AS5	Oil rich countries	12	222	289	38	0	0	560
AU1	Australia - N Zealand	405	277	475	430	230	0	1818
AU2	Oceania	0	0	0	0	0	0	0
EU1	Western Europe	198	349	310	275	34	0	1167
EU2	Central Europe, Turkey, Israel	193	159	97	116	5	0	570
EU3	Developing Europe	197	95	257	105	0	0	654
RUS	Russia	219	173	205	251	0	0	848

Transport End-Use

The transport sector typically is responsible for about a third of the final energy consumption, and as could be expected, liquids are its predominant fuel.

31 Wood here comprises also charcoal.

Table 3 Transport end-use (in watt per capita)

REI	Geographical region	coal	oil	gas	el	total
AF1	South Africa	1	396	0	10	407
AF2	Maghreb	0	136	0	1	136
AF3	Sub-Sahara Africa	0	35	0	0	36
AM1	North America	0	2620	97	3	2720
AM2	Brazil, Argentina, Mexico	31	393	4	1	429
AM3	Caribbean & developing L. America	18	297	0	1	316
AS1	Japan and Four Tigers	0	934	0	15	949
AS2	India group	0	83	0	1	84
AS3	China	0	23	0	1	24
AS4	Developing Asia	25	131	0	5	161
AS5	Oil rich countries	0	656	0	0	656
AU1	Australia - N Zealand	5	1813	14	11	1844
AU2	Oceania	0	0	0	0	0
EU1	Western Europe	0	1021	1	19	1041
EU2	Central Europe, Turkey, Israel	4	417	1	8	429
EU3	Developing Europe	0	154	2	13	169
RUS	Russia	4	205	106	53	367

Source: own calculations.

- It is interesting to note that there must also be a sizable gas share in the North American market.
- The electricity intensity is generally very low, with the exception of South Africa, Japan and the Tigers, Australia-New Zealand, Western Europe, Developing Europe and Russia. A reason is the appearance of public transport in those regions, and for the raw materials' extracting countries that long transport lengths and bulk transport will demand much energy.
- The coal era in the railway transport seems to be over now, as input with the exception of some regions is insignificant.

Other Sectors' End-Use

This sector is a collection of residential and commercial applications. The *other sectors'* energy end-use typically is between 30 and 50 per cent of the total end-use per capita, and as can be seen in Table 4, the share of the energy carriers shows no prejudice towards specific fuels, with the exception of electricity, where demand typically is more than half the total.

Table 4 Other sectors' end-use (in watts per capita)

REI	Geographical region	coal	oil	gas	el	waste	wood	total
AF1	South Africa	71	60	1	144	0	57	333
AF2	Maghreb	0	133	23	55	0	24	235
AF3	Sub-Sahara Africa	1	11	0	5	0	291	309
AM1	North America	9	365	958	883	75	2	2291
AM2	Brazil, Argentina, Mexico	0	129	36	82	29	192	469
AM3	Caribbean & developing L. America	2	78	18	49	0	172	320
AS1	Japan and Four Tigers	27	508	123	378	1	8	1045
AS2	India group	0	36	7	23	0	124	190
AS3	China	1	25	36	10	0	35	107
AS4	Developing Asia	313	78	12	59	0	157	618
AS5	Oil rich countries	0	575	242	210	0	7	1034
AU1	Australia - N Zealand	18	150	212	518	131	1	1031
AU2	Oceania	0	0	0	0	0	291	291
EU1	Western Europe	51	385	442	358	70	1	1306
EU2	Central Europe, Turkey, Israel	167	182	100	145	87	41	722
EU3	Developing Europe	98	88	273	108	0	12	579
RUS	Russia	178	259	528	186	0	53	1205

Source: own calculations.

End-Use Conclusions

As could be seen, the energy end-use intensity of the regions and the shares of each energy carrier vary quite strongly. These variations in part reflect socio-economic and cultural differences, in part simply the fact that some regions will only provide certain energy sources in abundance, so that human populations tends to exploit those first. This is a very understandable fact.

Energy and Financial Flow between the Different Regions

Energy carriers are being traded between the different regions of the World. This is a result of the uneven geographical distribution of energy reserves and consumers, that in the light of the generally easy transportability[32] of carriers like coal, oil and natural gas, necessarily leads to transport patterns from an increasing demand for energy services.

To a certain degree such an increase in demand could be covered by so-called *Negawatts*, which means increases in efficiency that allow further energy services to be fulfilled without creating an increase in energy demand, but the natural efficiency growth of about one per cent annually in the last decades[33] has not outpaced the increase of services that are being demanded. Therefore energy demand has been increasing until now, and in the light of an ongoing global industrialisation, exemplified by the so-called *Tiger* and *New Tiger*[34] nations around the Pacific basin, it seems certain as if this trend will continue the next decades, before it will be stopped by policies leading to an enhanced efficiency of the total energy system, *i.e.* including the end-use sector.

We will now shortly present the pattern of the energy flow between the different regions of the World.

Inter-Regional Energy Flows

This short presentation rests very much on the *BP Statistical Review of World Energy 1996* (BP 1996). This publication is based on official publications, and BP stresses that "no use is made of confidential information obtained by BP in the course of its business" (BP 1996, 41).

For petroleum the major trade pattern is from the Middle East OPEC members to South and East Asia, Europe and North America. There is a sizeable flow from North Africa to Europe and North America, and from Latin America to North America. Also there is a flow from Russia to Europe.

Most of this transport is via tank ships, and to some degree via trans-national pipelines.

For natural gas the major trade pattern is from Russia and the new independent states to Europe, from Canada to the United States, from Australia and Oceania to Japan, and from North Africa to Europe.

Most of this transport is via pipeline, otherwise by ship in the form of liquefied natural gas.

For coal the trade patterns are from North America, Colombia, Australia and South Africa to Europe and East Asia, from China to Japan, Europe and North America, and from the Former Soviet Union to Europe. Coal is normally used domestically, so that today only about 10 per cent of the production is being exported and traded (WEC 1995a, 18).

This transport is via ship or railway.

According to a data extraction run with the EIA database electricity is being traded from Canada to the United States, Brazil, Argentina and Mexico are importing from the other Latin American Countries, and Russia is exporting to other countries in Europe.

Costs of Energy Imports

With the data available we can present a short overview of the costs that the energy import cause for each region. The following values have been assumed: coal: 1.6 Euro per GJ, electricity: 3, gas: 4, oil: 3, and petroleum products 4. The result in Table 5 shows that total fuel and electricity import with these cost assumptions

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[32] This is probably more a result of years of technological development, as can be exemplified by the natural gas trade, which only originated, once means had been created to transport it to the consumers. Before that the volubility of gas had prevented such a trade. This resulted in a large part of the associated natural gas being flared, *i.e.* burned from the oil platforms.

[33] This is called an *autonomous* decline of the World's economic system's energy intensity.

[34] Hong Kong, Singapore, South Korea and Taiwan, res.: Malaysia, Philippines, Indonesia and Thailand.

in 1994 had a value of about 140 billion Euro. Oil and petroleum products were responsible for about 80 per cent of this cash flow, while followed by coal. No data were given for gas import, so that the costs for this energy carrier could not be estimated, although gas import actually is taking place: Japan for example employs liquid natural gas tankers, for terrestrial transport pipelines are used.

Table 5 Costs of energy imports to the regions (in million Euro)

REI	Geographical region	gas	el	coal	oil	total
AF1	South Africa	0	0	25	25	50
AF2	Maghreb	0	15	223	903	1141
AF3	Sub-Sahara Africa	0	0	0	412	412
AM1	North America	0	635	856	17521	19011
AM2	Brazil, Argentina, Mexico	0	382	678	4750	5810
AM3	Caribbean & developing L. America	0	3	127	1625	1755
AS1	Japan and Four Tigers	0	0	8693	21103	29796
AS2	India group	0	24	759	8491	9274
AS3	China	0	18	48	3495	3560
AS4	Developing Asia	0	299	365	1634	2298
AS5	Oil rich countries	0	0	26	1569	1595
AU1	Australia - N Zealand	0	0	0	1171	1171
AU2	Oceania	0	0	0	149	150
EU1	Western Europe	0	1841	6863	40892	49597
EU2	Central Europe, Turkey, Israel	0	483	928	4551	5961
EU3	Developing Europe	0	209	959	2160	3328
RUS	Russia	0	256	1079	358	1693
global	**Global Sum**	**0**	**4164**	**21630**	**110808**	**136601**

Source: own calculations.

Note: assumptions on energy prices: gas: 4, electricity: 3, coal: 1.6, petroleum: 3, oil products: 4 Euro per GJ.

Economic Conclusions

The import of energy carriers is a very large global market, and the estimated total costs are equivalent to about 0.7 per cent of the total global GDP[35].

[35] Baratta (1996) gives a global GNP of about 19 trillion Euro ($24 trillion).

4. ENERGY RESOURCES

Introduction

In the following work we shall try to elaborate on the existing current and probable future energy resources that can be exploited to provide for the energy needs of humanity. After a description of the reserve and reservoir definitions we will start with a presentation of the fossil energy carriers, as they are the most important energy sources of today's energy systems. Then follows a presentation of the future renewable energy resources. Finally an overview is given of uranium resources for any potential[1] exploitation of the nuclear energy source that can be perceived.

1 inherently secure

Stock, Reservoir and Reserve Definition

A reader who has followed the last decades of energy discussions might realise a certain confusion with respect to the term energy reserves. While many discussions in the 1970s took their starting point in "limited" energy reserves - at that time only about a 30 year period was given as a limit for the production of oil and natural gas - we should now experience that those fossil reserves were being diminished today, as production globally has even risen. Yet this is not the case, today one is still speaking about oil reserves lasting of the order of 30 years at current production[2].
How did this happen? Obviously there could not have been new occurences of oil or natural gas being created within this short timespan[3]. The answer is to be found in a simple question of how to define your point of view. What is a reserve, and how is it defined? We start from the top with a very theoretical consideration and then work our way down to the actual reserve definition.

Theoretical Maximum Physical Stock

Obviously for us to be able to produce petroleum, natural gas or coal, there has to be some amount of those. If we now imagine that we knew all the occurrences of *e.g.* petroleum, then we would know the total amount of petroleum that is in the World. Obviously we will never know exactly how much petroleum there will be in total. Therefore we call this absolute upper amount as the *theoretical maximum physical stock*, or abbreviated: *TEMAPS.*
This phrase shall express that we will never know exactly how much of an energy carrier there is hidden in the World.
In principle we can imagine that we could exploit all of the TEMAPS, but in reality this will never happen. There are environmental, technical and economic reasons that speak against such a total exploitation. This will be exemplified in the section on reserves. Before this, another question arises. How much of the TEMAPS do we actually know of? This will be analysed in the following section.

Resource Base

If we look at how much of a fossil energy carrier that is available to us, we cannot use the TEMAPS value, simply because we do not know it. The only information we actually have, is the one gained from exploratory activities. These are performed to find new occurrences of energy carriers[4]. Several technologies are used to do this, as described in *e.g.* Sheriff (1992) for the case of petroleum. During the exploration process a larger share of the TEMAPS amount is being identified.
And the amounts that have been found and proven by exploratory technologies are the ones that in principle could be used by humanity, the so-called *resource base.*[5] It is known to exist, its location and magnitude is known with considerable certainty, yet it is not clear that we can exploit this resource base. The reason for this is that not in all cases would it be profitable to actually exploit those resources. It might also not be technically feasible to exploit the total resource basis, or environmental considerations restrict the amount of the resource basis that can be exploited. Those three extra considerations are being taken care of in the reserve definition.

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[2] In fact during the 1970s the R/P ratios, the proven reserves compared to the production figures, did go down, but this changed, when in the early 1980s changed production technologies extended the reserves in the Middle East region (Internet Page 2).

[3] Petroleum is an end-product of the decomposition of prehistoric, several million years old, organic material. The same is the case for coal, and most likely (see Gold's theory later on) for natural gas.

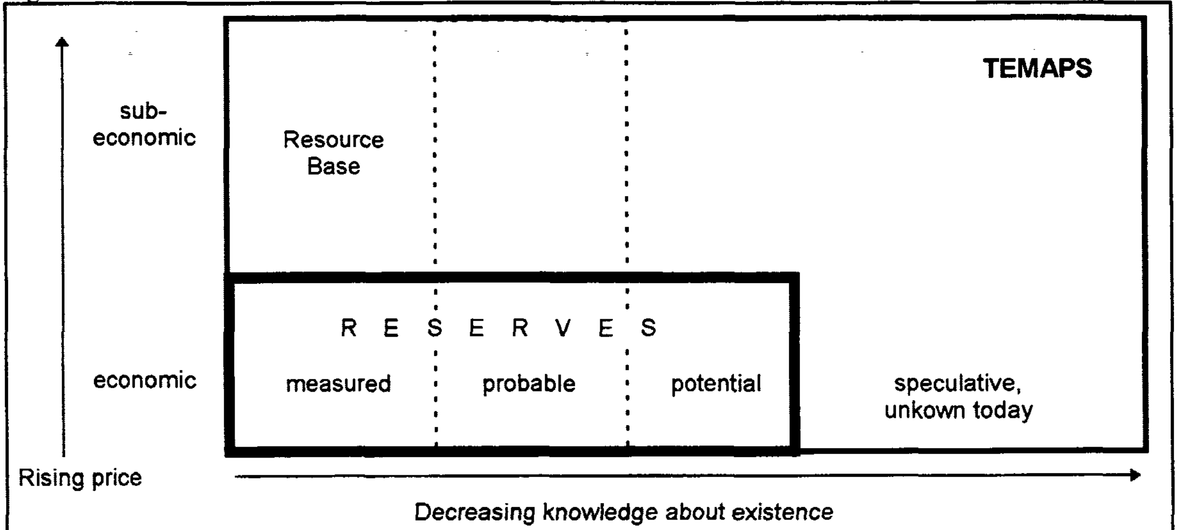
[4] Or also other minerals, and in many instances minerals (metal ores) and fossil energy carriers are treated in parallel in the literature.

[5] IPCC II (1996, 85 f.) further defines the resource base as the sum of reserves and resources, where *resources are those occurrences with less-certain geological and/or economic characteristics, but which are considered potentially recoverable with foreseeable technological and economic developments.*

Reserves

While the resource basis expresses our current knowledge of occurrences of a mineral, certain other considerations actually limit the accessibility of those resources. The *International Panel on Climate Change* (IPCC II 1996, 85) gives the following definition for an energy reserve, if its resource basis is known: *Reserves are those occurrences that are identified and measured as economically and technically recoverable with current technologies and prices.* We could also mention other restrictions that would limit the reserves, like ecological or regional planning considerations that would prohibit for example an open coal mine in an area of scenic attraction.

Figure 1 CLASSIFICATION OF MINERAL RESOURCES AND RESERVES



Occurences of energy carriers can be divided into a series of groups depending on how certain one is on the size of the occurence, and how expensive it would be to exploit this occurence.
Occurences that either are surveyed or rendered probable at a more limited survey, or possibly only estimated out of a common geological knowledge, are belonging to reserves, under the condition that they can be exploited with a technology known today and at today's prices. Other occurences belong to the resource base.

Source: After Schmidt *et al.* (1975, 13).

Opposite to the very theoretical notions of TEMAPS or the resource base, the more down to earth expression *reserve* takes into account that not all the occurrences that we know of actually would be economical to exploit. In Figure 1 we have tried to express the differences between the three expressions in a graphical way. This figure also shows a subgrouping of the reserve phrase, which we will explain in the following.
So while the reserve classification actually seems to take into account known factors, we have to extend our definition by the analysis of the various economic and technological parameters that influence the size of the reserves. To prevent any confusion: the problem here is **not** that the actual reservoir base is known only partly, rather the problem is that changes in our technological abilities and of the economical situation influence the size of reserves.
To illustrate this point we can repeat the example given before on the development of the global petroleum reserves. Even though it should be clear that no more petroleum is being formed today[6], and that the ongoing production reduces the total reservoir base, the reserves have actually risen over time. The reason for this development is that there have been made both new discoveries and technological advancements. The first are due to some exploratory activity going on steadily by energy companies. The latter describe developments that are being made and that enable a larger share of the resources to be exploited.

[6] At least not in amounts necessary to keep our present exploitation going for a significant time scale.

So when for example prices of a commodity rise, then there will be an incentive for the producers to provide more of it, and they will be more inclined to invest in exploration and development of their resources. But the opposite is true, too, and there can be other constrictions that limit the resource base – and so the size of the reserves.

Perry (1981, 242) describes such a situation for the case of coal reserves. As in many countries the reserves are sufficient to fulfil the expected demand, there is no incentive for the producers to invest more to identify new resources. And for the case of most developing countries with potentially large occurrences this is aggravated by a general lack of capital. This leads to an underestimation of the resources and prevents a more intensive exploration that might lead to the discovery of new resources and so of more reserves.

Even more until the so-called "oil-crisis" in the beginning of the 1970s, coal was so costly that it could not compete with oil products. After oil prices soared, coal became more competitive for areas where it had not been before, and coal resources and reserves rose between 1974 and 1977 (do, 247, 251). Similar developments, albeit of the opposite sign were noticed in the 1980s, when decreasing energy prices led to the abolition of programmes to investigate energy savings potential in many countries, and when investments in renewable energy resources declined.

Energy Reserves as a Consequence of Various Factors

Energy reserves are, as has been explained in the foregoing sections, dependent on various conditions. In the following we will present some arguments and analyses of economic, technical and political factors that influence reserve sizes, and to a certain degree also the resource base. The reader will notice a slight discrimination by putting emphasis on the oil industry. This is not to be unfair but justified by this industry's current, and also expected in the future, large importance for global energy carriers' economical situation[7].

Energy Reserves as a Consequence of Energy Prices

Higher energy prices will give incentives to invest in more exploration and in technologies to exploit the known resources to a higher degree. At the same time high energy prices also give incentives to find more energy savings, which opposes rising demand, and according to the rules of the market economies could lead to a lowering of prices, which again will diminish incentives to do exploration works.

One could now speculate that ever increasing energy prices would occur, when the fossil energy resources will be exploited so much that energy reserves will dwindle sometime in the future. This would be a market reaction to the increasing scarceness that the World will experience in this situation. But some indications do not point into this direction.

First, already today renewable energy sources are contributing to an ever increasing degree to the global energy consumption, and more are being developed. Renewables are in that respect a back-stop technology for declining fossil reserves, and they will also be a back-stop on the question of how high energy prices can be expected to rise, when this situation should become reality.

Second, in the light of the last decades, we should rather not argue for an imminent scarceness of fossil energy carriers causing some price rise. We will later argue that judging from the current reserve situation we cannot necessarily assume such a limit of the resource base. Rather a development is perceivable, where renewables will gain very much in importance in the next decades, and on the background of this back-stop technology and prices this development will actually mean that the fossil reserves will decline, as it will not be profitable to exploit the resource base fully.

In a following section we will also shortly describe the influence that the political *Organisation of Petroleum Exporting Countries*[8] (OPEC) had on oil and energy prices during the last decades. This is a matter that also has economical implications, which will be treated in that section.

Generally speaking one may argue that higher energy prices will result in higher reserves estimates and also more prospecting being done by energy companies, so that the energy resource base will increase. It is important, though, to acknowledge that this process is not only limited by geological but very much by economical considerations: "Just as other industries do not try to produce and hold in inventory all the goods they will ever sell, the oil industry does not try to find all the oil it will ever need to produce." (Dahl 1991, 116). This is one explanation for a R/P ratio of about 30 years for oil, a fact that also is acknowledged in IPCC II (1996, 86).

It is important to note that although rising energy prices in principle will result in increased energy reserves and resources, this outcome is normally taking place only after a lag of several years. This is due to the long lead times between exploration and actual exploitation, as is very much the case with natural gas[9], where additions to reserves in the last decades have outpaced the summed consumption so that the R/P ratio for this fuel rose as between 1989 and 1993, where estimates of gas resources were in strong augmentation in spite of 4 extra years of production (Maire and Bouchart 1995, 12): "The reason is that production has habitually lagged

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7 It also is caused by the easy access to literature covering this industry.

8 OPEC was established in 1960. Its members are currently: Algeria, Gabon, Indonesia, Iraq, Iran, Kuwait, Libya, Nigeria, Quatar, Saudi-Arabia, the United Arab Emirates and Venezuela. Ecuador was a member between 1973 and 1992.

9 It is important to remember that development projects for this energy carrier are 'front end loaded', *i.e.* they will only be effectuated if financing and consumption have been assured (Hedley 1986, 29).

behind the additions to reserves by about 12 years. (...) much of the natural gas to be used (...) is gas that has yet to be discovered" (Deffeyes 1982, 19)[10].

Technological Developments and Energy Reserves

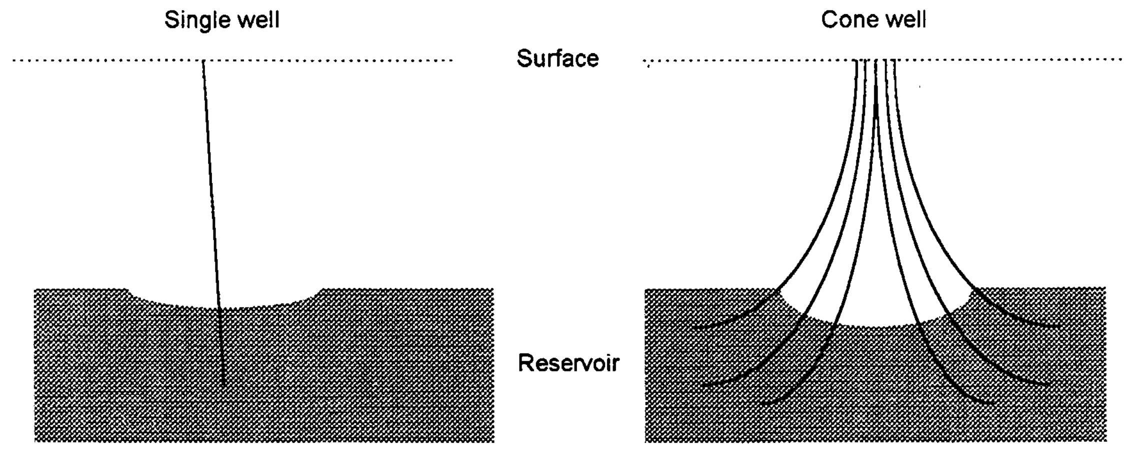
There definitely has been going on a steady development in the extraction and exploration technologies that are being used by energy companies to increase resource exploitation and so also create better economic conditions for their investors.

One of the latest improvements in reservoir exploitation is the introduction of deviated or directional (sometimes even horizontal) drilling, which is necessary to avoid drilling through layers that are impossible to drill through or impractical due to high expenses (Chapman 1973, 185). This technology also enhances the contact space between a reservoir and the wells. By having a cone of various deviated wells drilled from one spot[11] one can produce from a larger volume than is the case, if only one vertical well had been drilled, see Figure 2.

To present another example oil production was enhanced in 1960 by installing a steam-driven system in a small oil field in the Netherlands so that the recovery rate[12] increased from maximal 18 to 33 per cent (Odell and Rosing 1983, 37 f.). This specific field was giving very heavy oil with a high viscosity, so that the flow rates of the oil to the well were slow. For other fields, where the oils were lighter, even higher recovery rates were achieved, up to 60 per cent. The importance of such developments is clear, because at 1980 production levels, every 1 per cent increase in the recovery rate was equivalent to one and a half year of production.

This so-called *Enhanced Oil Recovery* (EOR) is performed with various physical and chemical measures. The techniques range from pressing water and gas into the oil layers, supplying heat by steam injection, or using chemicals to increase the flow rate of the crude. All these measures increase the production of existing wells. And the effects are typically largest for new fields, where the technologies are already implemented, or at least prepared, from the start of the exploitation works.

Figure 2 Deviated versus Vertical-only Wells



Opposite to a single vertical well (shown in the left part of the picture, a cone of several deviated wells (shown in the right part of the picture) increases the contact space between the reservoir and the wells and so enhances productivity. (The indention in the grey reservoir marks the so-called drawdown which is caused by the restricted flow in the reservoir to substitute the produced amount.)

[10] The fact that additions to reserves have been smaller in the last few years, so that the R/P ratio for natural gas has declined somewhat should not be overinterpreted. There is an ongoing exploration taking place, and new resources will be discovered which will lead to bigger reserves.

[11] Like is automatically the case for an off-shore rig.

[12] The recovery rate explains how much of the original oil resource base, known from geological investigations, in a field actually has been produced.

But also theoretical considerations in fluid dynamics and other research areas are playing a role, as exemplified in a recent masters thesis by Orlien and Specht (1996), who investigated the phenomenon of viscous fingers and tried to model this effect. The same can be said for the exploration side, where extended and new considerations and theories help to find possible new discoveries of fossil and nuclear fuels. Examples of techniques and technologies to enhance production are given in *e.g.* Sheriff (1992), IAEA (1991), Chung *et al.* (1988) or Millich *et al.* (1988). They include several visualisation techniques, 3-D scanning, vertical seismic profiles (VSP) and other tomographic techniques, various nuclear analytical techniques, and modelling attempts.

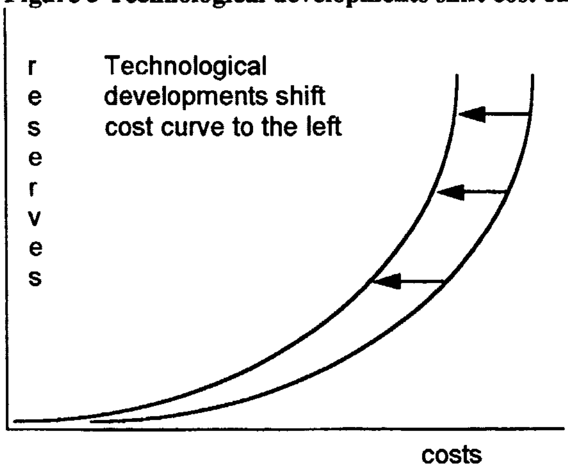
The progress in exploitation and exploration technologies seems to explain the regular spectacular errors in estimates of oil resources, in most cases to the lower end (Hedley 1986, 41), and also the: "lag between discovery of a field and the knowledge of its total reserves gained as the field is developed." (Dahl 1991, 115). And investigations by Masters *et al.* (1992, 56) have proven the effect of such developments in that most of the spurious discoveries in oil reserves actually was due to "field growth", *i.e.* reassessments of existing field sizes due to developments in exploitation technologies.

And if we look at so-called *frontier* locations, then the off-shore exploration for oil and gas seems to have taken a large step forward with the introduction of the *Tension Leg Platform* (TLP) technology as exemplified by the "Auger" and "Mars" platforms that are producing in the Gulf of Mexico (Der Spiegel 1996). Those platforms are installed in a water depth of 872 metres, 896 resp., and enable production from a larger part of the *Outer Continental Shelf* (OCS) than has been the case so far.

Similarly the production in the *Alaskan North Slope* (ANS) or in parts of Siberia of crude oil and natural gas, and the generally problem free transport of those products to the large consumer regions show that technical progress in the exploitation and infrastructure technologies is taking place, and it would be wrong to assume that no further progress will take place in this area. And those developments[13] should ensure that production costs for similar types of reservoirs should go down in the future compared to today's situation.

To conclude we have to acknowledge that technological progress shifts the cost curve, shown in Figure 3, to the left so that for given real, *i.e.* corrected for inflation, energy prices a larger reserve can be exploited in the future than is the case today. This process is, however, limited, as we can never exploit more than the TEMAPS amount, and another limiting factor is the exploration activities that have to be done to find new reserves at all.

Figure 3 Technological developments shift cost curve to the left



Political Impacts on Energy Reserves

While technological and economical conditions can be assumed to be less variable, this might not be the case for political considerations. For example the "Gulf War" had only some minor impact on the global energy situation, while the "Yom Kippur" war led to political pressure being laid on industrialised countries by the

[13] Often called a learning curve approach. When the staff learns to exploit the technologies better, and when innovations are made on the way to improve a process.

Arab or Muslim dominated OAPEC, via a so-called oil-blockade, in the aftermaths of which global energy prices soured.
Any consideration on the global energy situation will have to omit such scenarios, as they appear to be unforseeable. We can predict, to some degree, political stresses resulting from economic developments, for example when a region seems to suffer from a lack of development so that its inhabitants experience some frustration over living standards. But as the example of Central European and Soviet political and economic systems has shown us, we are way from predicting exactly when, or how, such developments will end. Nobody would have been able to predict the decline of the Soviet empire before the inauguration of Mikhail Gorbatjev. Neither woud anybody have been able to predict the consequences of Glasnost and Perestroika, resulting in the German unification. Nevertheless, whenever such revolutions happen, they will influence the global energy system, either through changes in demand patterns or through impacts on the reserves and production patterns.
Normally the energy supply is under the very strict auspices of at least the United States, who is especially dependent on the import of petroleum, as her own production will go down in the near future due to resource depletion[14]. But also other countries are very much aware of their situation with regard energy import, and they will try to influence the supply side. Both by trying to avoid unnecessary conflicts with producers and by ensuring unrestricted transport of the energy carriers.
We may argue that in a World, where the ongoing globalisation plays a large role, political stresses will tend to go down. It will become ever more vital for any country to ensure unrestricted access to possible markets and to stay attractive for potential investors. This should reduce conflict potentials.
Another point to note is the preponderance of different governments to influence the reserves and resources estimates by political considerations. One example is the increase in petroleum reserves in the late 1980s, which is more or less exclusively caused by a re-evaluation of the Middle East hydrocarbon reserves. This was drive4n by technological development and the identification of new reserves (Masters in Biswas 1992, 66), but could also have been driven by the wish of some of the OPEC members to cause even lower energy prices, which would be considered helpful in preventing research and investment in *e.g.* renewable energy forms[15]. On the other hand one could also imagine a situation, where an administration would be trying to downplay the reserve size. One reason could be to try to evade interest from other sides, one could imagine a country that was not interested in attracting exploration activities, because of various political considerations. For example, if a country was interested in keeping away influences by others to protect its culture like North Korea or Cuba. And if we direct our attention to the so-called Western World similar examples are known, like the nationalisation programmes in various Latin American nations from the wish to gain control over vital industrial activity in those countries or as a result of political considerations. As a result multinationals[16] had to withdraw from those countries. This again has led to those companies to discount the region's potential for hydrocarbons, and so can cause smaller reserve estimates than otherwise would be the case (Odell and Rosing 1983, 31).
Other reasons aside from the strategic ones could be the wish to underestimate reserves from a, possibly more far-fetched, strategy. Countries might be interested in manipulating the market price, to make it rise, by trying to argue for smaller reserves than actually is the case. One has seen a similar approach not by a country, but by the diamond merchandiser de Beers in the 1970s. In that case it was not literally the reserves that were being artificially reduced but rather the supply of industrial diamonds from the former Soviet Union when de Beers decided to buy a sizeable fraction of that export to keep high prices. The example might illustrate that such strategies indeed exist.
And indeed from the newest history we know the example of another cartel trying to harvest the monopoly rent, *i.e.* gaining higher prices than one would otherwise expect in a free market situation. This is the well-known OPEC group of countries, which despite members like Nigeria, Venezuela or Indonesia generally is being

[14] We abstract from the newly developed *Mars*-field off the Mexican Gulf coast (Der Spiegel (1996).

[15] An indication of this might be the following quotation of Sheikh Yamani (the Saudi Arabian Oil Minister) in Jidda in the fall of 1981:

"As a result of the Saudi production and pricing policy many major companies have been very reluctant to implement their energy substitution projects. This is in the interest of the Arab cause in that it restores the importance of oil (...) Oil as a political weapon will come back once again when there is a balance between supply and demand." (McGeer and Durbin 1982, 14)

[16] Also called the *Seven Sisters*: BP, Chevron, Exxon, Gulf, Mobil, Shell, Texaco.

considered as an "Arabian" organisation. We will shortly analyse the development that led to the so-called "oil-crisis"[17] around 1973, and another one around 1979.
The importance of petroleum rose until 1974, where it covered 48 per cent of the global commercial energy supply (Baratta 1995, 1027). This development was apparently also a result of the *Mandatory Oil Import Control Program* (MOIP) enacted by the United States. MOIP protected the US industry from global low oil prices, but it also resulted in a more rapid depletion of the US reserves. So the energy shock in 1973 could not be absorbed by increased US production, and worse still, MOIP very likely led to slightly lower global oil prices before 1973 than would have been the case otherwise (Vance 1991, 67 f.). This enhanced reliance on petroleum in other regions of the World. So in 1973 no country could evade the OPEC monopoly prices.
Demand growth rates until then were about seven per cent every year, or equivalent to a doubling every decade. This trend was seemingly perceived to continue for a long time, because as late as 1972 major oil company representatives would defend it and argue for the industry's preparedness to supply the large amounts that would have been necessary to fulfil their predictions (Odell and Rosing 1983, 43, 83 ff.). But as we all know this kind of periodic doubling can not go on forever (Hedley 1986, 7), especially when resources in principle are limited. And this was what the World seemed to realise in 1973.
At the same time the oil price rises initiated energy savings and oil substitution programmes in the industrialised countries, OPEC's largest customers, so that global oil consumption actually fell between 1979 – when the Iran-Iraq war started (Hedley 1986, 49) – and 1985 by about 8 per cent (Krapels 1991, 48). This led to imbalances between supply and demand, which can also be seen in the high degree of the price volatility after OPEC had established price control compared to the decades before (Vance 1991, 80). OPEC recognised that it was suffering from declining revenue from loss of market share, which hid Saudi Arabia that worked as a swing producer[18] hardest. This was especially critical, as the country turned out to have an unbalanced domestic budget .
In the end OPEC's economic situation became unbearable. Saudi Arabia declared that it was willing to sell oil not on the basis of the crude oil OPEC price but rather on the revenue generated from the final products after refining, the so-called *net-back* pricing system (Askari 1991, 35). The price for crude oil plunged from $28 before to $8 in August 1986. This ended a period of higher energy prices, and in real terms fossil energy has become as cheap as in the 1960s.
Another trend that was an important factor when we look at the current low energy prices was the brake up of the major, multinational oil companies' horizontal concentration, *i.e.* their access to a large market share of the produced crude oil. During the 1970s they lost their grip on the production facilities in the OPEC region, when the members enacted nationalisation programmes (Verleger 1991, 88f.). The multinationals lost their controlled access to crude oil and subsequently closed or sold about a third of their refinery capacity. This opened up for new, or smaller already existing, companies. It also meant that multinationals no more were the actual price maintainers. This role had to be played by the OPEC members, with the results shown above.
It is important to note, the *global petroleum and derivatives market* only started to become important in the late 1980s after those incidents had made their impacts. Before 1988 there was no literal market, as noted by Verleger (1991, 101). The OPEC cartel, due to its large market share, controlled global supply. But the high price of petroleum since the first "oil price shock" had a back side of the medal: it furthered large investments in other regions, like the North Sea[19] or the ANS, which brought onto stream large oil reserves[20], so that non-OPEC production rose from 35 per cent in 1973 to 60 per cent in 1986, and the high oil prices provided for by OPEC benefited independent those independent oil producers (Al-Chalabi 1991, 7, 12f.), also known as *free-riders* or the *competitive fringe*. This development caused the market share of the OPEC members to dwindle.

[17] Which never actually was a real supply crisis, cf. figures 4.2 and 4.3 in Vance (1991, 70 f.).

[18] *I.e.* it changed its own production to keep prices high and diminish any price trends that OPEC could perceive by means described by Morse and Nanay (1991, 178), while the other OPEC members generally did not follow the agreed upon production . There was also a technical reason: the country needs a minimal oil production to satisfy its natural gas needs, in the form of associated gas (Askari 1991, 31).

[19] Together with the Mexican production 10 per cent of the world oil production (Hedley 1986, 11).

[20] However, it would be wrong to accept this as the ultimate reason. Vance (1991, 74) states that the rise in non-OPEC oil production was 5.5 per year between 1960 and 1973 – and only 3.3 per cent from 1973 to 1986.

Currently we are facing a situation, where the market share of both the major petroleum producers, OPEC, and of the major oil refiners and distributors, the multinationals, is large, but not determining. These trends mean that the power of OPEC or the multinationals has been reduced, and they oppose any measures to enact a new price control action, like OPEC has done in the past, so that "Future changes in oil prices will depend upon trends in market concentration" (Verleger 1991, 105)[21]. This is affirmed by Morse and Nanay (1991, 195), who conclude that the "movement from setting prices administratively by exporters to market-based mechanisms (...) took decision-making control over pricing away from producers. It is likely to be a durable change".

At the same time the OPEC nations do not have the financial capacity or human resources to extend their influence by increasing the vertical concentration, by acquiring more downstream activities (Morse and Nanay 1991, 196). This will be even more the case, as a probable price increase in the crude will not be totally transferred to the refined products. Therefore the refining step will lose somewhat in profitability, so that increases in petroleum prices could have a zero net effect.

In other words: presently it looks as though low energy prices are a reality for the immediate future, and as petroleum still is the most important fossil fuel traded globally today, this generally should influence total reserve estimates to lower margins!

If we look at the hydrocarbon situation, then we could imagine another situation that would argue for lower reserves being published than actually is the case. This one is not very likely, but not impossible. Judging from the current fossil energy reserves, equivalent to about 1000 gigatons of carbon (1000 GtC) (IPCC II 1996, 87), there is not much incentive to argue for a still higher resource base, eventually leading to larger reserves, if we assume political considerations like the following:

From the *status-quo* we know that only about half the carbon that is emitted as CO_2 by burning of fossils will actually stay in the atmosphere. The other half gets currently absorbed in the oceans and the terrestrial ecosystems. The 1000 Gt Care equivalent to an increase of the atmospheric CO_2 concentration of only about 230 ppm from the current 360 ppm resulting in "only" about 590 ppm, or somewhat larger than the doubling of the pre-industrial CO_2 concentration.

In the light of the public interest in the climate change scenarios from such changes we can imagine that it might be considered unwise to argue for much larger reserves, which would imply that much higher concentrations could be reached, as this could hasten decisions to curb CO_2 emissions due to public awareness of the seriousness of the situation.

Actually Suma (1992) is one example for this kind of strategy. Considering only the current proven reserves, and ignoring the very likely reserve extensions by technological progress or also finds of new discoveries[22] the author argues that only about a doubling of the atmospheric CO_2 concentration was possible, contrary to the arguments by the IPCC that argues rises up to several times the current levels can be expected during the next centuries if also additional occurrences were exploited[23].

Finally we also have to mention underreporting due to economic reasons, as predominantly will be the case in developing countries, where different investments compete heavily against each other and where high interest rates cause an orientation towards projects with short pay-back periods. Investments in energy exploration or prospecting will then be of minor importance due to the long time ranges involved in such projects. Normally this results in severe underreporting, which is involuntary but nevertheless unavoidable.

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21 It would be completely wrong to say that OPEC's primary successes were due to high capacity exploitation of the petroleum production. First capacity is not a well-defined expression as explained by Krapels (1991, 64). Second high capacity exploitation is not the equivalent of automatically high prices. Every production company aims to keep capacity exploitation high to ensure large profits, but this will not automatically cause the producer charging high prices to harvest the monopoly rent, as a monopoly might simply not exist.

22 "Forecasters often produce calculations valid in themselves, which lead us to believe that present figures for reserves and production mean that there is, say , 30 years of oil and 60 years of gas left in the World's enegry bank. What should be remembered is that 10 years ago the conclusions were exactly the same and who is to say that in 10, 20 or even 50 years's time they will not still be the same – in other words 30 years of oil is an eternity not worth worrying about" (Hedley 1986, 44).

23 The figures Suma used for his calculations are indeed similar for the resource base as given in IPCC II (1996, 87) for natural gas and oil, but for coal his resource base is only about half of IPCC's. The latter could be the major reason for this departure of viewpoint.

If we look at environmental considerations, then the lack of enforcement agencies or their low status in most developing countries in companion with the high profit demand to service loans and shareholders will normally cause rather severe damage from exploration and especially exploitation activities, as environmental considerations play a minor role. The opposite is the case in most industrialised countries, where actions by political pressure groups can result in the exclusion of potential resources from being prospected.
Environmental legislation can prevent activities in certain regions[24], technical norms can exclude some, otherwise profitable, technologies from being applied; all those together will be preventive for further exploration and production activities. The result of such boundary conditions is that the reserves will have to be reduced.

Logistic Approach on Reserve Size

We have before presented some general arguments on the economic, technical and political factors that determine reserve size. We will here shortly present another important approach to the reserve size problem: the question of the logistic factor. By this we do not mean logistics as a science to describe a company's distribution system. Rather we concentrate on the logistical curve approach, as exemplified by the so-called Hubbert's curves[25]; however we extend this train of thought in the light of other knowledge.
As has been indicated by Odell and Rosing (1983, 73), it is not necessarily imperative to follow Hubbert's argument of having a symmetric relationship between production growth and decline before and after the peak. This symmetry is a result of an arbitrary choice that distributes half of the total resource base to a growth period, and the other half to a decline period. If this argument is not followed then an asymmetry develops between both periods. This generally leads to a vastly changed behaviour of the production profiles.
The basic argument of this sections is that in order for the supply to grow there have to be increments in the reserve additions of the same magnitude as well. We have before seen that technological progress enables a larger share of the resource base to be exploited, this means that reserves generally will grow in size over time, so that when one today finds *e.g.* a new oil field and estimates the size of it to be a billion barrels of oil, then it is very likely that in the end, *i.e.* in some decades from today, when the field finally will be exploited, the total production from that field will surpass the billion barrels, so maybe 1.3 billion barrels will actually have been produced. This "field growth" is one explanation for the spurious rise in reserves that Masters *et al.* (1984, 234) have pinpointed as being a critical factor for the oil industry (Masters *et al.*, 1992, 58).
Even if we accept the origin of some reserve written up as a result of technological progress, another problem arises, which simply originates from the fact that fossil energy resources are limited, that we know there is a TEMAPS. This is related to a question of how fast we can discover new resources, and also how fast technological progress will allow us to extend the resource base, to make up for the ones that will be exploited every year. Theoretically we could allow as high reserve additions as necessary for an ongoing rise in production, but in principle they will be limited.
There will be technological and economical limits to reserve additions, as not only production but also the transport structure will have to grow at the same rate to ensure that the energy carriers will reach their customers. And there will be financial restraints, if such investments have to compete with other investments which probably have even higher rates of return. It is therefore important to acknowledge these constraints, and to take them into account, when one looks at the probable development of the reserves additions and so the production profile.
And the constraints of the reserves addition rely very much on the actual growth rate of the demand. Imagine the standard situation, where demand is growing at some rate. The current R/P ratio says something about how long the presently known reserves will last at the present production figure. Strictly speaking the R/P is only valid for a constant production. As soon as there are ongoing changes in the production, either growth or decline, the actual, or the effective, R/P ratio has to change. This is illustrated in the Figure 4, where a normal R/P of ten years for no growth is confronted to different annual demand changes[26].

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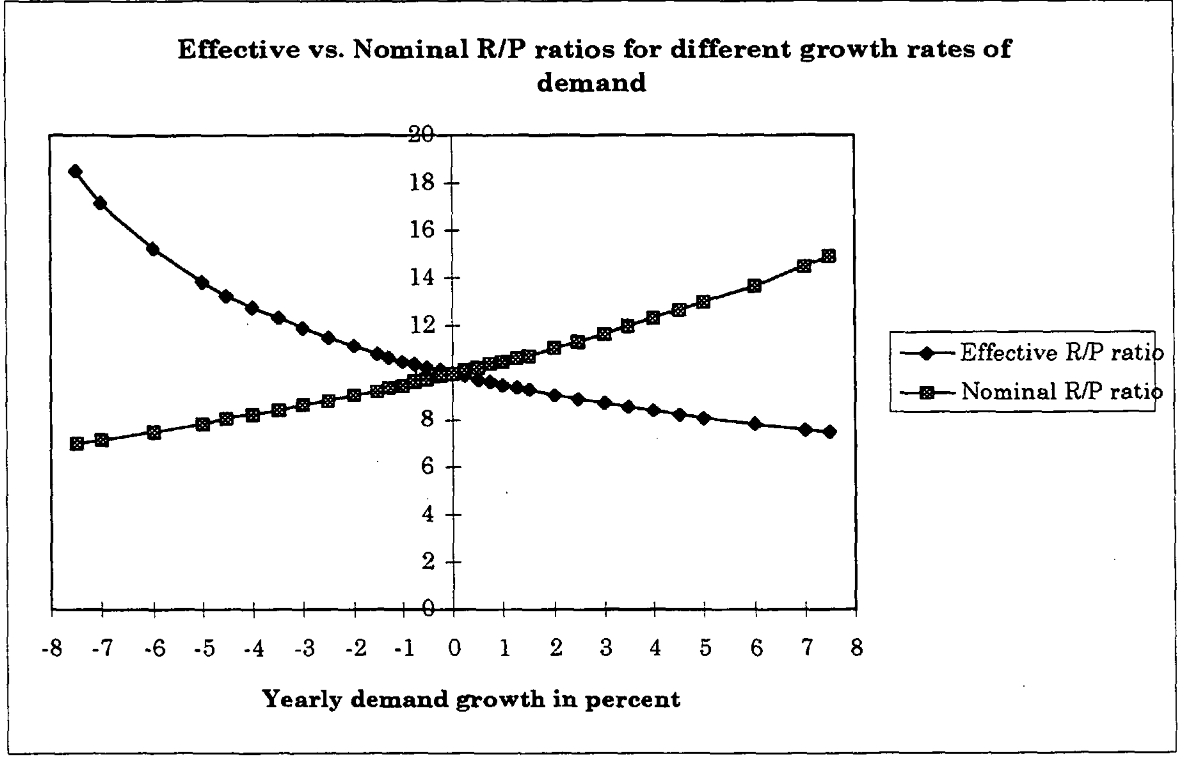
[24] For example the losses in proven reserves in the US states of Louisiana and California in 1986 were caused by larger areas being exempted from possible exploitation by state authorities (Dahl 1991, 112).

[25] The Hubbert curve is a means to investigate how, in the light of a limited resource base, oil production would develop over time. It resembles in shape somewhat the well-known bell curves from statistics.

[26] We have to stress that the figure is based on exponential growth. This signifies that an annual growth of ten percent over two years actually means a growth of 21 per cent, and not as in linear calculations only 20 per cent. This is the result of the rent's rent effect.

The difference between the nominal and the effective R/P ratio means that at any time reserves will last much shorter than given from the current nominal R/P ratio, when consumption is growing. This means that the actual reserves additions will have to be higher, in fact they will have to grow at the same rate as the consumption itself. Considering the long lead times in investments for energy resources exploitation, this principle therefore puts an upper limit on the actual consumption growth that may be accomplished.

Figure 4 Growth rates and effective and nominal R/P ratios



This figure on effective vs. nominal R/P ratio is an extension of figure 2.1 from Odell and Rosing (1983, 57). The curves are normed to a 10 year R/P ratio for steady consumption.
The effective R/P ratio indicates that for growth (right hand side of the picture) a given R/P for current production levels actually overestimates the R/P ratio. So for about a 5 per cent growth every year the current ten year reserves in fact only will last for about eight years. In order to ensure that we have in fact enough reserves to cover the next ten years of consumption we should have a current R/P ratio of about 13 years, as is indicated by the curve for the nominal R/P ratio.

It is also important to take an extension of this idea into account, when we look at the possibility to have a sustained production at a certain level, which would be necessary to extend an energy system over a longer period. We do not in this investigation have the resources to perform a full calculation necessary for this purpose, but we can follow some of the results given by Odell and Rosing (1983, 143 ff.). They have done these calculations for petroleum, but the ideas apply equally well to other energy carriers. What they have calculated are the production profiles, *i.e.* the way the annual production will behave over a period from 1980 to 2080[27] for several different cases of assumed growth rates, resource size and reserve addition limitations.
A fundamental result of several of the calculations of Odell and Rosing is that in many instances production will not evolve smoothly over their integration period, but that the production will show a very sharp peak, and a very sharp decline afterwards (do., pp. 164-170). The reasons for this phenomenon are: At the peak production level a large share of the resource base has already been discovered so that the size of the reserve additions will become much smaller than for the period before. And there will only be modest increases in

[27] They have used the historic development for the period before 1980.

reserve additions from technological development, and those will be very expensive, so that they will buy fewer increases than at the start of the development.
From the examples given in by Odell and Rosing we can conclude that for reaching a plateau:

- a low yearly increase in consumption is very favourable,
- higher growth rates in the start will normally lead to a sharp decline in production later on,
- large resource size will only be advantageous if the growth rate in demand is low, otherwise there will occur production catastrophes.

These are important conditions for finding out, whether it might be possible to establish a future scenario, where fossil energy carriers are still being used, and where the inertia given by the long life time of energy system components and other considerations will not lead to major economical distress, when the production of the fuels, limited by the factors presented above, is drastically reduced.

Conclusions on Reserve Size Influencing Factors

Political vagaries can not be taken care of in normal reserve calculations, and we have to submit to the arguments given in (WEC 1993, 97) that international conflicts or trade disputes may interrupt supply, but that they cannot be forecasted properly, and normally will be of intermittent influence, so that they should not pose large problems. WEC and IIASA (1995, vii) have made the point that most scenarios make the lack of such discontinuities a strong assumption about the future. It is probably only fair to acknowledge that this can not be done differently.
In the future we will hopefully see fewer of those cases, the economy becomes globalised, countries' cultures will converge, and the information flow liberalised. Manipulations with the reserves or the resource base will therefore be of decreasing importance. However, we have to be aware that practices as have been mentioned before, or the lack of adequate data, can lead to underestimates of the current energy reserves and the resource base.

Current Global Fossil Energy Reserves

As we have explained in the foregoing paragraphs, the term *energy reserves* is not defined in an absolute, physical, way. Economic, technical and political considerations play a large role in determining the actual size of those energy reserves that we presume to play a role in the immediate future. It is important to keep this in mind, when we now present the global energy reserves, where we start with an aggregated overview of them from sources like IPCC (1996), WEC and IIASA (1995) or Masters *et al.* (1992).

Global Reserves' Data

An analysis of the data of the different sources mentioned above (not shown) has shown that the differences between them are small with regard the size of the total fossil energy reserves and the resource base. We there think that for a general overview on the global energy reserve situation, it suffices to quote the data from IPCC (1996, 87), see Table 1 on the following page.

When we, as a first approximation calculate the Resource Base/Production ratio (RB/P), it can be seen that the fossil resources are rather large, and no immediate scarcity can be expected. Also the supply situation has been rather stable in the last years, and barring major national and international conflicts this will remain so in the next decades. There are several reasons for this, as has been explained before:

- an ongoing exploration activity and the development of new technologies to enhance the exploitation of existing reserves, especially in the oil and natural gas industries.
- after the turmoils of the 1970s and 1980s a period of more stable and in real terms only slightly higher prices compared to the stable pre Yom Kippur period (BP 1996, 14), which has made long term planning easier, especially important for energy infrastructure.
- the lack of a political control of energy prices on a global scale as OPEC has done historically.[28]
- global energy prices are also stablised by an increasing share of renewables, as they serve as a back-stop technology[29].
- global energy prices are prone to stay low as they already contain the very small resource exploitation rent (Cline 1992, (?). This means that producers do not have to gain a larger amount extra from their customers.

If in spite of the rather low energy prices, the reserves are actually rising, this shows that the markets serve to balance supply and demand, and that energy reserves look to grow and stay high in the near future[30].

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[28] This does not exclude that in some countries energy prices via fees and taxes have been stabilised against the weak markets during the 1980s to enable long-term planning and rational energy use schemes.

[29] According to (?) wind energy has already become competitive to coal fuelled power stations.

[30] This interpretation could change drastically, if the basic conditions change. However, I am unable to do such forecasts.

Table 1 Global fossil energy reserves, resources, and occurrences, in EJ

	Consumption		Reserves	Conventional Resources			Unconventional Resources		Resource Base	Additional Occurrence	RB/P Ratio	AO/P Ratio	R/P Ratio
	1860-1990	1990	Identified	95 %	50 %	5 %	Currently recoverable	Recoverable w/ technol. progress					
Oil													
Convent.	3343	128	6000	1800	2500	5500			8500	>10000	66	>78	47
Unconv.	-	-	7100					9000	16100	>15000	126	>117	55
Gas													
Convent.	1703	71	4800	2700	4400	10900			9200	>10000	130	>141	68
Unconv.	-	-	6900				2200	17800	26900	>22000	379	>310	97
Coal	5203	91	25200				13900	86400	125500	>130000	1379	>1429	277
Total	10249	290	50000	>4500	>6900	>16400	>16100	>113200	>186200	>987000	>642	>3403	172
Nuclear	212	19	1800		2300		4100	>6000	>14200	>100000	747	5263	95

Notes:
-: negligible amounts,
blanks: data not available,
all totals have been rounded.
RB/P: Resource Base to Production ratio (in years)
AO/P: Additional Occurrences to Production ratio (in years)
The data for nuclear are based on current technology. If breeder reactors were used, the energy reserves and resources should be about 60 times higher.

Original source:
IPCC (1996, 87)

The original source contains more references to the data that have been used for the aggregation that we cite here.

Current Global Rewable Potentials

While the reserve and resource definition is quite straightforward for fossil energy carriers, this is not the case with the traditional and new renewable energy forms. We cannot speak of reserves, rather we need to talk about *potentials*. The potentials for these energy forms are not defined in a simple way, rather they themselves depend on the technological situation.

One example may illustrate this: We can assume that in a country like Germany, there will be a certain area available on buildings where we can attach PV elements on roofs and façades. If we assume that we use all the areas available, then for given meteorological conditions the total production, the potential, depends on the conversion efficiency of the PV panels. The potential then will double, when efficiency increases from on average six to twelve per cent, *i.e.* the conversion of the incident light energy to the electrical output.

The same is in principle valid for some other renewable energy forms, like the conversion of organic material to biogas, or the use of resumes from agricultural crop production for energy purposes. Research in different technologies can lead to enhanced biogas production compared to today's technology. But the potential of those energy carriers also depends on how much there is available for energy purposes.

The example of whether it may be possible in organic farming practices to take out straw for energy purposes, and to feed back the rest products to the fields to recycle the minerals, is highly discussed in different circles, and it certainly is an important aspect to take into consideration: if organic farming can be shown only to be feasible, if no such extraction is taking place, then the potential of agricultural resumes from such farming practices will be reduced, compared to traditional farming practices. The same will then probably also be the case for biogas production from slurry and manure from husbandry.

Traditional Biomass and Waste

We have not assessed the potential of traditional biofuels in the scope of this project but only quoted the current use of fuelwood and charcoal. Whether or not this present use is sustainable, remains an unanswered question. Waste is being exploited as a fuel in several countries in power stations and heat plants. In the future, we assume that complete recycling will take place, so that waste will no longer appear as a fuel. We have to indicate here, that many forms of waste are not CO_2 neutral, as they are produced from fossil hydrocarbons or coal. Globally today the equivalent of about 7200 PJ of oil and 600 PJ of natural gas are being used for non-energy purposes, plus some coal that we have not considered explicitly.

Hydropower

Electricity from hydrologic reservoirs is a primary energy source that in places can have extraordinary large significance. We have not assumed any development in this energy form, and use current day production figures also for the future scenarios. The reason for this is that we, despite initiatives to increase their acceptance (Flanders 1997), assume a growing resistance towards the establishing of new hydropower installations, as those will mean loss of natural reserves and also relocating many people, which will be restricted in societies with high moral standards.

The disadvantage of this choice is that we also assume a very long lifetime for existing installations, an assumption that can be critisized, as we know that some of those already are experiencing a tilling up phenomenon, whereby till is transported via the rivers feeding into the reservoirs filling them up, so that capacity decreases. Basically this means that we also have to assume new reservoirs will be built to substitute for the older ones being lost to this account.

The total significance of hydropower is, however, diminishing. Today about 15 per cent of the total electricity generation is from hydropower plants. In the fossil scenario this share will decrease to about 8 per cent.

Regional Resource Overview

Fuel Characterisation

In this section we describe the fuels from a more general point of view, and we try to present a more detailed overview over the currently known and perceived resource situation of the following energy carriers: coal, petroleum, natural gas, and traditional biomass. The reason for this is to indicate to reader the current energy import and export flows, and also, by looking at probable further energy resources, to indicate possible future such flows. This has some strategic importance, and we will later on try to estimate the importance of those relations for the geopolitical situation. The EIA database, BP (1996), and information from Masters *et al.* (1992) will be used predominantly for this purpose.

Coal

Petroleum

Natural Gas

As explained by Deffeyes (1982, 19) natural gas actually is not just pure methane (CH_4). A few percent of higher numbered carbon molecules[31] will accompany the methane extracted from the wells. However, those by-products are being removed from the natural gas stream and sold separately at a higher price. The product is then called *dry natural gas* opposite to the original *wet natural gas*, a *lean gas* falls in between.
Natural gas is occurring either associated with petroleum or alone, in the latter case often in regions, where no petroleum would be found (Deffeyes 1982, 20 ff.) as so-called *non-associated*, generally dry (Hedley 1986, 27), gas. As non-oil regions are relatively easy to recognise and therefore easily can be avoided by petroleum companies, those regions now are valuable as being unexplored with the incentive of being very probable gas reservoirs. We will only mention theories that argue for methane emanating from deeper layers of the Earth's crust (Gold 1982)[32], which would result in a possibly much larger resource.
It seems as if it was not possible to estimate natural gas resources fully, at least new additions have outpaced the aggregated consumption, and so reserve estimates for natural gas have been climbing in the last decades, so that they would last about 60 years at current consumption.
Impacts on the environment of natural gas production are similar to the ones for crude oil production. Water based drilling fluids are used that may be liberated, and cuttings from the well drilling are dispersed around drilling sites; but all in all such emissions are characterised to be insignificant, and there are regulations forcing the producers to reduce the amount of oil in the discharged cutting muds (EU 1995d, 266 ff.). We have not assessed those any further.

Regional Energy Resource Distribution

Table 2 shows the regional energy resource base (=sum of known reserves and additional occurences as explained before) distribution based on data from Masters *et al.* (1992) for oil, natural gas and NGLs and EIA (1997) for coal. The data for coal do only comprise the currently known reserves, not the total resource base as is the case for the other energy carriers. We see that the energy resources are very unevenly distributed around the World. The oil rich nations of the Middle East and Russia top the energy resources, while the Japan and the Four Tigers group and Oceania are very badly equipped with own energy resources. Skal data ordnes efter størrelse, region eller alafabet?

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[31] So-called *natural gas liquids* (NGLs).

[32] What Gold means is that methane, and to a certain degree also petroleum is created via processes in the Earth's crust. If that poses to be true then case natural gas could also be described as a renewable energy carrier. It is, however, not known to the author, whether the isotopic composition argues against this theory, or how large this source currently is.

Table 2 Regional Energy Resource Distribution

Regions	Geographical region	Coal	Oil	NG	NGL	TOTAL
AF1	South Africa	1662	0	0	0	**1662**
AF2	Maghreb	4	633	433	20	**1089**
AF3	Other Africa	20	412	453	21	**906**
AM1	Canada and United States	6329	1131	1573	198	**9231**
AM2	Brazil, Argentina, Mexico	83	969	476	21	**1549**
AM3	Caribbean & Latin America	212	1028	587	69	**1896**
AS1	Japan and Four Tigers	26	0	0	0	**26**
AS2	New Industrial Countries	2323	406	645	31	**3404**
AS3	Asia	7	1168	204	10	**1389**
AS4	Oil rich countries	6	8299	4216	173	**12695**
AU1	Australia - N Zealand	1888	48	196	7	**2139**
AU2	Oceania	0	0	38	2	**40**
CHI	China	2394	588	238	15	**3235**
EU1	Western Europe	1065	536	690	32	**2323**
EU2	Central Europe, Turkey, Israel	949	1	8	0	**959**
EU3	Poor Europe	57	32	52	3	**144**
RUS	Russia	4372	1604	4131	206	**10314**
	SUM:	21397	16855	13939	809	**53000**

As we have here only taken account of the reserves and traditional additional resources, our data are underrepresenting the total resource base. There are larger untraditional resources left for natural gas (*e.g.* hydrates) and oil (*e.g.* tar sands and oil shales), and there are more resources known of coal, for which the EIA database is very conservative.

All in all the data may serve as a first approximation of not only the current but also the possible future global fuel transport patterns (IV: Håland 1997), as we may assume countries that have a large R/P ratio today very likely also will play a major role in the international energy market tomorrow, as they so to speak save their resources for any possible future exploitation. This may cause some changes in trade patterns compared to today.

5. DEMAND CONSIDERATIONS OF THE SCENARIO

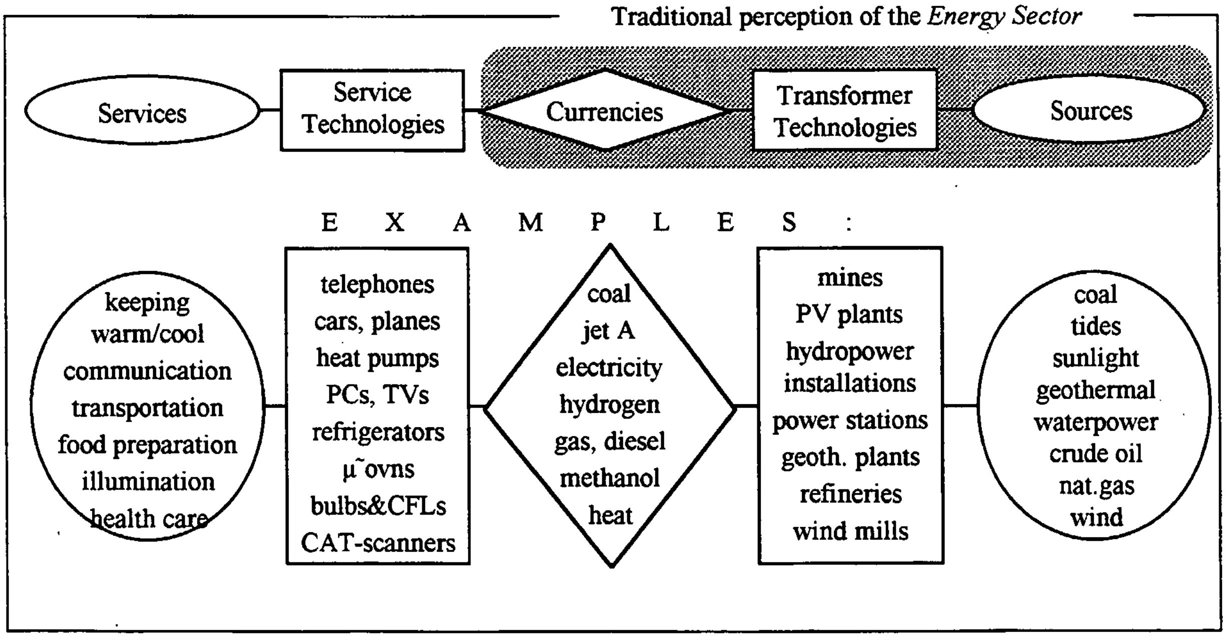
Introduction

Here we will describe how the energy demand within a society depends on various parameters. This description is kept rather general so that, if necessary, the assumptions given here may be used in other conceivable scenarios, too. Examples could be the use of renewable energy sources, or the reliance on various forms of nuclear energy, like large scale fusion, if this technology turns out to become technologically feasible. It will be possible to use our final energy demand patterns for such purposes, as our scenario is based on a mixture of hydrogen and electricity as the *energy currencies*, to phrase it with Robert Scott (1995).

General Demand Description

The basic idea behind this text is a prolongation of ideas put forward by e.g. Scott (1995) who described the thoughts that led him to abolish the general energy chain approach which starts at the point of the primary extraction. He explains also that those thoughts did not come easily to him. He really had to change his normal way of thinking, before he finally accepted the ideas that are connected to the service chain instead of the energy chain, see Figure 1.

Figure 1 Energy chain turnied into service chain



Source: Scott (1995, 91)

Two aspects are most important: First, putting emphasis on the actual services that energy can provide leads to a completely different way of interpreting the energy conversions finally enabling this service. Second, even if we believe to have gained some freedom on the way the energy for the service is provided, we also have to acknowledge another limitation in that the very service that we choose already can fix a large share of the energy provisions and the primary energy form necessary to fulfil the service.

For example sending a letter will, today at least, mean that we have to consider the refining of automotive fuels and the extraction of crude oil to feed the refinery. In that way this service limits our choice in the primary energy carrier finally used. On the other hand, when we choose to send a fax, a series of energy carriers is left that can power the teleconnection lines: wind, PV, fossil, hydro or geothermal power stations, heliostats or fuel cells.

Thus, it is important to look at the actual needs of people before choices can be made on the energy carriers that will have to provide the necessary energy. And it is services that we want, not just energy. The notion of a kilowatthour will not mean a lot to me, 12 hours of television entertainment, however, do a lot more to my well-being. Especially when we consider a situation that is so far in the future as the one given by the scenario's foundation – around the year 2050 – it is allowable to start by looking at the actual demands, before we decide on the rest of the energy system.

And in order to look at the demand of people we also have to have some idea on the services that will be requested. We do this by starting at the end-use side, which are the services provided. This approach has been described by e.g. Sørensen (1995b) or Toop and Aulakh (1996). Basically the idea is to look at what services that we really need, and to use physical assumptions to analyse, what energy amount actually would be sufficient to provide those services, when the optimal technology has been chosen.

We also take into account other factors that influence end-use energy pattern like climatic and economic parameters, that should be taken into consideration for an optimal description of the demand patterns.

Starting Point: Bottom-Up Energy Demand Analysis

The basic principle is going through all the services that we actually need and optimising the energy system by taking account of synergy effects, we reach an service energy demand pattern, and from this we acquire the final energy consumption and its pattern which then has to be provided for by an energy system that is completely newly designed.

So we describe the energy services that relate to *e.g.* the living environment (shelter, HVAC, lighting), various forms of services, industrial energy uses and transportation by using some assumptions on socio-economic and climatic factors and some technologies that we choose from a catalogue of various future options.

The following energy services are being considered:

- Refrigeration and Cooling
- Space Heating
- Provision of Low, Medium and High Temperature Heat
- Stationary Mechanical Energy
- Electrical Appliances
- Transport Work

Figure 2 on the next page may give the reader an idea of the values stemming from such an end-use type analysis by Sørensen (1995b, 81) that takes into account service energy demands for societies at different geographical locations and of varying economic systems.

A short Warning

Here is probably the right place to provide a short warning: our end-use assumptions are very general and they are based on our current understanding of matters. They therefore cannot take into account trends that will evolve during the next decades but that could have a strong influence on the final energy consumption and the end-use pattern. As one example we might mention the introduction of office automation and the use of personal computers in the residential sector. Such a trend would not have been able to be forecasted in the 1960s, when the general thought was that the World could suffice with "five, maybe six large computers"[1].

On the other hand, the same example also may illustrate that a development can be used to improve an energy system's efficiency: Electronic circuits made possible processes that need less energy and materials. This rationalisation had some share in the generally declining energy intensity of the traditional *industrialised countries* (ICs)[2].

It is generally feared that this built-in weakness of bottom-up analyses leads to underestimating mitigation costs, where *top-down* analyses should overestimate them, but recently this viewpoint has been challenged, too (Krause 1996).

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1 As far as I remember, this was uttered by a respected IBM top manager. History has proven him wrong, but that obviously did not harm IBM.

2 Another share was due to exporting part of the heavy industry.

Figure 2 Scenario for the rate of end-use energy needed for satisfying goals in different societies at different geographical locations (in W per capita, 1 W per capita is equivalent to a yearly consumption of 8.76 kWh or 32.536 MJ)

	Cooling & refrigeration	Space heating	Process heat <100 C	Process heat 100-500 C	Process heat >500 C	Stationary mechanical energy	Electric appliances	Transportation work	Food energy	TOTAL
Biologically acceptable surroundings	0-24	0-1500	0	0	0	0	0	0	0	0-1524
Food and water	14-24	0	15	2-6	0	0	0	0	120	151-165
Security	(0)	(0)	0	0	0	(0)	0	(0)	0	(0)
Personal Hygiene & Health	0	0	80-150	20-40	0	0	(0)	(0)	0	100-190
Relations, leisure	(0)	(0)	0	0	0	0	10-60	25-133	0	35-193
Industrial activities:										
Construction	0	0	0	0	0	30-60	0	7-15	0	37-75
Services and trade	1-8	0-600	0-12	0	0	6	10-20	30-70	0	47-716
Agriculture	0	0	2-12	0	0	3-6	0-2	3-6	0	8-26
Manufacturing industry	1-16	0-600	10-100	20-70	12-30	20-60	15-30	7-15	0	85-921
Raw materials and energy	0	0	0-30	0-20	0-250	0-170	0-30	0-20	0	0-520
Education	0-2	0-160	0	0	0	0	1-2	0	0	1-164
Commuting	0	0	0	0	0	0	0	0-30	0	0-30
TOTAL	16-74	0-2860	107-319	42-136	12-280	59-302	36-144	72-289	120	**464-4524**

Source: Sørensen 1995b, 81, based on previous work by Sørensen.

Notes:

(0): means less than 0.5!

The ranges indicate geographical and socio-economic differences leading to different demands.

Security means protection against outer enemies and police work. As can be seen energy demand for this activity is negligible. Also recent trends in the breakdown of the formerly well-established political and economic blocks and the steady industrial globalisation indicate that outer security might become of even lower importance in the near future, so that neglecting this factor is admissible.

End-Use Determining Factors

After having described the general current end-use patterns we have to start with a description of other factors that determine service demands. As is explained later on, we follow a kind of IPAT-method. This means that we will treat populations depending on their affluence to gain values for the energy demand, and in order to do this we take into consideration some determining factors for this.

The most important parameter is the living standard. In this project we have assumed further development leading to improved living conditions for most people in the World. We might expect that this development decreases the differences between the industrial and the developing regions of today, although this could be a too optimistic assumption. It is, however, supported by the difference in growth rates between ICs and industrialising or developing countries over the last decades[3].

The living standard is influenced by the expected economic development in the regions and geographical conditions:

- Climatological and environmental conditions determining space and cooling demand to a high degree are assumed to be the same as today, although his assumption might be doubtful.
- For the development of the economic situation we have assumed a change to take place according to estimates of the economic development following a so-called "Business as usual" scenario by IPCC II (1994, this refers to IS92a).
- For some countries we make special assumptions on the energy demands due to economic peculiarities.
- Cultural, social, organisational and other factors that determine the amount and kind of services demanded by a society have not been modelled explicitly. They are to some degree being implicitly treated by the economic assumptions.
- Population development is taken from an official source.

Changes in lifestyle will be described by the values that we apply for the service patterns. Those depend on the kind of society for the different countries. A development leading towards more industrialisation in a range of countries means that we have to adjust the end-use energy consumption accordingly. This is generally done on the basis of the country grouping that we have performed before (see the section on today's energy system) and that determines what type of society a country will group in.

From the analysis of the service patterns we continue by taking into account the population development of the different countries and the life-style factor that essentially determines the end-use size. The section will be concluded by remarks on the technological developments and an overview of current industrial emissions. We start with the technology part.

Technological Developments

Another important factor is technological development that leads to improved efficiencies compared to today's average employed technologies. The values quoted in Figure 2 are for the latter, but in order to not confuse the reader we have to remark that we in the following analysis have used assumptions on much better technologies, which leads to reduced end-use energy consumption compared to today.

For example we have assumed that building shells will be much more insulated than today, that a larger share of the heating demand can be fulfilled by passive solar heating, and that cooling demand would be less compared to today for more adequate building codes and practices in generally warmer regions.

Other practices might be to use different technologies to perform the same kind of services, in short we are talking of *rational energy use*, and it has been assumed that the service technologies will be very efficient and advanced in order to provide the services at a minimal energy demand.

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[3] Here it is important to look especially at the small group of countries around the Pacific basin (the Tigers and NICs) that have undergone a rapid industrialisation so that some of them have surpassed the old industrialised countries' income levels. For example Singapore's per capita GNP is higher than that of the UK (19,850 vs. 18,060 US 1993-dollars) (Baratta 1995).

Some Examples of Rational Energy Use

Rational energy use is a basic principle behind the end-use philosophy. It consists of finding out how little energy actually is necessary to obtain the services that we desire. This approach can be helpful in finding out, where savings potentials could be found, see Figure 1, on page 45. For example an exergetic analysis shows that today the final services are provided at an exergetic efficiency of under 10 per cent compared to the exergy of the energy sources. The largest gap is in the conversion of the final energy to the useful energy at the consumer end of the energy chain. Therefore the energy service technologies are the critical components for improving overall energy system performance (Rogner 1994, 856).

When we, to take one example, look at the job of keeping food fresh, then this can be done in a refrigerator. We know that today's models might not be the most efficient ones, and we can apply some simple rules to calculate the actual energy theoretically sufficient to perform the job. This is a rather low value, and the difference is due to design flaws that make current refrigerators use more energy than we could imagine they needed to – like non-ideal insulation, design flaws in motors or case or the different compartments, or choice of technology.

A factor that could reduce consumption slightly today, but should become more important in the future, when consumption will be still lower, is to use the outside as a receiver of the compressor heat (Nørgaard 1989,130). Today this heat is kept inside of buildings. This is thermodynamically unsound in winter, as the extra heat is provided at a high cost compared to general space heating. Even worse, in summer this causes an extra heat load, which in places is counteracted by an air conditioning system at a very high energy cost.

The energy savings example *par excellence* is the introduction of *compact fluorescent lamps* (CFLs) instead of incandescent light bulbs. This new technology has increased lighting energy efficiency several-fold, and for certain applications newer developments pose for even higher efficiencies (Eberl 1997) in providing the same energy services.

Such trends ensure that the same services can be supplied at a lower energy intensity, and this phenomenon is called *autonomous efficiency gains* (AEEI). The trick will be to enhance this process, so that the necessary energy efficiency will be reached in time to ensure that the scenario will not die from a too high primary energy demand. To illustrate this: although there can be factor two differences in the efficiency of energy conversions at the power side, the differences at the service side can be even larger. One refrigerator exists using 80 kWh per year another 400 with the same service fulfilled: keeping cold one's staples – a factor five difference!

The refrigerator example might indicate that only if the most efficient technologies are made available to the final energy consumers can we easily describe the energy systems, otherwise we have to correct for the end-use efficiency. This is not done in this text, and we have assumed the same standards all over the World. Only the degree to which services will be demanded is different, with a higher penetration in the high income countries than in the poorer countries.

Other examples that minimise the total energy demand of an energy system is by load management. This signifies the control of energy consumption by price or other signals. For example, if electricity prices are graduated according to the size of the load, the higher the load, the higher the price, then consumers get the incentive to ask for energy intensive services in times of generally low load in order to reap in price advantages.

An example is the use of cool storage systems in some air conditioning systems. In the night time, when electricity prices are low, a refrigerator system is working at peak power to cool the cool storage. This can then be used during the daytime, when air conditioning demand is high but so also are electricity costs, to provide for cooling, while the refrigerator system is working not at all, or at very low intensity.

Load management serves to even out load demand, so that peak demands should be reduced, and in that way they reduce the amount of peak capacity necessary in an energy system to serve all clients. This reduces material consumption and the indirect energy demand needed for providing the energy technologies.

Population Considerations

The World has been experiencing a steady population growth in the last centuries[4]. This development is prone to continue in the future, although growth rates have been declining lately due to decreasing fertility and the effects of increasing literacy and the spread of information on family planning.

According to different forecasts global population will rise to about 10 billion people by the middle of the 21st century, although this question is under further scrutiny. A study of IIASA has recently shed light on the steady decline of the population growth by means of a Delphi-type investigation, where several experts are asked to

[4] With respect to human beings at least.

comment on and to give some range of trends and developments. Bendtsen *et al.* (1997) have also investigated the difficulties of global population forecasts exemplified by the ones of the *World Bank*.

We need a projection of the countries' population figures for the year 2050. In this study we have had access to the population figures for the year 1990 from the *Food and Agricultural Organisation's* database[5] (SOFA 1996). With respect to the population figures for the end year of our scenarios, 2050, we have chosen to use the data from the UN *Department for Economic and Social Information and Policy Analysis, Population Division* (IR 14), as we could not get the original World Bank data, that are used in the original work by Sørensen (1996), on a country-wide basis.

In this way our population assumptions are slightly lower, 9.4 against 9.8 billion people, than in the scenario sketch. One could as a first relief scale the different countries' population figures by the global population for that year so that the total also would be 9.8 billion people. This is probably not a good idea, as it would under-estimate the population decline in the traditional ICs, and it would also be neglecting the recent downward trends in global fertility that point to a smaller population growth in the next decades than assumed in the World Bank source. Anyway, these slight aberrations, of about five per cent magnitude, should not influence the final results significantly.

The result of the population part of the scenario is shown in Table 1, and in Figure 3 a graphical description of the regional development in population figures is given.

As can be seen the World's population nearly doubles within the next 50 years, and the biggest growth is taking place in the Sub-Sahara Africa, the India and China groups. Populations are expected to decline in Western Europe as a result of the demographic transition. Developing Europe and Russia have been experiencing a shrinking population already, after the decline of the Comecon order and falling living standards, a trend that could continue. It has to be remembered that in the last decades of the Soviet Union population numbers in Russia were declining, whereas they were only rising in the southern republics (Kennedy 1994, 34), so this trend is no new experience for Russia[6].

The growing population in the developing countries will mean an increasing pressure on the ICs to accept in-migration, but we do not know, whether this has been taken care of in the population forecasts. Kennedy (1993, 44) gives a series of examples where developing countries lie nearby developed ones, and where the population gradient will rise steeply. These trends might very well lead to concern and could influence population development of the regions.

Table 1 Regional Population Development (in thousands)

code	Geographical region	Sum 1990	Sum 2050	Difference
AF1	Southern Africa	37066	95711	58645
AF2	Maghreb	118206	269263	150848
AF3	Sub-Sahara Africa	480561	1776382	1295821
AM1	North America	277770	401786	124016
AM2	Brazil, Argentina, Mexico	265535	472872	207337
AM3	Caribbean & developing Latin America	174190	375098	200908
AS1	Japan and Four Tigers	174837	179459	4622
AS2	India group	1289636	2563551	1273915
AS3	Asia	391927	897066	505139
AS4	Oil rich countries	110209	344841	234632
AU1	Australia - N Zealand	20244	31975	11731
AU2	Oceania	6120	15842	9721
CHI	China	1155305	1587048	431743
EU1	Western Europe	366295	352716	-13579
EU2	Central Europe, Turkey, Israel	154648	208119	53471

[5] For the following countries there was no data in SOFA (1996), though: Eritrea, Cook Islands, Gibraltar, Greenland, Montserrat, Nauru, Niue and Tuvalu. For those countries data from Baratta (1995) were used.

[6] It is, however, currently accompanied by shortening life expectancies with regards Russia and some Central European nations..

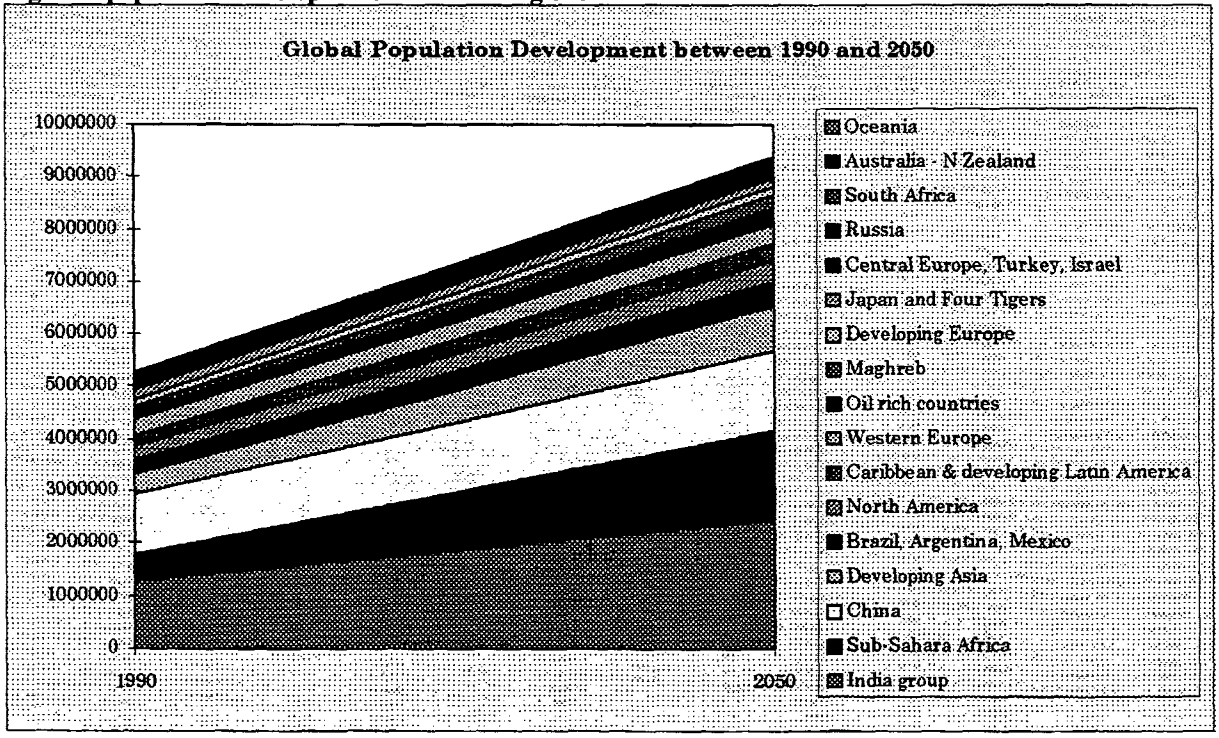
code	Geographical region	Sum 1990	Sum 2050	Difference
EU3	Developing Europe	117725	107898	-9827
RUS	Russia	148309	119623	-28686
Total		5288583	9799250	4510458

Data in thousands.
Source: own calculations based on SOFA (1996), data from UN (IR 14) and Baratta (1995).
Note: the country groups have been presented in the *Overview of the Current Cnergy System* before.

Last, but not least: the realisation of the CFS, or of a different energy scenario, might in itself impact living conditions of the people in *developing countries* (DCs), and also in the ICs[7].

Improving economic conditions in the DCs would, via the demographic transition phenomenon[8], again lead to changes in population development. Although this is a possible source of uncertainty, we cannot consider such developments, as the population data are assumed to be used in other, similar scenarios, too. This remark is, of course, also valid for other potential energy supply scenarios. For example, in a biomass intensive scenario, where for obvious reasons the rural population would play a comparatively larger role than in *e.g.* a centralised fossil scenario, living conditions in the countryside could be expected to improve faster than if development was restricted to the larger metropolitan areas.

Figure 3 population development for the 17 regions



Source: own calculations based on UN (1993).

7 For example enhanced technology and knowledge transfer to poor countries will also improve living standards and thereby influence population growth. Or in the ICs by making it more or less attractive to live in the countryside compared to the towns.

8 By which people choose to have fewer children after living conditions improve and fatality rates decline.

Urbanisation

There has been a very pronounced development of the global urbanity, with an increasing share of the global population living in *megacities* and larger metropolitan areas; in fact the urban population share is rising faster than the global population (IR 15). This trend has some importance for the assumptions on living standard that we have to make.
We follow estimates by the UN *Department for Economic and Social Information and Policy Analysis* (IR 15) that more than half the global population will be urban[9], and that most of the megacities will lie in the today's developing countries' group[10]. This growth is mainly caused by the so-called *natural growth*, the excess of births over deaths, *migration* from rural areas, and cities' incorporation of rural surrounds (redefinition of administrative boundaries). The relative importance of each component changes as urbanisation proceeds (IR 15). The physical living conditions of most poor people in the megacities are not necessarily better than in the countryside, as can be seen in the large share of the deprived population living in slum-like favelas[11]. So, if the increasing urbanisation will have an effect at all, it will be in the provision of energy services such as entertainment or chilled food storage. Therefore we have to assume that those kinds of services will increase in importance in the future – and necessarily their share of the final energy consumption.
Why do we follow the assumption of ever more urbanisation — might not the coming *information society* abate it? We need to look at the way cities have evolved in the recent past, where they were the corner stones of manufacturing, industrial and administrative developments, and see whether we can perceive trends leading to less urbanisation in the future. In fact Knox (1995, 234 f.) gives five reasons for the late twentieth century trend to more intensive agglomeration:

1. The *New International Division of Labour*[12] which has expanded the concentration of high-level management functions, mostly in major cities;
2. new production technologies and introduction of telematics which have followed patterns of initial economic advantages, so that a *tripod skeleton*[13] has evolved with existing cities with major concentration of trans-national corporate headquarters, of international news, (business) information and entertainment services benefiting most;
3. the trend towards global *neo-Fordism*, which resulted in the renewed importance of major financial centres for servicing, marketing, innovation, the raising and consolidation of investment capital by more sophisticated, internationalised financial business services;
4. deregulation and the ideology of competitiveness fostering the development of world cities within the cores of the world-system; and
5. the proliferation of trans-national *non-governmental organisations* (NGOs) localised in centres of international politics and mediation.

Although Knox (1995, 236) acknowledges that those trends <u>also</u> have led to economical decentralisation between regions, from metropolitan areas to smaller towns and cities and from downtowns to suburbs and edge cities, “world cities are not so much an exception to this decentralisation as they are a consequence and shaper of it.”. World cities are necessary to generate and disseminate collective beliefs, evolving memes as replicators of behaviour patterns (Gadgil 1996), and to sustain settings of sociability where key actors (the *global nomads*) can gather and interact, and to foster innovation by the creative process stemming from various forms of interaction.

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[9] In 1994, 45 percent of the world's population lived in urban areas, up from 34 percent in 1960, and 19 percent in 1920. By 2005, more than half the world's population will reside in cities (IR 15).

[10] Today urban population is 2.6 billion, 1.7 billion of which in developing countries. The urban growth will almost exclusively take place in the latter group. By 2025 nearly four out of five urban dwellers will live in developing countries (IR 15).

[11] But examples of the opposite can be found. For example the vast difference in living standards between rural, inland China and the coastal provinces and cities in the free trade zones. This would actually argue to collect the latter with the tigers from an economical analysis, but this has not proven to be practicable.

[12] By which industrial processes have been split up and are being performed in those countries, where it is most economical to do so.

[13] Europe/North America, Europe/Far East, and the Pacific Rim.

Other important trends with respect to the ongoing urbanisation are *e.g.* the mechanisation of agriculture which releases workforce to industrial and commercial activities, several forms of temporary (or lasting) migration taking place within a country and between countries as described by Kliot (1995, 177 f.). In China, for example, more than a hundred million peasants have already migrated from the countryside to the cities (Spiegel 1997c, 163), this number could easily rise even more. Globally there are 17 million registered refugees (Kliot 1995, 178), who normally end up in the major cities, as a means to keep contact to the home culture. The number of between-country migrants is estimated to be 125 million people (IR 17).

While the introduction of telematics on a wide front actually might have the potential to abate urbanisation to some degree in the established ICs, it seems more probable that the trend to a larger share of the global population living in ever larger cities will continue than that it will stop or even reverse in the near future. So therefore we have to consider the increasing urbanisation as an important factor that has influence for the energy consumption, too.

If we look at the way cities work, then we might speculate that economies of scale could even argue for an advantage of cities compared to more wide-spread centres, as:

- Infrastructure can be optimised by proper town planning, investments in *e.g.* public transportation reduce the necessity of individual transportation but can only be done when the customer base is available. As an antipode imagine the average distances that one has to cover when living in the sparsely populated rural countryside and having to interact physically with other people of the same industry. The ongoing specialisation of work steps seems to guarantee a further growth in transport demand, as such contacts will only be possible amongst a steadily declining share of the population.
- Although the infrastructure in many larger metropoles is choking from a too strong demand for services, it is in those regions that many services can be provided for businesses, so that they dare not move to other parts of a country. This is also caused by the mobility restrictions of the work force that has arranged their living conditions[14] accordingly and would have difficulties relocating.

Urbanisation will also lead to a higher number of households compared to rural conditions. In the countryside family sizes will generally be larger than in the large towns, where the demographic transition will be at work on a larger scale. We therefore have to follow the trends in urbanisation described by the UN (IR 15) as a factor that determines living conditions and so the energy end-use pattern.

This trend has implications for the energy assumptions on the biologically acceptable surroundings and other energy services that will be demanded (page 48). Most people will in the future live in urban areas and therefore will demand more services of the type that we have described before. This means that our assumptions should reflect the global urban civilisation trend. On the other hand we may still expect that other factors, like the average income, will have a larger impact on the living conditions than the urbanisation *per se*. It would be difficult to get the data material necessary to treat this matter in more detail.

One important feature in that respect is the heat supply. Where space heat demands are high, urbanisation lets us fulfil it by district heating (DH) systems. They can supply the major share of the heating demand, generally the case in countries that also in the future have higher incomes than the global average. In other regions the heat demand will be mostly covered by cogenerated heat from fuel cell installations or by heat pumps. DH systems will become more widespread as a means to reduce primary energy input of a country's energy system.

After having described the general population patterns we have to start with a description of another important factor that determines end-use patterns. This is the life standard which is influenced by the economic situation of the population.

Economic Developments

There are two questions that we have to look at: first, how does the economic situation look like around the World, today? Second, in what way will it change, and what regions will experience the largest changes?

For the present situation, we have basically used some meta-information on the recent developments around the World and have distributed the countries into geographical groups, where we also have taken the economical situation into account. Mostly this was done quite automatically, but for some countries this was not feasible. Those were manually distributed into the various groups taking into consideration geographical and economic factors.

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[14] Schools, entertainment facilities, property possession, personal relationships, customs, etc. all hinder mobility. On the other hand they also are the most important means to refresh your work efforts.

For the future situation we have to get some idea of how the economical situation will change in the regions. Establishing the economic development of the various countries was restricted by the data that we had access to. Data from WRD (1994) for the countries' per capita *gross domestic product* (GDP)[15] has been folded with the per capita GDP indexes from ICCC II (1994) for different regions[16].
This approach is not without neglects: For example the use of the regionwide scaling factors from IPCC II (1994) generally will underestimate the economic growth of countries lying below a regions' average growth rate, as for those economies even comparatively small absolute increases, *e.g.* by connecting to the global economy as in the case of some minor industrialisation taking place, will lead to rather large relative changes. The advanced economies in that region will probably grow slower than the average. These kind of errors should not become important, and we also have to take into account that it generally is not possible to give a complete picture of any future development.
But if we follow the recent developments, then our future World would look something like a continuation of the present trends, anyway. These are described in the following:
In recent decades, growth has somewhat stagnated in the traditional ICs, while a group of new high-growth *Newly Industrialised Countries* (NICs[17]) has an increasing share of the global GNP[18]. This trend seems to relate to the quality of the supply of demands. After a certain threshold has been surpassed, traditional industrial growth is taking place at a rapid speed[19], similar to the booming development in the ICs after industrialisation had commenced[20].
But after some time certain basic, physical demands have been fulfilled, and markets change from being supply dominated to becoming demand oriented with an increasing share of the Hi-Tech, service and research sector[21]. This leads to bottlenecks, when the working population's qualifications are not geared to the demands of the economic sector, and this seems to slow economic growth by making a proper resource allocation more difficult[22].

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[15] Actually the GDP data in WRD (1994) are only available for the year 1991. For the countries, where we did not find data in WRD (1994) or in IR (12), we have used the average regional figures given in IPCC II (1994). For Taiwan we used data from the *Penn World Tables* (IR 12) provided for by Heston and Summers.

[16] The regions that we have chosen to investigate and the ones given in IPCC II (1994) are not exactly the same, so we have applied some of the latter factors to other regions. A description of this is given in the appendix.

[17] Sometimes we can find the expression: NIE, *Newly Industrialised Economies*. We stick to the former, as this fits better with our approach on basing our analysis on a country base.

[18] For example the East Asian NICs had a share of World trade in manufactures of 1.5 per cent in 1965. This share rose to 8.5 per cent by 1986 (Kennedy 1993, 195).

[19] The growth in the NIEs is clearly export driven: while in Korea, Singapore and Taiwan GDP on average grew by 8.1 per cent during the 1980s, their total exports grew by 10.8 per cent annually, and the same is true for a range of other NIEs and developing countries (Bradford 1994, 16).

[20] For example between 1980 and 1986 the GDP in current dollars grew by 3.0 per cent annually in the developing countries, while it grew only 2.5 per cent in the industrialised countries (Forstner and Ballance 1990, 37). For the latter group, growth rates were 5.1 per cent annually during the 1960s, a result of the post World War II growth period, or the *Wirtschaftswunder*, and declining from then onwards. The rapid economic development in the NIEs is also a result of a high national savings rate (Kennedy 1993, 198 f.) enabling competitive financing through large amounts of low-interest capital.

[21] Some countries have managed to spring over some steps in this development path, as argued for by (Naisbitt and Aburdene 1990, 214 f.) with the example of South Korea, Taiwan, Singapore or Hong Kong that directly have engaged themselves in information technology without the traditional way via heavy industry.

[22] Historically growth has been measured in relative terms, *i.e.* in yearly changes. In absolute terms a growth of one percentage point from a basis of 1,000 is still larger than one of 5 per cent from a basis of 100! This is the basic argument behind the exclamation that most developing countries have been lacking more and more behind the industrialising countries. This apparent misalignment can be slightly ameliorated by using *Purchasing Power Parity* (PPP) corrected GNP data that also takes into account that a dollar in *e.g.* Ghana buys much more life quality than in Denmark.

If we follow Paul Kennedy's (1993) description of the trends that will shape the coming decades, then the following patterns become clear:

- Western Europe, North America, Australia and New Zealand will be very high developed regions. They will have only little industry and rely to a high degree on service sectors for their economic performance, with industry only contributing minimally. For some of the countries minerals and raw materials extraction will play a role.
- Japan, and the four tigers'[23] economy will rise very much. Japan will surpass all the other countries per capita income and become the richest nation in the World. The four tigers will reach Western European levels. Japan will have a large service sector, though probably not so large as in the before mentioned regions. In this group industrial activity will play some slight role, especially for the tiger nations. Those countries are generally poor in raw materials.
- Central and Developing Europe, the Brazil group and Southern Africa will reach about half the current Western European levels. Also these regions will be heavily industrialised and with a medium degree of service sectors.
- The India group, some countries in Latin America and South Africa will experience large income rises and will reach or even surpass the present Central European levels. These countries will rely to a very high degree on industrial activity, and their service sector will be comparatively small. Raw materials extraction will be of medium importance.
- For Sub-Saharan Africa and many developing regions distances are today so large, and the socio-economic situation so bad, also because of low educational levels within the population, that they will not play a large role in industry and even less in service sectors, except maybe for tourism in places. Raw materials extraction will take place, where appropriate.
- The oil producing nations, which are assessed as the ones having a high R/P ratio today, will also have a very little industrial share and no service sector of importance.

In all those regions, despite the oil-rich ones, agriculture will be of importance to a rather high degree. This will not be explicated here.

Table 2 Average GDP in the geographical regions 1990 and 2050

REI	Geographical region	avgGDP 1990	avgGDP 2050
AF1	Southern Africa	2821	8545
AF2	Maghreb	1003	3063
AF3	Sub-Sahara Africa	338	980
AM1	North America	21928	65725
AM2	Brazil, Argentina, Mexico	3264	10734
AM3	Caribbean & developing Latin America	1505	4650
AS1	Japan and Four Tigers	21269	75155
AS2	India group	458	2596
AS3	China	317	2993
AS4	Developing Asia	796	3681
AS5	Oil rich countries	3145	8776
AU1	Australia - N Zealand	16516	62098
AU2	Oceania	2385	7746
EU1	Western Europe	19039	58786
EU2	Central Europe, Turkey, Israel	3097	7561
EU3	Developing Europe	2739	7174
RUS	Russia	3780	9920

Source: own calculations.

The average incomes in the 17 regional groups is shown in Table 2 for present and as described before the assumed situation in the year 2050. As a result of the large growth factors for the Asian region, the per capita

[23] More fittingly they should be called "dragons".

GDP in the Japan and the Four Tiger group actually will surpass that of North America, the Australian group and Western Europe. Also it can be seen that, although a comparatively large annual growth of almost 4 per cent has been assumed for China, this country's per capita GDP still will only rise slightly above other representative countries in the Asian region, like India's or Pakistan's.
A description of how this economic segregation influences the energy services that are a consequence of the economic development is given in the following. Later on we will also use the economic arguments on some other end-use features.

Per Capita Income Classes

As described before, we have collected the countries into three classes, which depend on the per capita GDP with respect to the present state, and which also have some relevance for the future. To support the aggregation we refer to Dietz and Rosa (1997, 178, fig. 2), who have established a relationship of the affluence from the IPAT theory[24], which shows that there currently is a group of ultra-low income countries, with about constant affluence, a middle group with about a linear relationship between per capita GDP and affluence and a top-income group, where affluence reaches a plateau[25]. By inspection of their graph we infer the values given as GDP limits today in Table 3.
For the 2050 limits we likewise have to divide the countries' per capita ratings into three groups. We have done this by scaling the limits from Dietz and Rosa's IPAT analysis with the global growth factor of the per capita GNP from IPCC II (1994), which is 2.43. The global average is the best ad-hoc way of finding the new intervals. We may expect that on average per capita GNP in the countries will develop according to this benchmark figure[26]. The result is shown in Table 3 as well.

Table 3 Economical country grouping depending on per capita income

Income Class	GDP limits today	GDP limits 2050
high	*>10000*	*>24000*
middle	*300-5000*	*1200-24000*
low	*<500*	*<1200*

Source: Dietz and Rosa (1997, 178) for today' values. The GDP limits 2050 were computed using the World's average GDP growth by a factor of 2.43 given in IPCC II (1994).
Note: The GDP limits are given in US dollars as given by our original sources. Dietz and Rosa's figures are in 1989 dollars, the difference to 1990 dollars is negligible.

Table 4 Changes in Countries' Income Classes

Income Class 1990	Income Class 2050	Number Countries
high	high	62
low	low	15
low	middle	10
middle	high	7
middle	middle	125

As can be seen 10 countries, today in the poor group, will reach the middle income group, and 7, today of middle per capita income, will reach the rich group.

[24] According to this theory the environmental impact can be constructed in the simplest form as Impact = Population · Affluence · Technology (IPAT). Here the affluence can be related to the income, the GDP, and Dietz and Rosa (1997) have found an S-curve like relationship between those two parameters.

[25] For the largest per capita incomes the affluence actually goes down again slightly.

As a result of the economic developments, as we have described them above, for some countries the per capita income position change, they become better off, as shown in Table 4. This trend generally seems to be positive, also only 15 countries stay in the poor, low per capita income group.

Residential and Service Sectors Energy Consumption Patterns

Based on the data presented in Table 3 we have to infer the energy end-use patterns for residential and the service sectors consumption, shown in Table 5. These data have arisen on the basis of a more detailed investigation shown in the Appendix. The basic idea is that the higher income countries also will show a trend towards demanding more services. This is the reason why the values for the low temperature process heat demand in rises with income[27].

Especially for transportation demand the income relationship has been assumed to be very strict, so that the richer populations will demand about three times as much transport work as the poorer ones. This seems to be the case, if we look at the transport demand in industry compared to developing countries. Especially a larger share of the energy demand for transportation is related to spare time and holiday traffic, which indicates that societies need to become rich before these pastimes gain in importance in the general population.

Table 5 Residential and service sectors' end-use demand grouping

Income Class	Process heat <100 C	Process heat 100-500 C	Stationary mech. energy	Electrical appliances	Transportation work
high	120	30	6	75	120
middle	75	20	5	55	70
low	20	8	4	30	20

Note: Data in watt per capita, estimated on the basis of Sørensen (1995b, 81) and own estimates.

The same trend also is assumed for electrical appliances, where saturation is expected only to be reached in high income countries, with the other groupings following. Electrical appliances are somewhat peculiar, in that we have assumed a wide proliferation so that they also will show a large ownership rate in low income countries.

Stationary mechanical energy stems from services and security.

The service sector's definition comprise Services, Trade, Education, and Commuting. We have decided to put those together with the residential sector, as the demands patterns are comparable with respect to energy quality. Commuting also is included here, as we think this end-use is more related to private peoples' behaviour and choices than to the structures of industry. The fact that urbanisation is assumed to continue is seen in the rather high amount of transport energy that is being demanded.

A more detailed aggregation for the various income groups and energy services in different industrial and other activities may be found in the appendix.

Industrial Energy Consumption Patterns

We have arbitrarily defined the middle income group to bear the brunt of the industrialisation, also on the background of the experiences of the last decades, where heavy industry and work intensive manufacturing processes have been moving out of the traditional ICs; a result of environmental, macro-economic, technical and structural trends. For example, NICs are now providing the mass produced steel that formerly had been produced in the ICs, major ship yards are now situated in the Far East, even chemical companies have relocated

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[26] In that way differences between low per capita income countries today with a high growth and high per capita countries with an expected low growth leading to the same per capita income in 2050 will even out.

[27] For example spas and Jacuzzis for "personal hygiene".

parts of their production outside of the traditional ICs. Globally, this has extended employment, but in the ICs the result has been to make work force abundant.
On the other hand, there is a group of less industrialised countries, and most of those will stay so in the future, as they will not grow strong enough to enter the middle income group. Especially in Africa this will be the case.
Of the arguments given above we conclude that we will apply the industry end-use energy values given by Sørensen (1995b, 82) for Denmark as being representative for the high income grouping, while higher values shall be applied to the middle income and lower for the low income groupings.
We shall also graduate the industry energy end-use figures for the kind of industries that we think will be located in the respective regions. In low income countries, we will have to admit a comparatively high share of energy intensive industries, which would generally not be expected located in the middle to high income group. For example heavy industry and raw materials extraction. Consequently very high process heat and stationary mechanical energy are prevalent with this group.
Manufacturing would be preferentially located in the middle income group, where wages have not yet soared to prohibitively high values, and where a sufficient infrastructure exists to support somewhat more advanced industries. This will cause a large demand for low and middle temperature process heat as well as stationary mechanical energy.
In the high income group we will locate a minor share of manufacturing industry, as we assume that the service and development sector will be of most importance in those countries. In that way we shall also try to realise the observation made by Dietz and Rosa (1997) that affluence levels off in high income countries[28].
The results for the industrial end-use depending on the countries' income grouping is shown in Table 6. The list of the countries and their economic and industrial classification is included in the appendix. The values are based on satisfying the most basic needs a society can have. For the energy intensive raw materials and energy extraction countries some extra energy demand will occur, as explained below.

Table 6 Industry end-use energy grouping

Income Class	Process heat <100 C	Process heat 100-500 C	Process heat >500 C	Stationary mech. energy	Electrical appliances	Transportation work
high	20	10	5	64	25	35
middle	35	30	30	145	60	35
low	10	7	5	21	20	15

Note: Data in watt per capita, estimated on the basis of Sørensen (1995b, 81) and own estimates.

As industry can be expected to be the first large energy consumer, when a country starts to develop, the differences between the income groups are not as large as for the residential and service sectors.

Exceptions

Despite the provisional class description presented before, there are some necessary extension from the rules. One is the group of energy source extraction countries. We have before identified the oil rich group. For this group per capita energy end-use related to energy extraction has been increased separately. Similarly one could treat the countries with natural gas or coal production. However, as those energy sources are geographically more evenly distributed, we believe that the energy amount for those activities already is implicitly included in the end-use figures.
The other group of countries is performing raw materials extraction. We have considered three basic materials: copper, aluminium and steel. For each of this activities we have assumed an average per capita end-use energy adder for the industrial processes that we deem necessary. An overview of the countries, their production, and the individual adders is given in the appendix.

[28] Dietz and Rosa have concluded this on the background of CO_2 emissions, but as those to a large degree are related to heavy industry our argument holds.

Oil extracting countries industry end-use adders

Energy form	Process heat <100 C	Process heat 100-500 C	Process heat >500 C	Stationary mech. energy	Electrical appliances	Transportation work
	5	5		5		5

Note: Data in watt per capita, estimated.

Climatic Classification

Climate is an essential parameter for the space *heating, ventilation and cooling* (HVAC) energy demand[29]. Unfortunately for lack of easy to access data we could not make an automated, detailed classification of the World's nations with respect to climate zones, so we have only considered five climate zones. Depending on this grouping we have estimated the respective energy demand of space heating, air conditioning and food chilling.

It is clear that climate is a determining factor for a human physiological categorisation, and we think that this grouping catches the basic aspects of the climate related impacts on the heat regulation of human bodies, which basically is given by the effective temperature, the chilling factor and other impacts like water vapour density or wind speed that are determining the air's enthalpy (Hendl 1991, 219, 251).

We have classified the countries manually according to a map presented in Hendl (1991, 252), where we have only considered five of the six classes explicitly. The *permanent-euthermal* climate apparently only covers a very insignificant share of the Earth's area, so it is ignored. The two *hyperthermal-euthermal* groups have been combined into one on the background of low space heat demand for both groups today. The result is shown in Table 7, where the space heating, air conditioning and food chilling end-use energy demand have been taken from Sørensen (1995b, 82) for Denmark. We assume that this value is representative for the rest of this climate group's members.

The values shown in Table 7 are for all activities and so already contain the share of industrial and service sector activities. They implicitly include major improvements in the average building shell quality and design to reduce space heating and air conditioning demand by so-called passive solar architecture[30].

The polar climate group only contains Antarctic Fisheries, Canada, Greenland and Iceland. One might argue that Russia, due to this country's large Siberian area and a major development east of the Ural mountains to extract the large mineral and energy resources that have been indicated in that region, would be a special case, however according to the bioclimatic climate classification it is not. This is partly caused by the large interval size given by Hendl (1991, 252).

We have assumed that smaller islands in the tropics with respect to heating and cooling belong to the arid tropics. Our justification is that most of the population is situated near the coast and so will benefit either from the land-sea breeze circulation[31] or from the moderating influence of the cooler water masses of the sea nearby,

[29] Although we shall not forget that technology probably is more important. Single window panes will lead to much larger heat losses in winter than thermopanes, and architecture also is influential.

[30] Often the approaches taken for such design are copied from Nature's examples. A new office building in Harare, Zimbabwe, has been erected, where the "air conditioning" follows principles found in termites heaps. Air is being circulated through shafts during day and night time to create a constant, comfortable interior temperature of between 23 and 25 °C independent of the exterior climatic conditions at about half the electricity costs an office building would cause that was built according to conventional architecture. The same principle has also been applied outside the tropics: The Queens building in Leicester and the residence of the Nottingham tax authorities follows the same principles (Spiegel 1997).

[31] This is a local phenomenon by which a small circulation cell is induced by the difference in temperatures between the land area and the sea. During day time the warmer inland causes winds to blow from the colder seaside, in the night the winds blow in the opposite direction.

which minimises the demand for air conditioning. This also reduces heat demand somewhat for islands in less warmer regions.

Table 7 Climatic macroregions and average HVAC energy demand

Climatic Region	**Bioclimatic Classes** according to Hendl (1991, 252)	**Space heating demand (W/cap)**	**Air conditioning demand (W/cap)**	**Food chilling demand (W/cap)**
tropical, humid	Permanent hyperthermal	0	40	15
tropical, arid	Hyperthermal-euthermal, shifting	20	15	12
middle latitude	Euthermal-hypothermal, shifting	300	10	10
polar climate	Permanent hypothermal	1000	0	9
special mixed	see text	100	15	12

Source: based on Sørensen (1995b, 81).
Note: Data are averages over the year.
The two *Hyperthermal-euthermal* classes by Hendl (1991, 252) have been combined.
The special mixed class is explained in the text.

The small space heat demand for the arid tropics group is due to some cases of winter heating required when temperatures are extraordinarily low, as for snow falling in Italy during otherwise mild winters.
In a preliminary trial it was found that the classes could not represent the United States well enough, as this country stretches over many climate zones. Therefore a fifth class, the special mixed one, was needed. It combines the energy requirements for the colder North Western USA and its warmer Southern regions and reflects the ongoing migration from the former to the latter regions. In this group were also placed Italy, Greece, Spain, Portugal and South Africa not for migration causes but to better describe the demands necessary for providing appropriate service levels.
Our grouping is somewhat subjective[32], as no stringent physical units were available for the classification of the countries; rather we based it on the very general regional aggregation given by the EIA database (EIA 1997) and the map in Hendl (1991, 252). This is a point, where more refining could be applied. Ensuring biologically acceptable surroundings normally is related more to the space heating than to the air conditioning demand; especially with respect to the hypothermal class finer intervals might prove advantageous.
And with respect to the comparatively small figure that we have assessed necessary for the end-use energy demand for air conditioning, we argue that the cooling of the air should not be excessive. Opposite to space heating in the winter in the euthermal-hypothermal climates, where a temperature difference of more than 10 Kelvin may arise in periods, a value of 5 K is generally taken to be more agreeable (Sørensen 1983). This takes into consideration that humans otherwise experience cardiovascular problems when they leave the climatised buildings, and the temperature difference between the chilled inside and the warm outside is too large[33]. Influenza is another widespread consequence of an, in places, exaggerated cooling rate compared to the actual demand for well being.
The list of the countries' climatic classification is shown in the appendix.

Seasonal Space Heating Demand Patterns

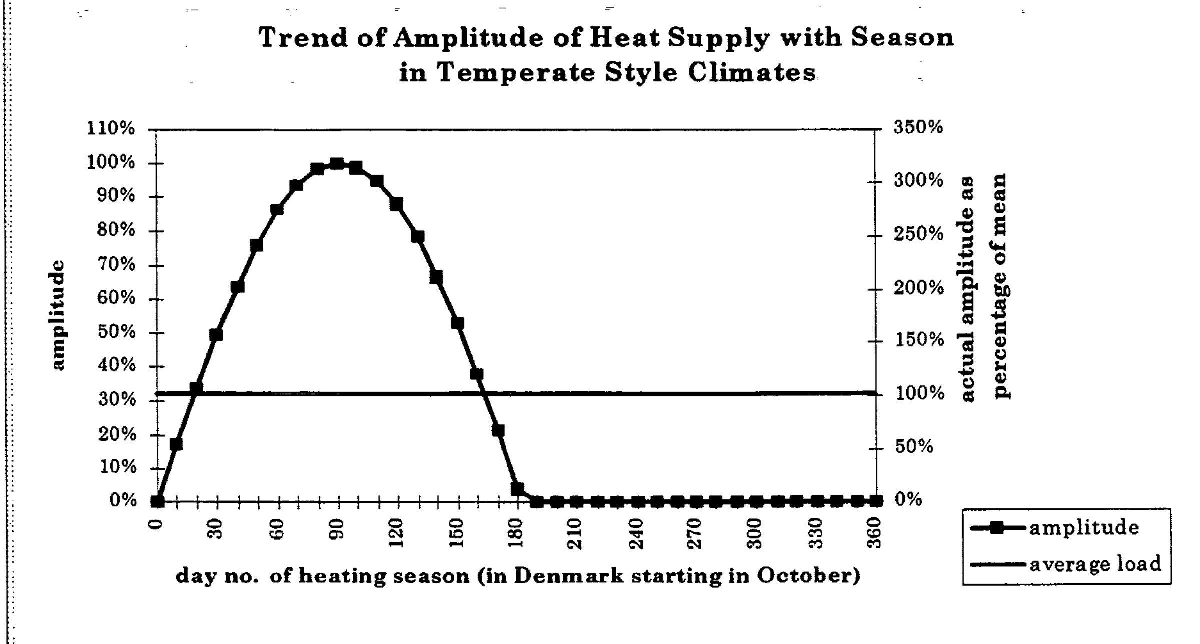
The values given in Table 7 are average values. They do not take into account that the space heating demand actually varies with season, being highest in winter and negligible in summer for the temperate regions. This

32 On the other hand, even strong definition criteria are no guarantee for a truly objective classification, as the limits themselves may have been chosen subjectively. "In the spatial value fields of the common climate elements only seldom isolines exist that truly are special relative to the other ones, like *e.g.* the 0 °C isoline" (Hendl 1991, 219).

33 The reason for this being the enhanced activity of the heart to increase heat losses by transpiration and counteract the volume increase from widening capillaries when one leaves from the chilled inside into the baking outside.

principle is illustrated in Figure 4. An equivalent curve would describe the average cooling load for air conditioning.
The horizontal line in Figure 4, passing through at about 31 per cent of the amplitude of the seasonal amplitude. In order to get the right values for the space heating demand, or where appropriate the air conditioning in winter, the average values given in the tables before have to be multiplied by the scaling factor shown in the right axis of Figure 4. This means that the average factors that have been given before need to be corrected for the seasonal peak to get the right dimension of the energy supply systems. This is shown in Table 8.

Figure 4 Distinction between average and peak heat load



Note: this figure is illustrating a theoretical relationship only.

Table 8 Seasonal peak space heating and air conditioning demands

Climatic Region	Peak space heating demand	Minimal space heating demand	Minimal air conditioning demand	Peak air conditioning demand
tropical, humid	0	0	40	40
tropical, arid	50	0	5	25
middle latitude	900	0	0	30
polar climate	3100	100	0	0

Sources: based on Sørensen (1995b), Hendl (1991) and own calculations (Figure 4).

The peak space heating demands are about a factor three higher than the average ones given in Table 7. The low value given for the arid tropics takes into consideration the seldom instances of cold spells in those regions and is an average value applied to all members of this class; actual peak values might be higher, but they would not be representative of the arid tropics, as those spells normally are limited to a small share of the total area. For the polar climate we have also assumed some minor heating demand in summer, this is possibly exaggerated, as we may assume better building standards in the future, so that this demand will be covered by passive solar heating.

The air conditioning demand is constant in the humid tropics, a natural fact as the seasonal temperature range in this region is smaller than the daily one. For the arid tropical regions we have assumed the same, although in parts of this region seasonality might occur. In the middle latitude regions air conditioning demand will vary with a high demand in summer and none in winter. We also have included a share of electrical equipment's waste heat that will have to be removed extra in the middle latitudes, therefore this value is larger than the one for the tropics, where the temperature differences between summer and winter are not so pronounced, and people normally are acclimatised to the generally higher temperatures.

Those peak values could be applied to give a better representation of the necessary energy system to cover the needs. We regard the changes in the food chilling energy demand with warmer and colder seasons to be insignificant, as this technology normally will be installed in the building shells and so will not follow larger temperature amplitudes.

Not only do the phases of the space heating and refrigeration demands differ between summer and winter on one location, they also have different phases between the Northern and Southern hemispheres. It is therefore easily seen that on an globally scale energy demand will be largest during the boreal winter, and smallest during the austral winter[34].

There are several reasons for this: The first one is that space heating is the prominent energy demand in our scenario. As it occurs predominately during the winter period, it will naturally skew energy demand towards this season. Already today the majority of the human population is living in the Northern hemisphere. In the future this imbalance will be further enhanced: 7.8 billion people in the boreal hemisphere against 1.6 billion people in the austral one!

We have also established the variations in energy demand patterns by taking into consideration the differences between the two hemispheres.

Economic Factors for Space Heating and Cooling

The economic well-being of a population will generally impact the end-use demand for space heating and air conditioning, as higher disposable income will make possible the individual to have larger or several flats, *i.e.* the living space demand of an individual increases and correlated with this also the energy demand for heating and air conditioning[35].

We therefore need to treat the climatically determined space heating and cooling demands with the impact of the income classes. Therefore we have chosen to scale the space heating demand by the income groups that we have established before. The scaling factors are given in Table 9. They also apply to space cooling, as this parameter is considered to be highly income dependent, but not to refrigeration, as we still would assume an optimally chosen technology for this service, *i.e.* properly sized refrigerators to match demand.

Table 9 Income dependent scaling factors for space heating and cooling

Income group	Scaling factor
high income	*1.2*
middle income	*1.0*
low income	*0.2*

Source: estimated values.

As has been explained in the section on urbanisation, space heating demand will be expected to be covered mostly by DH systems, if the demand is large. In other regions, hydrogen driven fuel cell systems will be chosen.

[34] Boreal and austral refer to the Northern and Southern hemisphere respectively.

[35] This assumption presently does not apply to the booming East Asian NIEs, where people on average live cramped, despite relatively high incomes. But the situation will change in the future, when affluence will make it possible for more to move to less populated areas. For example China's population density is about the same as Denmark's.

Food and Water

We have neglected and not modelled the energy content of the nutrition. The value given by Sørensen (1995b, 81) seems to be universal for all societies, although one may argue for a more graduated value depending on climatic impacts. In colder climates for example people will have to forage more to compensate for the larger heat loss when staying in the outside, whereas this will not be necessary in warmer climates.

End-Use Applications

In order to make a complete bottom-up analysis we need an overview of the end-use technologies. Here we do not argue as diligent, as in the case of the upstream parts of the energy system, because the emphasis and work effort generally will be put in the latter, as the major differences between possible future energy systems will be in those.
Basic assumptions are in any case that technology development will lead to major increases in end-use efficiency, and that the best technology available today is not yet sufficient. Thus, efficiencies will be much higher in the future than today.
We distinguish between eight different end-use applications. The idea is that they will cover the basic needs that we have identified from the demand-analysis given before. The technologies, that we assume will be necessary, are given in the following Table 10, and a short technology description of each of them thereafter.

Table 10 End-use technologies and their efficiencies

heat pumps	efficiencies (%)
heat pumps	440
H_2 boilers	95
H_2 furnaces	95
cooling/freezing	100
stationary motors	95
electr. appliances	100
H_2 (FC) vehicles	50
battery driven vehicles	50

Source: Sørensen (1996) and estimated data.

Heat Pumps

Heat pumps are assumed to be driven by electricity. Their efficiency in converting it into heat is assumed to be 440 per cent, *i.e.* for each energy unit electricity the heat pump will produce 4.4 units of low temperature heat. This implies that it will have to extract 3.4 units of heat from the environment for every unit electricity, or vice versa that for ever unit low temperature heat produced it needs 0.23 units electricity and 0.77 units environmental heat. The environmental heat is assumed to be cost-neutral.
Due to the assumed high efficiency, it would be difficult to argue for a widespread application of heat pumps in the very cold climates, where the temperature difference between the heated space and the outside would become too large, so that the heat pump would not be as efficient any longer. Therefore it is necessary to limit the widespread application of heat pumps to regions, where the winters are assumed to be mild, *i.e.* in the tropics and subtropics, where the high efficiency can be justified.

H_2 Boilers and H_2 Furnaces

Mostly for industrial, but also for some service applications, medium to high temperature heat supply will be necessary. It will be provided by hydrogen fuelled boilers and furnaces with a system efficiency of 95 per cent that takes into account design and start-up losses.

Cooling/Freezing

Cooling and freezing, and the cooling demand for air conditioning is here assumed to be covered by electrically driven refrigeration units. An efficiency of 100 per cent has been assumed, as the best perceivable conversion technology is believed to have penetrated the market. This implies also that heat transfer from the outside into the chilled volume has been minimised by proper insulation and other technological developments as indicated in the description on rational end-use technologies.

Stationary Motors

Here the conversion factor from the electrical to the motive energy is assumed to have risen to 95 per cent, which seems to be the best standard of today's technology.

Electrical Appliances

As full penetration of the most efficiency technology has been assumed, the efficiency factor has been set to 100 per cent. This means that the services provided by the technologies covered in this group are being provided at maximum efficiency, although the physical conversion efficiencies[36] might be lower.

H_2 driven Fuel Cell Vehicles and Battery Driven Vehicles

In order to describe losses from storage boil-off and other inefficiencies, the efficiency factor for hydrogen fuel cell driven vehicles has been assumed to be 50 per cent. The same applies to the losses for battery driven vehicles. Further development in a smaller scale H_2 and battery storage technologies may lead to less losses in the transport sector. For some purposes we might be expecting grid-driven public transport, where battery losses are minimal. However, current trends do not seem to argue for widespread use of this transport mode. Nevertheless, the energy demand by public transport is very small compared to individual transport, so that the neglect of this transport mode is not causing large uncertainties.

Generally

Changes in technology might argue for less process heat demand than is the case today. For example biotechnology would need less heat energy than metal works. Such trends are anticipated implicitly in the chosen end-use demands, and this argument is also valid for the other end-use energy types.

Transmission Technologies

In this part we give a short overview of the efficiencies of the various energy transmission technologies[37]. Table 11 lists the technologies that are being treated.

Table 11 Transmission technologies and their efficiencies

heat pumps	efficiencies (%)
heat transmission	80
electricity T&D	95
H_2 store and transport	86

Source: various sources.

Heat Transmission

As assumed in Sørensen (1996) the efficiency of the heat transmission in *district heating* (DH) is 80 per cent. This value is typical of current DH systems in Denmark[38] and will probably not become much better, although

[36] For example in converting electricity to light, where even CFLs today are still far from reaching 100 %.

[37] A more detailed literature overview is included in the fossil scenario description.

one may argue that for rising energy unit costs it will prove advantageous to improve the efficiency of the heat transmission, which can be achieved by better insulation.

Electricity Transmission

Transmission and distribution losses will be 5 per cent on a global plane as in the original scenario sketch (Sørensen 1996). It might be possible to have a large share of superconducting powerlines in the long-range electricity transmission system of the future. They reduce transmissions losses and, buried in the ground, will lack the visual impacts of current surface power lines as well as causing magnetic fields, which will reduce fears of health risks of power transmission.

Hydrogen Storage and Transport

The efficiency of hydrogen storage and transport is assumed to be 86 per cent, which is the best value we could find in the literature for a pipeline solution (Wurster and Zittel 1994). This is comparable to the value given in Sørensen (1996). Losses in the transport sector from hydrogen loss during storage and refilling are included in the vehicle efficiencies.

Non Energy Fossil Applications

Although it seems peculiar, this scenario also employs a share of fossil fuels that are used in non-energy related affairs, like the production of plastics. The amount of oil used for those purposes is equivalent to about 257 watts per capita. The regional distribution of this is given below.

Table 12 Per capita consumption of oil (W/cap)

REI	Geographical region	avg oil
AF1	South Africa	295.1
AF2	Maghreb	300.0
AF3	Sub-Sahara Africa	186.8
AM1	North America	150.0
AM2	Brazil, Argentina, Mexico	281.9
AM3	Caribbean & developing L. America	298.9
AS1	Japan and Four Tigers	150.0
AS2	India group	297.7
AS3	China	300.0
AS4	Developing Asia	258.4
AS5	Oil rich countries	261.0
AU1	Australia - N Zealand	150.0
AU2	Oceania	288.6
EU1	Western Europe	150.0
EU2	Central Europe, Turkey, Israel	245.4
EU3	Developing Europe	294.0
RUS	Russia	300.0

Source: own computations. These values are resting on the assumptions that per capita use are eqivalent to 150 W in the rich, 300 W in the medium and 50 W in the poor countries.

Basic Industrial CO_2 Emissions

For some processes, also in the future there emissions of CO_2 or of other greenhouse gases will occur from material conversion processes. Examples are the steel (actually pig iron) and cement production, where CO_2 emissions occur today not as a result of the energy input but caused by chemical reactions. With respect to pig

[38] Those systems are already working at a lower forward temperature than older, maybe even steam based, transmission systems, therefore the potential to reduce heat losses are restricted.

iron production the CO_2 emissions come from the use of carbon as a reducing medium to liberate the oxygen from the iron minerals, and with respect to the cement production the emissions are related to the burning of calcite to generate chalk.

Today CO_2 emissions from iron production globally are currently about 2.6 billion tonnes CO_2 per year (Walsh 1996, 711) and from cement production about 0.4 billion tonnes (Subak *et al.* 1992, 19)[39]. Those emissions can to some degree be reduced: steel and concrete can in principle be recycled, if by proper resource management it is ensured that the kinds of the various products are being treated separately so that the quality does not decline. Naturally, the development of the steel and cement use and the associated GHG emissions will depend on how the markets for these products develop, whether substitution options can be found, and to what degree they will be enacted. As a first rule growing economies that have started to industrialise will have a large demand for these basic materials for establishing and extending basic infrastructure installations in the transport, industrial and residential sectors. In already highly developed societies these installations will be almost totally established, and the demand will be for substitution and repair of existing installations and to a smaller degree for establishing new infrastructure projects: The transport sector might here be somewhat special, as the demand for related projects does not seem to taper off in the same degree as in the residential and industrial sectors.

If we assume that the recycling will become more important in the future, for example because several industrialists already have realised, like the founder of the *Club of Rome*, Aurrelio Peccei (Meadows *et al.*, 1972), or the Swiss industrialist Schmidheiny (1992), that impacts from our life-style and industry have to be reduced, then reductions of the emissions related to such materials can be expected, even if the global economy grows and will demand more of them. Not the least because exhaustion of raw materials otherwise might put a strong strain on further application of such materials[40].

For steelmaking Walsh (1996, 711) expects that it is possible to reduce emissions globally to 0.48 GtC in the year 2030. It might be realistic also to choose this value for the year 2050, although the possibility exists of having some of this CO_2 recovered, about 10 to 50 per cent depending on the efforts that are put into this project. This necessitates locating steelmaking close to other CO_2 recovering facilities, like central coal-fuelled power stations, where handling installations could be bundled. Another solution is to use hydrogen iron ore reduction (Wurster and Zittel 1994, 157).

Implications of Grouping the World's Nations on Economic and Technological Grounds for the Final Results

We have now the means to define a classification of the World's countries according to economic, climatic and population factors. To recall: we have found data on the end-use demands from the service and technology investigations for each country. The countries have been combined into regions so that we now can calculate the population weighted average per capita end-use demands for each region.

In practice the countries have been grouped into the classes semi-manually, by allocating indices to a matrix in the database that we have built up depending on the affluence, measure by per capita GDP and the climatic zoning as quoted countrywise in the appendix.

It is far from clear that the aggregated data will result in the same totals for the end-use or primary energy consumption that Sørensen (1996) made in his scenarios, which were based on a far more general approach. Our investigation is more detailed. Therefore differences may occur. Our demand patterns can be used in other scenarios[41], too, and this opts for a more general application of our results. The following Table 13 shows the

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[39] Total energy-related CO_2 emissions are presently about 22 billion tonnes. Original data: 0.72 GtC; 0.1 GtC.

[40] This point is not so imminent with iron or cement, but for other materials present knowledge would indicate that exhaustion can occur soon. However, in all such instances it has to be investigated, whether the reserves really are prone to exhaustion, or whether new resources can be found. This point is similar to the discussion on the life times of the fossil fuel reserves and has to do with the economic and technological situation that this term implies. In the relevant section we have shown that presently we may not argue for exhaustion of the fossil fuels within the next few decades.

[41] If there are differences in our end-use patterns, then those will necessarily also occur in the other scenarios, and we have then to apply the changed basics also in those. Whether this makes other alternatives more or less likely can not be determined at the present.

resultant yearly averages of the per capita end-use energy demands for the eight service classes that are considered:

Table 13 Average yearly per capita end-use demands in 2050 for the 17 regions

REG	Geographical region	avg cool	avg space	avg lo	avg me	avg hi	avg stat	avg el	avg trp	Total
AF1	South Africa	28.1	96.8	114.8	58.4	53.7	161.0	114.5	108.6	735.9
AF2	Maghreb	27.0	20.0	110.0	55.0	35.0	150.0	115.0	100.0	612.0
AF3	Sub-Sahara Africa	34.6	4.0	73.8	37.1	22.5	93.7	85.6	70.7	421.9
AM1	North America	28.5	219.3	142.2	48.9	54.4	82.3	100.0	162.1	837.5
AM2	Brazil, Argentina, Mexico	41.5	50.3	117.1	57.6	51.2	153.1	113.2	113.0	696.9
AM3	Caribbean & developing L. America	45.8	23.9	111.5	55.9	39.1	153.1	114.9	102.1	646.3
AS1	Japan and Four Tigers	36.8	229.9	140.0	45.0	43.4	74.4	100.0	158.5	828.1
AS2	India group	55.1	0.0	113.6	60.5	60.2	161.0	114.8	107.2	672.4
AS3	China	27.0	20.0	116.0	64.0	75.0	172.0	115.0	111.0	700.0
AS4	Developing Asia	37.9	64.1	99.3	48.7	30.3	129.3	104.9	92.3	606.8
AS5	Oil rich countries	27.8	21.0	121.1	53.3	29.8	134.2	111.1	117.6	616.0
AU1	Australia - N Zealand	28.6	82.0	145.0	47.4	48.1	88.2	100.0	164.1	703.4
AU2	Oceania	27.2	20.3	113.5	53.9	33.5	147.1	113.9	105.4	614.8
EU1	Western Europe	24.0	299.4	140.1	43.3	35.1	73.3	100.0	157.4	872.6
EU2	Central Europe, Turkey, Israel	22.3	271.3	121.2	49.7	28.4	121.8	109.5	120.5	844.7
EU3	Developing Europe	23.6	186.0	108.5	54.5	40.0	149.5	113.4	100.0	775.5
RUS	Russia	20.0	300.0	116.0	64.0	75.0	172.0	115.0	111.0	973.0

Source: own calculations based on various data.
Notes on abbreviations:
avg cool: average refrigeration and air conditioning end-use demand,
avg space: average space heating end-use demand,
avg lo: average low (<100°C) temperature end-use demand,
avg me: average medium (100-500°C) temperature end-use demand,
avg hi: average high (>500 °C) temperature end-use demand,
avg stat: average stationary motors end-use demand,
avg el: average electrical appliances end-use demand,
avg trp: average transport end-use demand.

There are some differences in the regional end-use demands. A clear reason for this is that: space heating varies the most — a result of the climate specifications of the countries. In the most energy intensive region, Russia, every capita is using more than double the amount that is being used in poor Sub-Saharan Africa. But there are also other profound differences between the regions. The living standard was chosen to be dependent on the per capita income and determines the energy services that are being requested. It also reflects the fact that Russia has raw materials extracting and has a high space heating demand.
Space heating is also a prominent contribution to the total energy consumption in Western Europe, North America, the Japan and the Central European groups which also are using more that 800 W/cap. As a result of economic and climatic classes most other regions have per capita demands of between 600 and 800 watts.
Similar calculations were made for the other two cases: the boreal and the austral winters. A condensed form is the global average, presented first as average over a year:

Table 14 Average global end-use demand during the year

avg cool	avg space	avg lo	avg me	avg hi	avg stat	avg el	avg trp	Total
38.1	50.7	108.5	53.4	47.8	136.9	106.9	105.4	647.6

Note: Abbreviations explained in Table 14

The total average is somewhat higher than in the aggregated calculations made by Sørensen (1996), although the space heating demand is very much lower. This is a consequence of more consumption for other purposes, like transportation and stationary motors.

As can be imagined the space heating demand is higher but the cooling demand lower during the boreal winter,

Table 15 Boreal winter end-use demand

avg cool	avg space	avg lo	avg me	avg hi	avg stat	avg el	avg trp	Total
34.1	136.0	108.5	53.4	47.8	136.9	106.9	105.4	728.8

Note: Abbreviations explained in Table 14.

while the opposite is true for the austral winter, please note also the complementary phase of the cooling demands:

Table 16 Austral winter end-use demand

avg cool	avg space	avg lo	avg me	avg hi	avg stat	avg el	avg trp	Total
43.5	13.5	108.5	53.4	47.8	136.9	106.9	105.4	615.8

Note: Abbreviations explained in Table 14.

As explained before, the larger demand for space heating during the boreal winter means that the average end-use energy is about 10 per cent higher during this period that during the boreal summer.

6. CLEAN FOSSIL TECHNOLOGIES

Introduction

The *Clean Fossil Scenario* (CFS) is a result of a diligent bottom up approach that takes its starting point in the end-use and works its way up to the provision of the primary energy necessary to fulfil the demands along the energy chain. The end-use part has been described in another section of this paper. Here we analyse the upstream extraction and conversion activities for realising the final energy provision.

Background for the Scenario

This scenario is a result of an idea that has been put forward by various sources, for example by Seifritz (1994). If we know that the current CO_2 emissions[1] lead to an enhancement of the *greenhouse effect* (GHE), then we should try to abate the overall increase of the atmospheric concentration of this greenhouse gas. Now this could be achieved by: improving energy efficiency (both on the demand and supply side), fuel switching or reforestation. However those *front-line* options are not sufficient (Herzog 1996, 233). Therefore other means have to be taken into use.

Preventing CO_2 – a result of the combustion of fossil fuels – from reaching the atmosphere immediately, can be achieved by storing it in *e.g.* the deep sections of the global oceans, in exhausted natural gas reservoirs, or solidified as a carbonate salt. In all those solutions the liberation to the air would be vastly reduced, and the atmospheric increase of this greenhouse gas, too. This is the basic idea of this scenario.

Research presented by Enting *et al.* (1994) can give an idea of the required reductions of the emissions to the atmosphere in order that atmospheric CO_2 concentrations can be stabilised at predefined values, see Figure 1. Such emission profiles are the results of the inversion of a carbon cycle model. Those models describe the absorption of CO_2 in various natural sinks, the oceans and terrestrial ecosystems, and can in a more direct way be used to estimate in what way the atmospheric concentration of CO_2 will change, when an emission scenario has been given.

In principle the emission profiles are not strictly defined, but they may be fit to a given current trend of emissions and atmospheric concentrations, *e.g.* during the 1980s or all the way from industrialisation until the year 1995. They can furthermore be fit according to some economic assumptions, *e.g.* that changing the present energy system will impose some costs, and that those should be minimised (Wigley *et al.* 1996). The other important parameter is the atmospheric target that has been chosen for a specific year.

One application of such inversions has been presented by Walsh (1996, 753): a rather simple relationship between the cumulative CO_2 emissions between 1990 and the year 2100 and the resulting stabilised atmospheric CO_2 concentration.

As one can see from Figure 1, emissions are assumed to continue to grow into the first half of the next century, but will have to decline thereafter to reach a very low value of about (?) per cent of the present industrial CO_2 emissions[2]. This development in emissions should then result in an atmospheric CO_2 concentration that will stabilise at 600 (?) ppm. In order to realise such an emission profile, it is necessary to introduce CO_2 free en-

[1] And the emissions of some other greenhouse gases!

[2] Some assumptions have been implicitly made on emissions from so-called land-use changes, that we will not present.

ergy forms. In this scenario it has been assumed that the CO_2 will be sequestered in such a way[3] that atmospheric emissions are minimised.

Figure 1 Idealised CO_2 emission profile

```
|   x
| x x
| x x
| x  x
| x    x
| x     x
|x T       x
```

Source: based on Enting *et al.* 1994
The curve describes the emission profile that should allow CO_2 stabilisation at 600 ppm in the year 2100.
T signifies today.

As CO_2 will not be allowed to be emitted directly to the atmosphere, the global energy system beside electricity additionally will have to rely on hydrogen as the kind of energy carrier that fossils are today in mobile and decentral applications. Hydrogen is assumed to be produced from *natural gas* (NG) and coal by reactions with water vapour, plus for the case of coal: oxygen.
Abundant fossil energy resources are necessary to make this strategy possible, and this seems indeed to be the case from the investigation of the resource base and reserves in another part of this study.
The attractivity of this scenario stems basically from its similarity with the basic trait of the current energy system its base on fossil energy carriers. By extending it with an end-of-the-pipe technology, it will be possible to exploit fossil energy resources for a longer time period than if CO_2 was emitted directly to the atmosphere. By preventing CO_2 from reaching the atmosphere directly, we could continue with the basic traits of the current energy system.
This scenario seems to be a small change of the current reliance on fossil fuels, but in fact we will show that the technological and social changes that this scenario necessitate will still be rather large.

3 That means that we have assumed that the residence time of the CO_2 in the reservoirs will be long compared to the current atmospheric one, so that the CO_2 concentration will stop growing when the scenario has been realised.

Technology Description

Before we present the results of the scenario, we give a description of the technologies that are needed in the future. This is done to give the reader an overview of what changes one has to perceive compared to the current energy system, and what developments that will be necessary to reach the situation described in the scenario foundations.

This section is probably not an easy to read introduction to the technologies that currently are being proposed to increase the efficiency of power generation. Such descriptions can be found elsewhere[4]. We have not deemed it successful to simply recite such works, so we refer the reader to these texts.

Instead we have chosen to present some new developments and thoughts on a.o. power station design and technology choice. The reader should acknowledge the long term perspective of this study so that the technologies described in the rest of the literature mostly are not sufficiently far-sighted to describe the developments necessary for realising our scenario, anyway.

An important question arises, when we consider that the different countries will show differences in population, economical situation and life style. How can we ensure that those differences will not mean economical problems? For example in smaller countries certain technologies might not be viable, as they cannot be operated economically due to economics of scale relationships. There are two possible solutions: either one does a detailed analysis country- or even regional-wise, or one assumes that no problems occur from scaling the sites to make demand and supply fit for any country or region.

A little relief from those questions is given by the fact that some technologies necessarily will be large scale, or be restricted to certain locations, *e.g.* at harbours or near coal mines or as to ensure easy CO_2 disposal, *i.e.* either near useful locations at the continental shelf or with approach to shipping sites. The question shall also be answered later on, when we compare whether it will be optimal to transport coal or the other fossil fuel carriers for a long distance compared to electricity or hydrogen.

Natural Gas to Hydrogen Plant

From the description of the energy flow given in the introduction it is seen that hydrogen is one important energy carrier. It can be produced from either natural gas, described in the following, or from coal, as will be described later. We have assumed that half the hydrogen will be produced from NG and the other half from coal as described by Sørensen (1996).

The basic reaction that one employs, is steam reformation, whereby hot water vapour steam is made to react with natural gas, which mainly consists of methane. The following equation shows the idealised reaction of that step[5]:

$$H_2O + CH_4 \rightarrow 3H_2 + CO$$

This reaction is endothermic, *i.e.* it requires an energy input, and this is taken from the heat of the water vapour steam, which is cooled down. For that reason the process is called *steam-methane reforming* (SMR). In order to minimise this heat loss, the reaction will in praxis take place over a nickel-based catalyst (Rosen 1996, 1081). The influence of a catalyst allows operation at lower temperatures than otherwise and also gives more control over the product composition (Hauserman 1994, 415). The resultant gas is called *synthesis gas*, or shortly *syngas*, the carbon monoxide of which later on is fully oxidised to CO_2 by the so-called *shift reaction*:

$$H_2O + CO \rightarrow H_2 + CO_2$$

The shift reaction is exothermic, *i.e.* it liberates some heat energy, which then again can be used to heat the water to steam for the first reaction.

---

4 *E.g.* in: Herzog (1996) on mitigation strategies and possible retrofit of existing power stations costs of CO_2 capture, implementation strategies and the deposition question; Rushing (1994) on the economics of power stations improved by CO_2 recovery and sales to industrial consumers; Riemer (1996) and Audus (1997) on the recovery from power generation and deposition of CO_2; Smith and Thambimuthu (1991) on coal related problems of greenhouse gas abatements; Farla *et al.* (1995) on CO_2 recovery from current industrial processes; Stibbe *et al.* (1996) rather generally on the Dutch programmes on introduction and enhancement of gas turbine and heat utilisation at the supply side.

5 As natural gas is purified, *i.e.* contains only very little amounts of *e.g.* H_2S, there will normally not occur catalyst poisoning.

After those two reactions we have gained a stream of hydrogen and carbon dioxide. The latter has to be removed, which can be done by one of several promising technologies, described later, before we have a stream of hydrogen. According to Rosen (1996, 1083) the product hydrogen purity typically is 97 to 98 per cent[6], and 50 per cent of it stems from the water vapour when using methane as a fuel. This means that there will also be a little amount (about one per cent) of CO_2 in the hydrogen stream. Rosen (1996, 1087) gives an efficiency of 86 per cent compared to the methane feed.

A different method has been described by Poirier and Sapundzhiev (1997): catalytic decomposition of natural gas with fuel stream recycling. In their proposal this would lead to a gas stream rich in hydrogen and some unconverted natural gas, but free of CO or CO_2. Up to a 50 to 60 per cent methane concentration in the stream is not believed to cause problems over a fuel cell stack, and the advantage is that the hydrogen stream would not be diluted with CO_2 as is the case with steam reforming (Poirier and Sapundzhiev 1997, 433).

Their concept is based on having two catalysts, of which one is working and the other is regenerated, whereby the carbon that collects on the catalyst becomes oxidised. The energy liberated so can be used to re-heat the catalysts and would also provide for cogeneration processes. The CO_2 can be recuperated easily. Carbon monoxide that comes from the partial reduction of the catalysts is catalytically transformed to methane, so CO concentrations will be below 5 ppm.

Despite the fact that the authors have not proposed natural gas desulphurisation, as part of the H_2S in the natural gas will be flushed in the form of SO_2 during the catalyst regeneration step, we think that as H_2S today is removed from natural gas to prevent corrosion problems, a similar problem would occur with hydrogen pipelines so that this existing technology should be applied in the future, too.

Such a catalytic technology is maybe another possibility to generate hydrogen from natural gas. This is not what Poirier and Sapundzhiev originally had in mind, but their figure 1 (p. 430) implies that the hydrogen harvest could be surpassing 90 per cent under certain pressure and temperature conditions. This technology might become an alternative to SMR, especially in locations near final consumers, where the heat from the regeneration could be used for steam and power generation, so that the original design would be realised.

Independent of what technology one chooses in the end[7], one important parameter is the cost of the produced hydrogen.

Costs:

We conclude that hydrogen from natural gas will be producible with SMR for about 5.4 Euro per GJ.

Blok *et al.*[8] (1997) propose to use the recovered CO_2 for enhancing natural gas production (NGR) by pumping the recovered CO_2 into almost depleted NG fields. In that way the cost of the hydrogen would only rise about 2 per cent[9] compared to simply venting the CO_2, as is the case today (Blok *et al.* 1997, 166). This gives a cost of the produced hydrogen of about 4 to 5.7 Euro per GJ[10]

Later on Blok *et al.* argue that unless CO_2 sequestration takes place, it would be more cost effective to transport the natural gas, but as we in this scenario have assumed a binding disposal that question is not left open to discuss. Technically it would be difficult to argue for a long range NG transport, if this also implies return transport of CO_2 on a similar scale[11]. This argument is supportive for the assumption that hydrogen generation generally will be taking place near the source of natural gas.

Most of the data on the SMR method shown in Table 1 were found in Wurster and Zittel (1994, 135), who have collected a series of hydrogen technologies.

6 This means that CO_2 emissions are about 0.6 kg per GJ.

7 Rosen (1996, 1080) summarises a row of hydrogen generating technologies and judges both catalytic decomposition of natural gas or SMR to be mature.

8 Actually Blok *et al.* investigate a SMR method for generating hydrogen, but independent of this their general argument is valid.

9 Although the costs depend very much on the distance between the fields and can rise about 10 per cent if this is increased from 100 to 500 km.

10 Original data \$5.18 to 7.19 per GJ, (for gas prices of: \$3 - \$5/GJ).

11 The cost of transmitting the CO_2 100 km would be 0.096 Euro per GJ (\$0.12/GJ), which is more than double than that of an equivalent hydrogen transport (\$0.05/GJ).

Table 1 Data for SMR of NG, Linde process

parameter	value	source	remarks
Technical data	**per unit**		
spec. investment, Euro/kW	250	Wurster and Zittel 1994, 135	
annual load, h	8000	Wurster and Zittel 1994, 135	
lifetime, ys	25	Wurster and Zittel 1994, 135	
overall efficiency	81.2 %	Wurster and Zittel 1994, 135	
O&M, in % pa	1		estimate
raw price (Euro / GJ)	3.9	Audus 1996, 840	
product price (Euro / GJ)	5.4		calculated from given data
product price (mEuro / kWh)	19.4		calculated from given data
capacity, MW	387	Wurster and Zittel 1994, 135	
Annual hydrogen output, 10^6 GJ / y	8.6	Wurster and Zittel 1994, 135	
Annual hydrogen output, 10^6 m^3 / y	800	Wurster and Zittel 1994, 135	
Pressure level, Input, MPa	4	Wurster and Zittel 1994, 135	
Pressure level, Output, MPa	3	Wurster and Zittel 1994, 135	
Specific CO_2 emissions, kg/ GJ H_2	16.4	Blok *et al.* 1997, 163	
Specific CO_2 emissions, kg/ m^3 H_2	0.82	Wurster and Zittel 1994, 135	
Specific CO_2 emissions, m^3 CO_2 / m^3 H_2	0.435	Wurster and Zittel 1994, 135	

Source: Wurster and Zittel (1994, 135), data for 2050.

This value should be compared with other literature data: today hydrogen costs about: 12.8 to 16.7 Euro per GJ (CO_2 free, *i.e.* probably the more expensive Kværner process) (Wurster and Zittel 1994, 130)[12]; an internet source gives 3.6 Euro per GJ for steam reformation (IR 10); and a Canadian investigation (Ouellette et al. 1997, 401): 13 (compressed) to 21 - 46 (liquefied) Euro per GJ. The latter source has given market prices for hydrogen for the chemical industry, so that those are probably not relevant for our investigation.
From a figure in Blok *et al.* (1997, 163) we conclude that CO_2 emissions for the EGR option amount to 16.4 kg per GJ H_2.

Coal Gasification Hydrogen Plant

This section will contain a description of the coal gasification process leading to the generation of process and syngas and the associated hydrogen generation. As a large series of coal gasification processes exists Kristiansen (1996, 16), we will not describe the technologies specifically here. Instead we will present the results of a few investigations on the subject. A part of this description is actually based on descriptions of coal power plants, which are treated below.
In principle the hydrogen production from coal is similar to the production from natural gas, described above, with the exception that there should also be a supply of oxygen for a reaction with the carbon of the coal[13]. In the case of coal gasification we need a stream of water vapour and oxygen led over the coal resulting in the following reactions (Rosen (1996, 1083):

$C_{25}H_{20} + 25\ H_2O \rightarrow 25\ CO + 35\ H_2$; and
$C_{25}H_{20} + 12.5\ O_2 \rightarrow 25\ CO + 10\ H_2$.

12 Original data: 46-60mEuro/kWh; US¢65/kg; CD\$3/kg (compressed) and CD\$5-11/kg (liquefied).

13 According to Rosen (1996, 1083) coal can be represented as $C_1H_{0.8}$, equivalent to our: $C_{25}H_{20}$.

83 per cent of the hydrogen from this reaction will, according to Rosen (1996, 1083), derive from the water vapour. The purity of the produced hydrogen should be between 93 and 98 per cent.

Smith and Thambimuthu (1991) mention a technology to produce hydrogen and solid black carbon from the coal, albeit only at a thermal efficiency of 24 per cent. This method does not seem to be very attractive from an energetical point of view.

According to Rosen (1996, 1087) the hydrogen production via coal gasification will result in an energy output of 59 per cent in the form of hydrogen. Another idea of efficiency of the gasification process can be gained from Hauserman (1994, 418), where the product gas[14] is supposed to consist of about 60 % H_2, 2 % CO, 29 % CO_2, and 9 % CH_4. This means that this technology will only be competitive with SMR, if the coal is sufficiently cheap.

In any case, the need to perform product gas cleaning from impurities arises. Jansen *et al.* (1992) propose to use a high temperature gas and fly-slag cleaning system[15]. In their description not the CO_2 itself but actually the hydrogen is removed from the gas stream by ceramic membranes at an efficiency of 88 per cent[16] (Jansen *et al.* 1992, 367, 369). The remaining hydrogen could be burned and so deliver energy for the steam generation.

The coal fuelled hydrogen plants could be installed together with the CO_2 injection sites on platforms at suitable locations on the ocean. Coal would be transported by large vessels[17] to the plant, the CO_2, the ash could be disposed of easily and without extra transport costs, and the hydrogen would be transported to the consumers in ships similar to today's LNG vessels. Part of the hydrogen would be used at the plant for fuelling electrical appliances or pumps via fuel cell solutions.

The fact that swimming production platforms have been developed for the off-shore oil industry should argue for the feasibility of such a technology, too[18]. Such production and deposition platforms might from a safety point of view be situated outside the regions exposed to tropical cyclones[19], *i.e.* within a 5°N to 5°S belt in the tropical oceans. But there slightly more energy will be needed for liquefying the CO_2 and the hydrogen compared to a more temperate location.

Other solutions could be to perform *in situ* or *underground coal gasification* (ICG, UCG, res.) in order to generate a process gas that can be used for hydrogen generation. In principle an oxygen and steam stream are injected in below ground coal reservoirs, where a path of increased permeability has been created by *e.g.* horizontal boreholes or chemical processes (IR 9). The product gas has a heating value of 8 to 11 MJ per Nm^3 (3 to 7 if air is blown instead of oxygen) and contains carbon monoxide, hydrogen and methane. This mixture could be used in some of the technologies that we present. For example the hdyrogen could be separated and sold or the mixture could be fuelled in power stations.

Myasnikov *et al.* and Myasnikov and Lazarenko (1995) have shown that ICG can be realised at some locations in the Kuznetsk basin, Russia, as a means to overcome ecological and logistic problems in the region. This technology would abolish the transport of the coal, minimise other environmental problems, as with slag heaps, and not the least it would make available coal resources that currently cannot be exploited due to large depths and consequential technical problems (Davies 1995, 56).

However, the problem with impurities contained in the ICG gas still has to be solved, and another challenge is to find a way to increase the rate of chemical reactions in the UCG process (Myasnikov *et al.* and Myasnikov and Lazarenko 1995). The deposition of the CO_2 is still a problem, unless it can be disposed of via EOR, res. EGR[20] in nearby depleted oil or gas fields, it will have to be transported to disposal sites.

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14 Normally product mixes are given as volume percentages for gases, we assume this is also valid here.

15 In fact this description is also one based on an IGCC method, but we have chosen to present the ideas on the H_2 separation and the cleaning processes proposed by Jansen *et al.* (1992).

16 This might be easier, as hydrogen ions have a very small diameter compared to all other ions. Still those membranes need more development (Audus 1997, 218), but as our scenario looks very much into the future, we think that the use of this technology can be defended.

17 There are obvious economies of scale in very large coal vessels, shown by Huang (1995).

18 As has been described elsewhere, the Mars TLP is one recent example (Spiegel 1996).

19 Those are trivially called hurricanes or typhoons depending on location.

20 *Enhanced Oil Recovery*, res. *Enhanced Gas Recovery*.

Hinman (1991, 121) bemoans the lack of interest in R&D on UCG, but his argument on potential ground water contamination by the resumes of UCG seems to be invalid, if this method was used with coal resources at great depth. Only when steeply sloping surface near seams are exploited by this technology, such problems might occur. We may assume that this will not be the case, and that those resources would normally be exploited conventionally or left untouched.

Costs:

The hydrogen from coal gasification would cost about 3.6 Euro per GJ to produce, Table 2. If UCG was exploited, costs might possibly be somewhat lower.

Table 2 Data for hydrogen from coal (Linde Prices, partial oxidation)

parameter	value	source	remarks
Technical data	**per unit**		
spec. investment, Euro/kW	500	Wurster and Zittel 1994, 137	
annual load, h	8000	Wurster and Zittel 1994, 137	
lifetime, ys	30		estimate
overall efficiency	60 %	Rosen 1996, 1087	
O&M, in % pa	1		estimate
raw price (Euro / GJ)	1.6	Kjær 1996, 900	
product price (Euro / GJ)	3.7		calculated from given data
product price (mEuro / kWh)	13.4		calculated from given data
capacity, MW	387	Wurster and Zittel 1994, 137	
Specific CO_2 emissions, kg/ m^3 H_2	2	Wurster and Zittel 1994, 137	
Specific CO_2 emissions, m^3 CO_2 / m^3 H_2	0.807	Wurster and Zittel 1994, 137	

Source: data for 2050 from Wurster and Zittel (1994, 137); Data for partial oxidation of coal, Linde process.

The data in Wurster and Zittel (1994, 137) seem to indicate that CO_2 emissions are about 14 kg per GJ (50 g per kWh).

Hydrogen Storage and Transport

Some of the technologies that currently are being used for NG storage will also be feasible , albeit modified, in a hydrogen energy system. On a large scale, hydrogen storage may take place in the form of empty caverns, in the same way that natural gas is stored today. But opposite to natural gas at the present time[21], the need may arise to store the hydrogen decentralised, *i.e.* in smaller units. For example the use of decentralised fuel cells will cause the need to address decentralised hydrogen storage.

Following Taylor (1994, 369) we conclude that hydrogen stores should not pose much larger risks than refineries or ammonia plants where the substance that may escape is poisonous. Hydrogen is very volatile, so that rapid dilution would reduce explosion danger. Data on the risks related to natural gas storage plants would probably also be representative for hydrogen storage, and be similar to interpret as indicated by Taylor (1994, 386). As with town gas, odorants may be added to the hydrogen for easier leak detection. If a sulphur containing odorant is chosen, it will have to be removed before use to avoid fuel cell poisoning.

Morthorst *et al.* (1993, 22) mention hydrogen's wide range of inflammability, a low ignition energy and a large range of mixture area for explosivity as important factors for a risk assessment. Another problem is that hydro-

[21] This comparison is not quite fair, as compressed natural gas (CNG) is being used in some cases, like for cars in New Zealand. Also other light hydrocarbons, like propane, are being stored in pressurised or liquid forms. However, those contribute not overwhelmingly to the global energy supply today.

gen can cause brittleness in various metals, so that different alloys will have to be employed for pipes and compressors and new materials for seals and valves compared to today's natural gas technologies (IR 10).
So far hydrogen has not been used on a very large scale as an energy carrier, so that storage technology for this fuel still are developing. Apart from storing it in gaseous form, as described above, attempts have been made to investigate other forms of storage (Zittel and Wurster 1994, 118 f.): in the form of metal hydrides, within sponge iron, as a liquid, by cryo-adsorption or in the form of liquid hydrides. All of these technologies have some relevance to the transport of the hydrogen, too. We will not present data on the storage systems separately, as they will implicitly be covered in the hydrogen transport.
If we look at the storage as such, then its efficiency is crucial. For example to compress hydrogen at a "petrol" station will need about a fifth of the energy in the hydrogen (IR 10). The efficiency of this process therefore is only about 80 %. It looks even worse for cryogenic storage, where the parasitic energy for the pumping is about 40 % (IR 10). This might be defensible for a high-cost application as in the transport sector – it might be unobtainable in other sectors, where fuel efficiency is of vital importance.
What these problems imply is that storage will have to be done in a pressurised form for decentralised and mobile applications. For maritime transport from remote sources of hydrogen, cryogenic methods deem to be reasonable, while for long-range terrestrial transport, pipeline solutions will be the technology of choice.
As has been presented elsewhere in this text, it might be realistic to introduce the full hydrogen energy system stepwise, *i.e.* by starting distributing natural gas and hydrogen mixtures by pipelines. In that respect it might prove less expensive to transport hydrogen rich mixtures at elevated pressures compared to natural gas at low pressures (Öney *et al.* 1994, 818).
This is not obvious from the start, as hydrogen actually has a lower energy content per volume than natural gas, which consists nearly exclusively of methane. To transport the same energy amount a larger volume has to be moved with hydrogen than for methane. This increases the power demand and numbers of compressors. As a balance between the costs for those and the pipe, whose diameter can be increased to enable easier flow, needs to be established, the pressure, at which the hydrogen is provided, has an important influence.
Already if one compares transport of coal, natural gas and electricity by rail, pipeline or by overhead cables for comparable distances, it has been shown that electricity transport generally is unfavourable. The costs for natural gas and coal transport by (slurry) pipeline are generally the lowest (Davies 1995, 65)[22].
If the transport distances to the markets are comparatively short then the advantage of using the CO_2 from SMR could be used for EGR has to be considered. However Blok *et al.* (1997, 167) also stress that the situation is complicated in that for distant hydrogen markets it would be less costly to transmit the natural gas to the hydrogen plant near the market, where pressure levels for distribution would be lower. In those cases the transport of the CO_2 becomes the economically limiting factor.
We also have to take into consideration that in the future due to the growing awareness of the limitation of the fossil resources the primary energy supply will have to be economised with. In this situation one would give emphasis to exploiting natural gas sources using EGR as compared to transporting the natural gas to the customers at the expense of not being able to exploit the whole resource. This can then be somewhat compensated for by gasifying an extra amount of coal to produce more hydrogen, but this will in reality very much be directed by the economics of each solution.
As a first idea it might be allowable to calculate with an overall efficiency of the hydrogen store and pipeline system of about 86 per cent, as proposed in Sørensen (1996). The actual distribution of the losses will then have to be gained from a deeper analysis.
One question arises from the transport of cryogenic hydrogen: where shall the energy come from to heat it up so that it can be sent out as a gas in the distribution pipelines? In some places this can be done at the land-based power stations, where the cold can be used to chill the CO_2 separated from the flue gas stream. This of course will dictate the location of most of the power stations, *i.e.* they have to be placed near the landing sites of the hydrogen tankers.
At other places this synergy might not be able to exploit, so the heat would have to come from the environment. In the winter period this would not be favoured. But in the summer period for example this can be a prominent solution, when the cold could be used for chilling purposes. This would in many instances save extra energy for air conditioning equipment. One could also imagine using the heat difference between the liquid hydrogen and the environment in a rankine kind of engine.

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22 For natural gas Jensen (1994, 248) shows a graph from which we conclude that transporting NG 3200 km (2000 miles) would cost about 1.3 Euro per GJ onshore and about 2.3 Euro per GJ offshore. For longer distances LNG transports cost about from 1.9 to 2.6 Euro per GJ (6400, res. 11300 km; 4000 res. 7000 miles).

Costs:
As explained above hydrogen storage costs will be implicitly included in the transport costs. We think the hydrogen transported to the customers generally would cost about 6 Euro per GJ. This value includes the intra-continental maritime and on-shore transport and storage.
The total cost of hydrogen from production to the distribution channels will then be about 9.6 to 11.4 GJ per Euro, depending on whether it has been produced from coal or natural gas. An average value might be 10 Euro per GJ.
The costs of pipeline hydrogen transport has been given by Öney *et al.* (1995, 819 f.) of about 0.3 to 1.0 Euro per GJ for a 200 km transport length (depending on the inlet pressure) and of 1.6 Euro per GJ for 500 km[23]. For a distance double that, we estimate that costs would be about 3 Euro per GJ, perhaps slightly lower[24]. Taking the value from Blok *et al.* (1997, 167) would result in a cost of only 0.04 Euro per GJ and 100 km pipeline transport, or 0.2 Euro per GJ for 500 km[25]. Values from Wurster and Zittel (1994) give a cost figure of about 0.6 Euro per GJ, Table 3.

Table 3 Data for hydrogen pipeline transport

parameter	value	source	remarks
Technical data	**per unit**		
spec. investment, Euro/kW	400	Wurster and Zittel 1994, 144	
annual load, h	8000	Wurster and Zittel 1994, 144	
lifetime, ys	30	Wurster and Zittel 1994, 144	
overall efficiency	86.2 %	Wurster and Zittel 1994, 144	
O&M, in % pa	2		estimate
product price (Euro / GJ)	0.6	Wurster and Zittel 1994, 144	calculated from given data
product price (mEuro / kWh)	2.2	Wurster and Zittel 1994, 144	calculated from given data
Inlet Pressure, MPa	10	Wurster and Zittel 1994, 144	
Outlet Pressure, MPa	5.9	Wurster and Zittel 1994, 144	
Capacity, GW	72	Wurster and Zittel 1994, 144	
Annual Delivery, GWh	774000	Wurster and Zittel 1994, 144	

In this respect it might be interesting to note that a majority of the global population is currently living within 60 km of a coast, and that this share will increase to at least about 75 per cent[26]. This means that transport distances on land would be small, if hydrogen was shipped from off-shore installations to the coasts.
As with the case of *liquefied natural gas* (LNG), where transport is currently taking place in special vessels, this can also be realised with liquefied hydrogen (LH_2). Problems arise from: extremely low density, very low boiling point and the safety aspects (Giacomazzi 1989, 603). In order to prevent boiling losses it is essential to have fast vessels (16 to 19 knots[27]), and the insulation of the containers has to be optimised (ibid., 605, 613).

23 about \$.4-1.2/GJ; about 2.3 $\$_{1994}$.

24 Costs would still about double at this distance, as compressor and pipeline costs develop almost linearly with the distance, and any economies of scale, for larger power transport, will have limited importance (Öney *et al.* 1995, 820).

25 Original data: $\$_{1991}$0.05/GJ (100 km) at a pressure drop of 2.5 bar per 100 km.

26 Today two-thirds, expected to rise to 75 % by the year 2010 (Scott *et al.* 1996, 404).

27 One knot is one nautical mile, nm, per hour.

Another challenge is making the vessels stable against rolling[28] to protect the ship's structures, the liquid gas containers, and make cruising less of a nuisance for the crew.
Opposite to Giacomazzi (1989, 614) we believe that the boil-off will be used for propulsion, as fuel cell electrical units will be applied in maritime transport, as described in Wurster and Zittel (1994, 150).
Giacomazzi (1989, 615) gives an overview of the costs of the LH_2 transport by the vessels. Actually those values need to be recalculated in order to take into account the substitution of the bunker with boiled-off hydrogen and fuel cell solutions. For a ride of 3000 nm costs could be as low as about 2 Euro per GJ[29]. For a similar solution another source results in a value of lower than about 5.6 Euro per GJ (Wurster and Zittel 1994, 146)[30].
On the other hand maritime and land-based transcontinental transport of LH_2 in containers could be realised gradually, by starting with standardised commercial vacuum super-insulated ISO 40 ft containers (40 m^3 LH_2) (Wurster and Zittel 1994, 119, 145) with boil-off losses of about 5 per cent for a holding period of 30 days (=0.01 % / d). Investments costs would be about 900 Euro per kW, which would result in fuel cost adders of about 3 Euro per GJ[31].

Hydrogen CHP Stations

Centralised IGCC power stations with CO_2 recovery will be presented later on, but there will have to be CHP power stations elsewhere in the energy system. They will be hydrogen fuelled, as this fuel is the *energy currency*[32] of the energy system. Therefore we investigate hydrogen fuelled fuel cell power stations or CC plants with *gas turbines* (GT). The reason that also GT solutions arise is that those can provide electricity at a very high efficiency, which in places will be a large advantage. We start with the presentation of the fuel cell technology.
In a flaming article Rogner (1994) boasts of *fuel cells* (FC) being the only technology in the power sector with a clear future perspective, as it can exploit several kinds of fuels and therefore opens up for new solutions. This all sounds very nice. But what is the FC technology actually?
A fuel cell is an electrochemical device to generate electricity from a stream of energy carriers like hydrogen or natural gas. The most prominent FC technology for utility application is probably the *solid oxide fuel cell* (SOFC) technology, which can be used reversibly, too (Morthorst *et al.* 1993). But a series of other FC technologies exists: MCFC, PAFC, etc.[33]. Common for all of them is that they convert the chemical energy of a fuel directly into an electrical voltage, which then can be fed into the electricity grid, after having been reformed to AC voltage[34], unless DC systems are being employed on a local scale.

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[28] This is related to the metacentric height, which results from the difference between the metacentric radius and the height of the centre of gravity (Giacomazzi 1989, 605).

[29] Original value: about 25 mEuro per normal cubic metre of hydrogen at about 12.7 MJ / Nm^3. With reference to the values for LNG tankers given in footnote 79: If we take into consideration that costs for hydrogen transport will be higher than for LNG, as the required storage temperatures are lower so insulation demands higher, then assuming about a tripling in costs will only mean about 1.5 Euro per GJ. Technological developments could mean lower realised costs than assumed here.

[30] Original value: <2 cEuro per kWh. If one uses the data given in Wurster and Zittel (1994, 119) to compute the average cost of LH_2 transporting, then a value of 2.6 to 3.2 Euro per GJ results. It has been assumed that the cost of the barge carrier will only appear with a weight of one tenth, as it would be shuttling between consumers and production sites and be able to carry five barges at a time. Using the same cost values for a larger so-called SWATH-ship design, transportation costs come down to: 0.3 to 0.4 Euro per GJ!

[31] The energy needed for this transport should be deducted from the end-use energy in the transport sector to make the analysis fair.

[32] Scott (1995, 90).

[33] Besides SOFC there are also several other types of fuel cells that are currently being investigated: *AFC* (Alkaline Fuel Cell), *PAFC* (Phosphoric Acid Fuel Cell), *PEMFC* (Proton-Exchange Membrane Fuel Cell), *MCFC* (Molten Carbonate Fuel Cell), or *SPEFC* (Solid Polymer Electrolyte Fuel Cell), *SPFC* (Solid Proton exchange Fuel Cell), *DMFC* (Direct Methanol Fuel Cell), (Stimming *et al.*, 1992).

[34] Losses for this process should be about 3 % (Lobachev and Richter 1996, 288).

When Lobachev and Richter (1996) present an investigation of a power station employing the SOFC technology, they also treat aspects as the influence of the FC voltage: an increase from 0.6 to 0.7 Volts is equivalent to an increase in the FC efficiency by about 4 per cent. Higher voltage during production leads to lower current intensities for the same power output[35] and this minimises ohmic losses[36]. On the other hand one then has to install more fuel cell clusters to achieve the same overall efficiency, so that an economic balance will have to be found.

The coupling of fuel cells with steam turbines (CC) is possible, but shall not be presented here. However, Kobayashi *et al.* (1997, 190) have presented a new and innovative hydrogen fuelled "chemical" gas-turbine system with an efficiency of 64 per cent. This is about 10 per cent higher than today's NG fuelled GT CC.

If we consider that electricity will have to be produced at a very high efficiency due to the relative increase in demand for this energy carrier, then we will have to choose such a technology as standard for the future energy system. The assumption of an electrical efficiency of 60 per cent (1300/2200 GWy) in the original scenario sketch (Sørensen 1996) therefore seems to be reasonable.

In decentralised installations FCs will provide space heating. In the later section on the scenario results and their interpretation it will be assumed that the transmission of this heat will take place with the same efficiency as in larger district heatign systems: *e.g.* 80 %. To indicate potentials to integrate FCs with other technology, one could use absorption cooling integrated in PAFC or MCFC systems to meet cooling or air conditioning requirements (Troost 1994, 190). Such integration will be a more natural feature in the energy systems of the future, but unfortunately we cannot take those into consideration to a high degree of detail.

<u>Costs:</u>

Electricity generation costs from hydrogen fuelled CHP would be around 18 Euro per GJ. This value needs to be corrected for the cogenerated heat, which will in places lead to cost reductions, see the section on cogenerated heat and electricity costs below.

Ippommatsu *et al.* (1996, 134, 135) have analysed the production steps in fuel cell manufacturing and considered six different designs of SOFC. They conclude that it should be possible to manufacture fuel cells at a cell cost of between 360 and 624 Euro per kW, so that system costs for a power station would be around 1600 Euro per kW[37]. In fact FC costs should become even lower: If one assumes a higher power density (in W per m^2) for coming commercial fuel cells, then cell costs should be in the 160 Euro per kW class.

If we, just for fun, combine information on the balance of plant costs of a total plant with a range of 65 to 85 per cent (Penner *et al.* 1995, 413) with expected costs of PEMFC fuel cells from the transport sector, where prices have to be very low: 24 to 32 Euro per kW[38] (ibid., p. 424), then we end up with estimates of: 28 to 49 Euro per kW, which might be far too optimistic, but probably may be realised in the end. The transport sector is not the least competitive sector in the World!

Penner *et al.* (1995, 380) state that the system costs of hydrogen fuelled FC CC power stations would reach about 800 Euro per kW[39] around 2010. A Danish source, DEA (995a, 83) estimates about 600 Euro per kW[40] for 2015. Judging from the necessary development in the transport sector economics for fuel cells should become much more favourable, so that even lower costs than those will be applicable. However, energy costs are not very sensitive to a change in the installation costs, 500 Euro per kW instead of the chosen 600 will only lead to a reduction by 2 per cent!

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35 The electrical power is equal to the voltage times the current: $W = U \cdot I$.

36 This means that the electricity flow through the FC will be reduced less by the normal electrical resistance of the material, so that more power is made available to the electricity generation.

37 Original data: $450.780/kW (FC); $2000/kW (system cost); $200/kW (cell cost future).

38 $30-40/kW.

39 $1000/kW.

40 5-6 Mkr_{1994}/MW for a NG fuelled CHP power station, *i.e.* the investment includes the heat generation part!

Data for hydrogen CHP

parameter	value	source	remarks
Technical data	**per unit**		
spec. investment, Euro/kW	600	DEA 1995a, 83	
annual load, h	7500		estimate
lifetime, ys	30	DEA 1995a, 83	
overall efficiency	64 %	Kobayashi *et al.* 1997, 190	
O&M, in % pa	5	DEA 1995a, 83	
raw price (Euro / GJ)	10		calculated from given data
product price (Euro / GJ)	17.9		calculated from given data
product price (mEuro / kWh)	64.3		calculated from given data
capacity, MW	100		estimate

Note: This technology would be modular, *i.e.* capacities could range from some kW to several hundred MW.
Overall efficiency: here means only of electricity generation. Depending on local conditions it will be possible to cogenerat heat, this will mean an extra of about 30 per cent, but at a reduction of the produced electricity amount!

Power Plants with CO_2 Recovery

In this study we assume that the *power plants with CO_2 recovery* (PPCR) are fuelled with coal[41], as this is the largest fossil energy source known today. The power stations are of the combined cycle type; where heat from a first combustion step is recovered to produce steam for a conventional turbine; and equipped with a CO_2 recovery technology. These power stations thus are different from most current ones[42].

One technology we cannot describe properly, as we were not able to find appropriate data for it. It may, however, be one option in the future: the *magnetohydrodynamic* (MHD) energy conversion, whereby heat can be converted directly into electricity. It is currently only in an investigative phase and will not be treated in the following, although it is expected to reach efficiencies of between 50 and 55 per cent for a second generation, triple cycle[43] configuration (IR 9) and might have the potential to become the large scale power technology of choice in some decades. Its main advantage, from an exergy point of view, is that it exploits the high temperature of the flame better than gas turbines (Sens *et al.* 1994, 275).

The combined cycle technology has been chosen, as only this will ensure high thermal efficiency, which is a vital fact when we recall that the CO_2 recovery itself will need some energy. Furthermore the *combined heat and power* (CHP) technology will be considered, its success in the Netherlands have been described by Blok and Farla (1996), and its energetical advantages are obvious.

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41 When we write "coal", we actually think of coal that will be useful for gasification. This will change, for example the specifications with respect to the ash fusion point temperature compared to specifications for current power stations (Scott and Carpenter 1996, 63). With respect to lignite (sometimes called brown coal, in German: Braunkohle) Haupt (1996, 107) describes an IGCC project with an efficiency estimated to lie between 45 and 46 per cent. This is impressively high for lignite, so this might open up the use of this kind of lower quality coal for power purposes.

42 Today's state of the art coal fired power stations are using a *pulverised coal* (PF) burning technology. The low CO_2 concentration in the flue gas makes CO_2 recovery difficult and costly. For various reasons pulverised coal fired power stations with CO_2 recovery will result in about doubled electricity costs and are suffering from other problems, for example a doubled space demand from the CO_2 recovery plant (Herzog 1996, 224 ff.).

43 Triple cycle refers to a combined MHD, gas turbine, steam turbine PP.

In principle there are three basic technologies to make power stations with CO_2 capture: burning the fuel with air and separating the CO_2 from the flue gas, burning the fuel with pure oxygen and recycling the CO_2, or reforming the fuel to a product gas, removing the CO_2 and fuelling with the hydrogen instead (Akai 1995, 801). The latter technology will here be treated as a modified version, and with respect to the first two we will argue for the second, *i.e.* the CO_2 recycling, as this most probably will lead to the lowest costs.

We have used following sources for information on this technology: Hendriks *et al.* (1989), Nakabayashi *et al.* (1995), Peters (1989) and several other texts[44]; and we argue for the use of an *integrated coal gasification combined cycle* (IGCC) power station technology with subsequent CO_2 recovery. In the first place this might seem to be proposing a completely new concept, but an IGCC PP can be realised in several phases, as explained in Haupt (1996), so in principle one could already today prepare possible IGCC sites.

If we start with the gasification part, then Peters (1989) describes several technologies leading to the production of a CO and H_2 mix, the raw or product gas, which afterwards is cleaned to remove dust and pollutants like H_2S, NO_x or SO_2. The coal gasification technology offers the advantage of pre-scrubbing of the raw gas – opposed to end of pipe *i.e.* after the end of the combustion process. This makes possible very low emissions of SO_2, and NO_x emissions can be abated easily too. It might not be essential to realise a hot gas cleanup, as the improvements will only be about one per cent in the total power station efficiency (Haupt 1996, 108).

Opposite to PF power stations low ash fusion temperature coal are preferred for gasification (Kobayasi 1994, 313). This will enable exploitation of coals not now favoured with the utilities, but the mixing of different coal types to reach the specifications most favourable for a specific plant is already today a well-established technology.

There may or may not occur the necessity to provide pure oxygen for coal gasification. At the time of Peters (1989, 682) no relief from this open question could be offered, and Peters referred to the need of more experimental work to infer, whether the need of pure oxygen becomes necessary. The disadvantage is that it is expensive to produce this gas by *air separation* (AS), the advantage is that the volume of the flue gas produced is reduced and that other gases like argon or nitrogen may be sold (Shao *et al.* 1995, 1117).

If we assume coal combustion with recycling of CO_2 to keep *e.g.* turbine entrance temperatures low enough or flame temperatures from smelting the boilers, the liquid oxygen from the AS can be easier compressed than gaseous oxygen by the gas turbine's compressor and it can furthermore be used to condense part of the CO_2. This integrated process saves significant energy amounts for this activity and should theoretically increase the efficiency of the gas turbine[45] (Shao *et al.* 1995, 1117 f., 1120).

Also the O_2/CO_2 technology almost reduces CO_2 emissions. The CO_2 can be separated easily, *i.e.* without the need of CO_2 separation from flue gases diluted by *e.g.* nitrogen, as occurs in today's airblown power stations. Another advantage of the CO_2 recycling is the reduction in NO_x creation. Okazaki and Ando (1997, 214) have shown that the reduction of recycled NO in the furnace is dominant and amounts to 50-80 % of the total observed NO_x reduction.

For an IGCC <u>without</u> CO_2 recovery Peters (1989, 689) gives a range from 47 to 49 gross and from 43 to 45 net electrical efficiency[46], depending on the gasifier types. This is higher than the 41 to 42 per cent mentioned by Nakabayashi *et al.* (1995, 17). A somewhat higher value is cited by Akai *et al.* (1995, 802) for an oxygen blown IGCC: 43.0 per cent, while the US Department of energy expects 52 per cent net by the year 2010 (IR 8).

The gas turbine solution is currently a very attractive option, and further development has been be noted[47]. On the other hand Hauserman (1994, 416) and Pruschek (1996, 443) declare that an IGCC plant with advanced fuel cells might exceed efficiencies of 60 per cent. And in fact Lobachev and Richter (1996, 289) have presented data that indicate an efficiency of 62 per cent for an IGCC SOFC power station.

If we then consider <u>CO_2 recovery</u>, the net efficiency, *i.e.* the power output relative to the energy input of the coal, will decline. This is a natural consequence of the energy demand necessary to separate the CO_2 from the flue stream, the compression and cooling of the gas for transport and disposal. However, the 38.1 per cent efficiency given by Hendriks *et al.* (1989, 136) seems to be too low, if one compares with later texts on the topic.

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[44] Some overview may be gained from MIT (1996), but the one-sided abstracts collected there give a sketchy picture only.

[45] In the case of Shao *et al.*'s example of a NG PP by about 3 to 5 per cent. For IGCC a similar amount might be achievable, if the power station is based on gas turbines.

[46] = after own consumption and transformer losses have been discounted

[47] For example Haupt (1996, 104) on the Siemens 3A gas turbine efficiency jump and achieved NO_x reduction.

Prutkovsky and Chavchanidze (1995, 217) describe CO_2 recovery by "freezing out" and argue that more than 100 per cent LHV efficiency can be achieved via an increase of the dew point temperature and the use of the latent heat of vaporisation. It is a little bit doubtful, whether this is correct; their text is not easy to understand, so we disregard their argument.
Haupt (1996, 107) considers an IGCC with gas turbines and mentions an efficiency of 40.5 per cent with a CO_2 recovery of 88 %. Jansen *et al.* (1992, 369) give a value of only 34.5 per cent for a gas turbine IGCC with about 97 % CO_2 recovery, but 47.5 per cent for an IGCC power station based on the MCFC[48] fuel cell technology. The CO_2 would be compressed to 110 bar. The advantage of the fuel cell technology is that the power drop due to the CO_2 separation is much smaller than for the gas turbine system. Another feature with the fuel cell system is that high-temperature flue gas cleaning CO_2 removal are easier (Jansen *et al.* 1992).
Altogether, *i.e.* after taking into account the CO_2 recovery (see a description of it in the special section later on), the electrical efficiency of such a power station would then be still at least 45 per cent. Some heat will also be available, we guess between 10 and 40 per cent, the exploitation of it depends very much on the local and climatic conditions. There should not be any objections to also have such power stations running in a cogerating mode.
So from an energetical point of view alone we would probably choose the fuel cell solution. We will therefore also have to look at the economical situation.
The correct location of power stations with CO_2 recovery depends very much on the transport costs of the various materials. Seifritz (1996) illustrates an example[49], where the correct location of a PP w/CR also depends on whether the coal is transported cheaply by barge, or more expensive by rail. Therefore we cannot answer the location question with confidence.
Costs:
With respect to electricity generation the IGCC w/CR power would cost about 11 Euro per GJ. This price has to be corrected for any cogenerated heat, see the section on cogenerated heat and electricity costs below.
As said before we have chosen to concentrate on the combined cycle technology for the electricity generation. Pruschek *et al.* (1996, 442) explain that conventional coal power stations have reached their technological and economical limits. Rising the steam temperatures above today's values[50] can only be achieved with the help of special Nickel-based alloys. Presently those are so expensive that the increase in efficiency will no longer outweigh the extra construction costs.
For the industrialised world today, with conventional *pressurised fluid bed* (PFB) *pulverised coal* (PF) fired power stations with *flue gas desulphurisation* (FGD), the standard solution would be to use a physical or chemical absorbent to capture the CO_2 (Riemer and Ormerod 1995; who have given an overview of CO_2 capture and sequestration studies of the IEA). This is probably not very effective, as the CO_2 concentration in the flue is diluted by the stream of nitrogen from the air, and the efficiency of those power stations is below 50 per cent[51]. Therefore electricity generation costs would almost double, if one wants to retrofit them with CO_2 removal.
Even the most optimistic case of a natural gas *combined cycle* (CC) with a chemical scrubbing agent (MEA) would cause a rise in generation costs, and also CO_2 recycling would, according to Riemer and Ormerod (1995), still mean almost a doubling of generation costs. Some other quotations are given in the next paragraph.
Peters (1989, 692) mentioned specific investment costs of 1350 $Euro_{1990}$ per kW for a natural gas fuelled 500 MW CC and 1130 $Euro_{1990}$ per kW for a conventional coal power station. Costs would decline below 830 $Euro_{1990}$ per kW, only if ISTIG gas turbines were applied. Hendriks *et al.* (1989, 131) gave a value of 1610 $Euro_{1990}$ per kW for a coal fuelled single cycle power station with CO_2 recovery.
And price expectations have continued to plunge. For a 500-600 MW IGCC power station the specific investment might go down to about 800 Euro per kW (Pruschek *et al.* 1996, 447; IR 8). This argument is followed by Haupt (1996, 105), who expects the same investment costs for IGCC as for conventional PF power stations at

48 MCFC = Molten Carbonate Fuel Cell

49 The mathematics of this is not trivial and necessitates solving a polynomial of 8th degree.

50 This would lead to *ultra super-critical steam cycles* (USC).

51 Even though Kjær (1996, 897) boasts of the PF Esbjergværket with a world record of 45 % rated efficiency, this technology will not be applicable for the mid-21 century treated by this scenario. One reason is that the higher value of electricity will make it essential to provide as much of this energy form as possible.

the end of the 1990s[52]. From the discussion given before we therefore conclude that estimated capacity costs will be about 2000 Euro per kW for an IGCC or IGMCFC with CO_2 recovery.
With respect to the costs of the produced electricity Jansen *et al.* (1992, 370) give a comparison relative to the IGCC system without CO_2 recovery at an efficiency of 43.6 per cent. Compared to this base line the IGMCFC, with 88 % H_2 recycling, would have generation costs about 40 to 60 per cent higher, and with 95 % H_2 recovery 30 to 50 per cent higher. If CO_2 removal was "optimised" the costs were only 20 to 40 per cent higher[53]. Thus, Jansen *et al.* conclude that CO_2 emissions can be reduced at only a modest increase in production costs.
Akai *et al.* (1995, 802) support the argument by Jansen *et al.*, in that they also only assume power generation costs rising by 20 to 50 per cent due to the CO_2 recovery. They also mention that the efficiency of each technology varies on the carbon content of the fuel, the temperature and pressure situation in the power station and the concentration of SO_2 in the flue gas. This has not so much influence for our analysis as we have assumed that coal will be the main medium used in central power stations, the only free parameter thus is the sulphur content of the fuel, which may vary.
The table that Akai *et al.* (1995, 804) give on PP technologies with CR, gives an overview of the generation costs compared to the reference case, *i.e.* without CR. There values are not directly comparable with the ones mentioned before, as they give values for a complete system and also take into consideration the actual sequestration. For the examples that fit best with our ideas, generation costs would rise by about 40 to 50 per cent. Also Audus (1997, 219) argues for a rise of generation costs by about 40 per cent above current levels. This is, opposed to Akai *et al.*, not yet covering the transport and disposal of the generated CO_2.

Data for coal fuelled IGMCFC w/CR

parameter	value	source	remarks
Technical data	**per unit**		
spec. investment, Euro/kW	2000		estimate
annual load, h	8000		estimate
lifetime, ys	25	Jansen *et al.* 1992, 370	estimate
overall efficiency	47.5 %	Jansen *et al.* 1992, 369	
O&M, in % pa	5	DEA 1995, 84	
raw price (Euro / GJ)	1.6	Kjær 1996, 900	
product price (Euro / GJ)	10.8		calculated from given data
product price (mEuro / kWh)	39.0		calculated from given data
capacity, MW	800		estimate
collected CO_2, g / kWh	710		calculated from given data
specific CO_2 emissions, g CO_2 / kWh	25	Jansen *et al.* 1992, 370	

Notes:
Overall efficiency: here means only of electricity generation. There will also be possible to exploit cogenerated heat, which depending on local conditions, will mean an extra of up to about 40 per cent.
O&M: contains membranes and fuel cells with life spans of only 5-10 years (Jansen *et al.* 1992, 370).
The **annual load** of 8000 hours is due to the fact that load evening probably will be better achieved with the hydrogen system than with using the coal fired power stations as reserves.

[52] The original prices were quoted as such: Peters (1989): \$1630/kW for a 500 MW CC; \$1360/kW conventional PP, <\$1000/kW if ISTIG gas turbines. Hendriks *et al.* (1989): Dfl3640/kW coal single cycle w/CO_2 recovery. 1000 \$/kW (Pruschek *et al.* 1996; Haupt 1996). 1050\$/kW (IR8).

[53] The efficiencies would be 42.1, 45.4 and 47.5 %, respectively. Relative CO_2 emissions per kWh compared to IGCC (100 %): 3.1, 2.9, and 2.7, respectively.

The low investment cost of such a plant might be surprising. However, if we follow the arguments by Haupt (1996) and Pruschek *et al.* (1996) then we have to acknowledge the rapid cost developments that are taking place in the IGCC technology. Probably the same, or slightly lower, costs are applicable, if the coal is to be gasified *in situ* (ICG).
CO_2 emissions would be 7 kg per GJ (25 g per kWh).

Electricity Transmission

We shall assume that a large share of the long-range electricity transmission in the future will take place with superconducting powerlines. They reduce transmissions losses and will have the advantage that buried into the ground they optically will not be stirring attention, plus that the lack of a magnetic field emanating from them will reduce fears of health risks of power transmission.
That so-called high temperature superconductors are being actively pursued, has become clear. The potential economic gains offered by this technology could prove tremendous. The first applications are already entering the market (Spiegel 1997a): superconducting power limiters and transformers or transmission cables for city wide use. The reader might find further information from *Asea Brown Boveri* (ABB) on the internet (IR 20 & 21).
It is therefore highly likely that this technology becomes widespread in the future. Here we assume that it also will be feasible for longer range electricity transport, so we do not follow suggestions to substitute electricity transmission by hydrogen pipeline solutions (Ouellette *et al.* 1997; D'Ajuz 1989)[54] for ultra-long distances.
The introduction of superconducting transmission decouples the location of power stations from the location of the consumers. Transmission and distribution losses will therefore go down to about 5 per cent on a global plane as in the original sketch (Sørensen 1996).
It might prove to be valuable to investigate the introduction of a low voltage *direct current* (DC) net to provide power for end-use applications. Fuel Cells by default produce DC electricity, which has normally is transformed to AC. Smaller, decentralised DC nets at clusters of customers near such DC sources will enhance the overall system efficiency, as they avoid the associated losses of frequency and DC/AC converters. The smaller transmission distances, the lack of converters and security advantages will mean reduced O&M costs for the total T&D system (Penner *et al.* 1995, 380, 396).
Costs:
Electricity transmission and distribution would cost about 1 Euro per GJ, as we assume that distances covered would be below 1000 km on average.
D'Ajuz *et al.* (1989, 520) give a value of 3.0 to 3.4 Euro per GJ for a transport of 2000-3000 km[55], and Davies (1995, 65) rather high values for 6.8 Euro per GJ for 1000 km to 11.0 Euro per GJ for 1500 km electricity transport[56]. However, we assume electricity will be transported only shorter distances.

Cogenerated Heat and Electricity Costs

It has been assumed here that the energy costs of the power stations have to be shared by both the electricity and the heat generation. But space heating demand is not occurring everywhere. This means that we also have to distinguish the cost reduction from cogeneration for the different climatic regions that have been established in the demand chapter. From Danish data in IR (30) we have a production cost of about 10 Euro per GJ, a different source (IR 31) gives a cost of about 12 Euro per GJ[57].
This values include the necessary heat storage facilities at the power stations to even out demand variations stemming from the daily temperature cycles. For even better optimisation seasonal storage systems can be applied, where heat losses naturally will become higher, but where the CHP station can be working at an optimal load.
Costs:

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54 In fact high temperature superconduction would also allow new solutions for electricity storage. This would make hydrogen somewhat superfluous in the electricity sector. It would retain its importance for mobile applications, though.

55 Original data US$13.4-15.4/MWh per 2000-3000 km

56 Original data: $£_{1990}$5/GJ@1000 km; $£_{1990}$8/GJ @ 1500 km

57 Original data: Dkr258.51/MWh; 90 Dkr/GJ for plain heating plants.

We assume that cogenerated heat will be worth about 10 Euro per GJ. This has importance for the electricity costs that have to be scaled according to the demands that vary with climate. We do not scale costs with season, as this would not occur to be a reasonable praxis.
For the electricity produced from IGCC power stations we have had a cost value of 11 and for hydrogen fuelled CHP of 18 Euro per GJ (pages 84 and 81). These values will be applied, whereever no demand for space heating exists. Although air conditioning is possible by exploiting the heat from the power stations and using absorption chillers, we have neglected this option due to the small energy amounts involved.
Table 4 shows the costs for electricity and heat generation in CHP-DH plants, where we have assumed a value of 10 Euro per GJ for the produced heat and an average efficiency of 0.2 for the heat generation. This average covers peak demand in the respective winter periods and no demand in summer period for space heating during the summer.

Table 4 Electricity and heat costs in different climatic regions (Euro per GJ)

Climatic Region	IGCC w/CR electricity costs	H_2 CHP electricity costs	CHP heat costs
tropical, humid	11	18	0
tropical, arid	11	18	0
middle latitude	7	15	10
polar climate	7	15	10

Source: own calculations.

Heat Transmission

Today central heating systems are customary items in the richer regions, where space heating demand is large: North America, Europe, and Japan. One could argue that in the future space heating will be zero also in these regions, as zero energy houses[58] are already a feasible solution in *e.g.* Germany, where they are being marketed at a price of about 140,000 Euro.
However, we have chosen to look at the average heat demand of the society, as the building stock is converted rather slowly: at a rate of about one per cent. This means that the large share of existing buildings, with their definitely non-zero-energy space heating demand, will still be in use at the time of the scenario, so that the space heating demand of those buildings has to be ensured. Also massive insulation is currently not cheaper than other solutions (private communication Harry Lehmann, Wuppertal Institute).
It is assumed that *district heating* (DH) to provide the heat for local central heating installations will be widely employed in the future energy systems, and that district heating lines will be a normal feature of existing and newly developed housing projects, where space heating demands qualify for this.
As assumed in Sørensen (1996) the efficiency of the heat transmission in DH is 80 per cent. This value is typical of current DH systems in Denmark[59] and will probably not become much better, although one may argue that for rising energy unit costs it will prove advantageous to improve the efficiency of the heat transmission, which can be achieved by better insulation.
What might argue in the direction of higher system efficiency is that decentralised solutions based on fuel cells, where the excess heat can be exploited easily, would generally be more convenient than having to rely on larger, more centralised schemes. This could be the case in the countryside, where low population density would not argue for large and widespread heating transmission systems, but where economies of scale might become a snag.
<u>Costs:</u>
Heat transmission will cost about 6 Euro per GJ.

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[58] The terminus is actually badly chosen: *zero energy* only refers to the space heating demand, in fact most of the heat supply is by passive exploitation of other heat sources: the inhabitants, applications and passive solar.

[59] Those systems are already working at a lower forward temperature than older, maybe even steam based, transmission systems, therefore the potential to reduce heat losses are restricted.

From IR (6) we have gained knowledge that in Denmark about 100 PJ of district heat were delivered at a sale price of 1.5 billion Euro, which would be equivalent to an average consumer price of 15 Euro per GJ. In IR (30) a price of about 14 Euro per GJ has been mentioned for consumers in Copenhagen[60]; of this total 4.7 Euro are taxes and fees. The fuel makes up about 3, production and distribution about 6 Euro per GJ.

Hydropower

Although this scenario will put emphasis on the clean use of fossil energy carriers, a share of hydropower electricity generation has been assumed in the scenario description, about 220 GWy. In principle we have assumed that the hydro production potential will not change. Extension of existing installations or planning and building of new ones will only happen to substitute for lost capacity by silted up reservoirs[61].

We have also assumed that the current geographical distribution of the hydropower installations and their production will not change in the future. Data for the hydropower generation have been found in EIA (1997, IR 5). Globally production is somewhat higher than in the original assumptions: 268 GWy as opposed to only 220, *i.e.* there has been some construction going on since 1990[62] leading to an increase in production. A regional distribution of the hydro-electric prodcution is given below:

Table 5 Hydro-electric generation

REI	PJ	TWh	GWy	W/cap
AF1	4	1	0.1	1.3
AF2	34	10	1.1	4.2
AF3	154	43	4.9	2.9
AM1	2141	595	67.9	174.2
AM2	1035	287	32.8	72.6
AM3	642	178	20.4	57.7
AS1	286	79	9.1	52.9
AS2	425	118	13.5	5.5
AS3	340	94	10.8	7.1
AS4	581	161	18.4	20.9
AS5	53	15	1.7	5.5
AU1	150	42	4.8	156.1
AU2	5	1	0.2	9.9
EU1	1565	435	49.6	146.8
EU2	235	65	7.5	62.0
EU3	163	45	5.2	28.6
RUS	631	175	20.0	174.9
REI	PJ	TWh	GWy	W/cap
globally	8443	2345	267.7	28.6

Source: own calculations based on EIA (1997).

Due to their large reservoirs the hydropower installations may be veritable sources of greenhouse gases and the liberation of mostly methane, but also CO_2 by the decomposition of organic materials (Rosa and Schaeffer 1994; Rudd *et al.* 1993). These emissions seem to cause CO_2 equivalents of about 18 to 180 grams CO_2 per kWh, which is between four and forty times lower than from current coal fired power stations without CO_2 recovery.

60 Original data: 391 Dkr/MWh. The effect fee of 113 Dkr/kW has been neglected.

61 This argument is based on political and environmental grounds: public perception of new, large hydro-electricity schemes is not unanimously positive any more. This means that the political side will have to prepare for discussion in the case new schemes will be planned.

62 The base year of the scenario assumptions by Sørensen (1996).

Costs:

Hydropower electricity would cost about 3 Euro per GJ to produce[63].

Non-Energy Uses

Masters *et al.* (1992) mention a likely trend towards heavier fractions in the oil produced in the future, as the lighter fractions have been preferably produced until now[64]. This might pose some challenge for the cracking technology in order to gain lighter hydrocarbon products as necessary feedstock for petrochemical industry. It is here that hydrocracking[65] will gain in importance.

An interview resulted in the view point that chemicals companies today might not be willing to pay more for their feedstock than private customers are used to (IV Jim Niven 1997). So in the future, with prices for oil and its derivatives higher than today, there might be a substitution pressure for finding non fossil feedstock for chemicals' production[66]. This would then argue for a lower oil input for non-energy purposes than assumed in the scenario description, although this is a speculative argument.

The most important factor to take into consideration with oil in non-energy use is that near-total recycling of the oil-based materials has to be ensured to prevent any carbon leakage from utilising "waste" as an energy carrier. Otherwise the fossil carbon of the chemicals might be released to the atmosphere, when recycling is not possible anymore[67]. This last problem will be solved by gasifying any non-recyclable oil-based materials for utilisation in the CO_2 recovering power stations, alternatively in a plant producing hydrogen and liquid fuels from waste and coal as described by Warren and El-Halwagi (1996). The latter case would reduce the net emissions only slightly, though.

In any case the additional CO_2 emissions in the worst case, *i.e.* if we assume that the total amount of the non-energy oil will be released every year, will only be equivalent to about 6 billion tonnes CO_2. This is less than a fourth of the current CO_2 emissions. Over a 150 year period this would probably lead to a stabilisation of the atmospheric CO_2 concentration at about 350 ppm, judging from information given by Enting *et al.* (1994, 32) on the cumulative industrial emissions for the stabilisation target.

Costs:

The costs of the oil for petrochemical applications have been estimated to be about 4 Euro per GJ ($30 per barrel).

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63 Data from the ExternE *Sauda Hydroelectric Development Project* (EU 1995f, 140) have been used: 2588 MNOK for 1308 GWh/y, with 50 years life time and 3 % social interest rate, = 9.7mEuro/kWh.

64 They are easier to exploit by primary production methods, as they are more liquid than the heavier fractions.

65 Where the petroleum is cracked, *i.e.* the longer chains are broken up into shorter ones, exposed to a hydrogen rich atmosphere.

66 As has already been successfully shown in the production of some palm oil based detergents by a major German household chemicals company.

67 The question of the release of fossil-based lubricants into the environment and the subsequent decomposition of those leading to fossil carbon emissions is answered by assuming that environmental standards at that time will prevent this from happening.

CO_2 Recovery and Deposition

We deem it rewarding to investigate the CO_2 recovery and deposition technologies that are being investigated today, and so have included this descriptive section.

Costs:

Costs for electricity, cogenerated heat, and hydrogen should be only increasing by less than about 1 Euro per GJ from the CO_2 sequestration chains described in the following.

CO_2 Recovery

Although we already have treated some of the CO_2 recovery methods when the different power station technologies were described, we want to give a collective picture of this technology.

There are a range of CO_2 absorption technologies ranging from dry to wet chemical or physical, membrane or cryogenic processes – as described by Audus (1997, 218) – which could be applied to current power station technologies. Generally the energetics of power stations with CO_2 recovery are worse than for normal power stations, though.

In Hendriks *et al.* (1989, 127 ff.) a chemical process is described, as it seems to be the best one applicable. It is argued for that the CO_2 concentration in the exhaust gases generally is low[68] so that chemical absorption is most suitable. A MEA-based[69] process is being proposed for the first absorption, thereafter it is desorbed at a higher temperature, compressed, dried and cooled.

The efficiency of this process with respect to CO_2 removal is 90 percent, and the total energy demand for those processes amounts to 5 (4.2 to 5.3) gigajoule for the absorption step and 90 (77 plus 13 kWh) for the compression and pumping. The technology, that Feron and Jansen (1995, 414) have proposed, today uses 140 to 200 kJ per mole CO_2 recovered; in the future 70 to 150 kJ could be feasible.

As with other aspects also in the case of CO_2 recovery new developments have arisen, and the technology palette has become wider. For example IGCC power station design with CO_2 recycling makes possible the extraction of CO_2 without any chemical absorbents at all, and the recovery rates for this process are generally approaching 100 per cent[70]. At the other hand of the spectrum gasification and shift reaction make possible the extraction of the hydrogen from a stream of CO_2 and H_2 by membrane technologies (Jansen *et al.* 1992, 369).

As we have argued for before in the technology descriptions of power stations and SMR, the membrane separation might be the most practical way to go, although there are a couple of challenges left: costs have to be brought down (Audus 1997, 218), and membranes reach saturation at high partial pressures so that Chakma (1995a, 410) argues that this technology would be better for lower concentrations[71], at least currently it does not have any cost benefits.

Depending on the disposal process the CO_2 might even be liquefied, which would cost somewhat more energy, but would make more easy the CO_2 transportation by pipeline (Audus 1997, 218).

Another method might be to treat the CO_2 in flue gas in a wet system using water as an absorbent and soil as a cation-exchanger Chohji *et al.* (1997, 151). Somewhat similar from a chemical point of view is a method described by Hirano *et al.* (1995), where a potassium solution under moist conditions allows for CO_2 recovery. It seems this kind of technology could be best applied at current power stations.

It might prove advantageous to remove SO_2 and CO_2 together (Chakma 1995a, 405). The sulphur generated so could be marketed. On the other hand, it might be necessary to dispose of the sulphur, if transport to possible customers turns out to be uneconomical.

While it has been estimated that costs of CO_2 disposal might decrease by 1 % per year between now and the middle of the next century (Kaya 1995, 376), a 40 % decrease in 50 years, the costs of CO_2 recovery will only have a minor importance for the total costs. Chakma (1995a, 405) has estimated that a 20 % reduction in CO_2 recovery costs will only mean a 10 % reduction in total costs.

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68 It could be enhanced by using a pure oxygen scheme

69 MEA = Mono Ethanol Amine

70 We can not exclude some losses from imperfect pipes or accidental releases.

71 This would imply that membranes of the type Chakra proposes would be better for CO_2 absorption from SMR, but not for O_2/CO_2 power stations.

CO_2 Deposition Capacities

Between the CO_2 recovery and the final deposition one step has been left out so far. It is the establishment of the CO_2 storage capacities of various potential sequestration solutions. In principle there are the land-based solutions and the maritime disposal option. The former can be divided into exploiting aquifers, depleted oil and gas reservoirs and reforestation measures. All of these have varying capacities, as presented by Audus (1997, 668), Table 6.

Other options have also been proposed in the literature, like using CO_2 as chemicals feedstock, sequestering it in the form of insoluble carbonates, or storing blocks of frozen, solid CO_2 in polar regions. We will describe some of those, but most can not contribute to CO_2 sequestration to the degree necessary by the large amounts that will have to be disposed of[72]. Another challenge is to realise an adequate retention period.

Table 6 Estimated CO_2 storage capacities and costs (incl. transport costs)

Storage option	Capacity (GtC)	Capacity ($GtCO_2$)	Costs ($/tC)	Costs (Euro/tC)	Costs (Euro/t CO_2)
Deep ocean	>1000	>3600	4.1	3.3	0.9
Saline aquifers	>100	>360	4.7	3.8	1.0
Depleted gas reservoirs	>140	>500	8.2	6.6	1.8
Depleted oil reservoirs	>40	>140	8.2	6.6	1.8
Reforestation	c. 75	c. 270	12.5	10.0	2.7
Enhanced Oil Recovery	65	c. 240	??		
Dry ice in polar caps	??	??	??		

Source: Audus (1997, 668), for EOR Riemer (1996).
Notes: **$:** assumed to be base year 1990.
Reforestation: Capacity interval 50-100; Costs interval 5-20.

If we compare the storage capacities with current fossil CO_2 emissions[73], currently about 6 GtC or 22 billion tonnes of CO_2, it can be seen that, except for ocean solutions, most sequestration options do not have the potential to provide a lasting contribution. For example saline aquifers and depleted reservoirs will only be able to absorb about 45 years of current emissions. As we can expect the potential CO_2 emissions to rise from the increased primary energy input in the scenario compared to today[74], we therefore have to acknowledge that ocean disposal will have to contribute the largest share to the sequestration.

It also appears as if deep ocean disposal has a cost advantage over terrestrial solutions, which would furthermore argue for this option. On the other hand technological questions still remain open with respect to maritime CO_2 transport and final deposition, and this also applies to the terrestrial solutions, although some experience already has been collected with EGR and EOR, and CO_2 has been collected for this solution from a conventional coal-fuelled power station in the United States.

Only if residence times of CO_2 storage options are sufficiently long, can CO_2 sequestration offer a contribution to mitigating climate change from the enhancement of the natural greenhouse effect. This increase has been fuelled by anthropogenic emissions that have disturbed the natural balance between carbon sources and sinks. As has been explained before, if CO_2 concentrations shall be stabilised at some pre-defined value, then CO_2 emissions to the atmosphere have to be reduced compared to current values. This can either be achieved by changing to renewable energy sources that do not cause greenhouse gas emissions, or it can be achieved by collecting the CO_2 and sequestering it in secure reservoirs. This section therefore treats the collection technologies, the CO_2 transport, and the final sequestration options.

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[72] For example (IR 22) gives some values for indirect biofixation (1.2 Gt C/y), direct biofixation (0.15 Gt C/y), and in chemicals (0.09 Gt C/y).

[73] Emissions from land-use changes can technically not be sequestered, as those sources are too wide-spread.

[74] From currently 20 billion tonnes CO_2 to more than 37 billion tonnes CO_2 (c. 10 GtC) with the primary energy assumptions given by Sørensen (1996).

CO_2 Transport

We have to distinguish between land-based and maritime CO_2 transport. The former will be covered by a description of pipeline installations[75] (also submerged ones), the latter by ship based solutions.
Pipelines are certainly the most viable solutions for the large quantities involved, but today one would be anxious about the high costs that they would cause. Therefore it will be essential to investigate large solutions with very large diameters (Skovholt 1993) to harvest economies of scale.
CO_2 can be converted into a so-called *dense phase*, where its density is much higher than if it is a gas at lower pressures (Skovholt 1993, 1097). This also means that given a certain energy amount one can transport about four times more CO_2 by pumping it in this state as compared to the gas state. However, this state is not very stable, and orography can cause the appearance of both gas and liquid states in the pipeline, which is unfortunate.
The best solution is therefore to transport CO_2 in the supercritical condition, *i.e.* above a pressure of 73.8 bars (Skovholt 1993, 1098). For later deep sea sequestration the advantage is that with further increasing pressure the CO_2 liquid will become denser than seawater at a pressure equivalent to about 3 kilometres water depth.
For economic reasons the pipelines will have to be very large in diameter, about 1600 mm (Skovholt 1993, 1100). The unsolved problem today, therefore, is how one should treat laying the pipeline in the dimension and at the water depths that are demanded. That current technology is approaching the demands for on-shore pipelines of sufficient dimension might be seen in that the Soviet Union had established a total of 54000 km with 1.5 diameter.
Skovholt (1993, 1102) concludes that the costs of CO_2 deposition by via a 250 km off-shore pipeline solution will be about 0.4 Euro per tonne[76] for the largest diameters (1600 mm) but already about double that amount for slightly smaller diameters (<1000 mm). Also costs tend to be c. double for on-shore compared to off-shore pipelines.
While Skovholt (1993, 1102) already mentions some measures to prevent accidents, or in case one happens worse damages[77], Kruse and Tekiela (1996, 1013) have explicitly examined the consequences of a CO_2-Pipeline rupture, where they have distinguished between gaseous and liquid CO_2 transport. Their conclusion is that it is more advantageous to transport CO_2 as a liquid as compared to a gas. For the parameters they have chosen, a six-doubling of the number of check valves will reduce the maximum distance where threshold values[78] are surpassed by a factor four.
Applying the large value proposed by Skovholt (1993) for the cross sectional area of the pipeline would still mean that the maximum distance will be 1800 meters, as the outflow scales linearly with the cross sectional area (Kruse and Tekiela 1996, 1016)! This means that for large on-shore CO_2 pipelines a 3.6 km wide stripe will have to be reserved to avoid possible fatalities! This will generally support arguments to place the power stations, and other CO_2 collecting units, in remote or near-shore locations to minimise such potential exposure.
One could then also look at ship based transcontinental CO_2 transport. For transport by barges on rivers the same security argument as for the on-shore pipeline applies. But maritime transport of liquid CO_2 to the right deposition locations will also be constrained by economics. To quote Adams *et al.* (1995, 450): "LNG carriers are among the most expensive types of commercial vessels to build."[79], and we may conclude that this will also

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75 Road or rail based solutions are unthinkable due to the sheer amount that has to be sequestered (Skovholt 1993, 1096).

76 Original data: about 0.5 $\$_{1993}$ / tonne.

77 Like having safety zones on both sides of the pipelines; increase the wall thickness near populated areas; section the pipelines with valves to minimise possible leakages, in populated areas the distances between the valves would be shorter; proper marking of the pipeline premises; proper surveillance and maintenance. Furthermore the pipeline would be routed through more wind-exposed regions so that a leakage would not lead to excessively high concentrations.

78 Chosen so as to minimise adverse human effects.

79 IEA (1994b, 50) gives price examples for new LNG tankers between 125,000 and 136,000 cubic metres: average about 200 million Euro ($250 million) with a 140 to 224 million Euro ($180-280 million) range. This translates into a capital cost of about 9 Euro per liquid m^3 (=0.34 Euro per GJ), at 20 roundtrips per year and 3% p.a.. To this should be added O&M costs of about 4-6.4 million Euro ($5-8 million) per tanker-year (=0.08 Euro per GJ).

apply to CO_2 transporting vessels. Also the large amount of CO_2 produced from the power stations means that many roundtrips are necessary – for a 1000 MW coal fired PP about 400 to 533 with a 15000 m^3 vessel. No cost figures were given.
Nevertheless, if the necessity of this kind of transport will occur, then a similar solution to the one presented for the LH_2 transport seems to become feasible: barges to carry the LH_2 tanks, a barge carrier to transport the barges to the sequestration platform. There the barges with full tanks are being exchanged with the emptied ones, which are then recycled. This in a way is a more rational approach than the one presented by *e.g.* Ozaki *et al.* (1997, 230).

Marine CO_2 Deposition

With respect to oceanic CO_2 deposition the basic difference is whether the CO_2 should be reaching the deep ocean via a shallow injection, that is possible near the coast, or directly into the deep sea by a vertical pipe carried by a floating vessel or platform. From a legal point of view neither the Global London Convention nor the Oslo convention currently prohibit or restrict the dumping of CO_2 (Adams *et al.* 1995, 451), but in the light of the Brent Spar episode one would have to be prepared to accept some stir of public attention[80].
Orr (1992), in a review article on Haugan and Drange (1992), mention the obvious advantages of shallow injection: natural conditions necessary for shallow injection are more easily met than those for deep injection, power station clusters could share the costs related to the necessary pipelines, the sea water density would increase near the point of CO_2 injection which would facilitate local sinking, and the sinking CO_2 rich water plume could reach calcite ($CaCO_3$) rich sediments (Stegen *et al.* 1995, 497), which by reacting to bicarbonate (HCO_3) would further enhance oceanic uptake. He also does mention the possible problems: appropriate injection sites have to be identified, there are substantial local, but supposedly minor global or regional environmental side effects, and power stations' effective rating would diminish[81].
Haugan and Drange (1992) themselves are cautious: "one should not recommend injection of CO_2 in the (upper)[82] ocean to slow down the increase in greenhouse warming unless the theoretical predictions are confirmed by experimental investigations and further analyses, and the environmental impact downstream of the injection point is judged acceptable. But the chemical carrying capacity of the ocean is formidable compared to the expected anthropogenic emissions. If shallow injection is working as indicated by these preliminary investigations, at least in some locations, it may contribute to obtaining the required reduction in net emissions to the atmosphere in the future".
Depsite their warnings some locations could prove to be feasible for CO_2 deposition by shallow injection. Adams *et al.* (1995, 450) narrow the range of locations to ones, where the "continental precipice reaches form 400-500 m to 1000 m in a few kilometres over a smooth bottom" and mention a series of appropriate locations[83]. The shallow injection technology might prove to be a first relief for implementing CO_2 disposal schemes on a larger scale. It will have to be realised within the next two decades, if more experience with CO_2 disposal should be made.
Adams *et al.* (1995, 450) estimate that for a 1 GW power station electricity costs would rise by about 1.8 Euro per GJ[84] for an offshore disposal at a depth of 1000 m and a pipeline distance of 100 km. The total costs of this technology are lower than the ones of the deep-sea injection technology, which will be described now.

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[80] On the other hand the public also argues that climate change should be mitigated, but this seemingly has not had a large influence on peoples' behaviour with respect to *e.g.* substituing incandescent light bulbs with CFLs on a larger scale. But exactly energy efficiency measures solutions have a much larger impact on the total efficiency of an energy system than upstream activities like more effective power stations.

[81] His argument that most power stations are located inland so that the CO_2 would have to be transported a long way will probably not be valid in the future, as already today power stations would tend to be located near the coast to ensure easy coal proliferation (Porter and Schmitz 1995). Nevertheless such a strategy has also been recommended by Skovholt (1993, 1103).

[82] My comment

[83] With respect to electricity generation the locations proposed by Adams *et al.* (1995) for shallow injection would imply a change in EU energy trade patterns, as coal fired power stations would have to be located in now remote locations like Portugal, Gibraltar or Norway. The Biscaya bay has also been mentioned (Skovholt 1993).

[84] Original data: 0.8¢ / kWh @ 15% interest p.a..

Deep sea CO_2 storage has seemingly attracted most attention in Japan (Ohsumi 1995)[85]. The basic idea with deep sea injection of the liquefied CO_2 is that the long residence time of the deep sea water[86] (of the order of magnitude of a millennium, Seifritz 1994, 926) ensures lower atmospheric CO_2 spikes than if the CO_2 was emitted directly into the atmosphere[87]. The CO_2 that directly diffuses from the deeper waters into the upper layers that are in equilibrium with the atmosphere will not play a large role for deep sea injection, and can typically be neglected.
In order to reach the deep sea water masses the CO_2 has to be deposited at a depth of at least 3 kilometres. At this depth the liquid CO_2 would reach a density equivalent to the one of the sea water[88] and so would not tend to rise again due to buoyancy effects (Teng *et al.* 1997, 765).
For industrial application of the deep sea injection a carrier, a ship or a semi-floating platform, would be equipped with a vertical, long steel pipe, and the liquefied CO_2 would be pumped down. Ozaki *et al.* (1997) have explicitly analysed the geometry of the pipe, taking into account the steel's ductility and strength, the pipe size[89], and the sea state with respect to the stresses stemming from the movements of the vessels caused by the surface waves, when the significant wave height is smaller than 6 metres. They conclude that such a system was feasible for pipe lengths of up to 4000 metres with ship type carriers, and somewhat longer for semi-submersible types. Even longer pipes rely on the introduction of new pipe materials.
We can here not investigate the possibility of finding locations fulfilling the significant wave height criteria, that we deem is the most determining one, but we very much assume that those can be found, although in places this criteria might only be fulfilled part of the year. In any way the delivery of the CO_2 to the diffusion platforms would be a ship based concept so that mobility of the injection sites could be ensured in principle[90].
It seems to be advantageous to fully automate the CO_2 disposal in order to minimise personal risk exposure. As CO_2 in large concentrations can impair human health, and accidents can not be excluded, the technology probably will be designed to not require manual assistance constantly. Experience has been gained with a similar technology: the production of petroleum by automated platforms in the North Sea.
Unfortunately Ozaki *et al.* (1997) have not given any cost overview of such platforms. To get some preliminary figures for the deposition platforms we therefore apply some of cost values for oil and production platforms. In the German Der Spiegel (Spiegel 1996 & 1997d) two concepts have been described: a floating TLP „Mars" costing about 800 million Euro and a GBS „Hibernia" costing about 5 billion Euro[91].
Now a disposal platform will be cheaper than the Mars platform, as the technology used will be less advanced and complicated, maybe 400 MEuro. Its only purpose will be to float freely and to submerse the liquid CO_2 that is delivered to it by LNG-like vessels. For a lifetime of 50 years and a yearly capacity of about 500 million tonnes of CO_2 capital costs from the platform alone would run to about 0.1 Euro per tonne of CO_2. An IGCC would still produce about 200 kg CO_2 per GJ, so that this would mean a cost of about 0.02 Euro per GJ (0.07

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85 Who also gives a short and concise overview of the research activities that have been undertaken to investigate the subject.

86 The deep sea water is slowly following the so-called *conveyor belt* circulation (Broecker 1991) from the subsidence regions in the Arctic Ocean, near Newfoundland and off Antarctica to the upwelling regions west of the American and African continents.

87 Although this also depends on the consumption of the fossil fuel reserves. Nihous *et al.* (1994, 232) remarked that a fast consumption pattern with a major share of deep sea discharge can result in higher atmospheric CO_2 concentrations than a slow exhaustion of the reserves!

88 This exploits that fact that liquid CO_2 is much more compressible than seawater.

89 Which is related to the amount of CO_2 that can be disposed.

90 Such pipe concepts could probably be coupled to a scheme exploiting the heat difference between upper and deeper parts of the ocean, although this extension is not within the scope of this study. In any case the mobility of the injection platforms will be limited, as frequent removal and installation of the pipe would interrupt the disposal process (Ozaki *et al.* 1997, 230).

91 Original data: $1 billion, CD$8.5 billion. The Mars platform should produce 100,000 barrels a day, which is equivalent to about 16 million tons of CO_2 yearly!

mEuro per kWh). This estimation has not taken care of the cost of the LCO_2 tankers, yet, but it seems to support estimates by Riemer (1996) on the ocean disposal costs[92].
Another possibility, as already indicated, is to combine the CO_2 disposal with the hydrogen generation plant in one common platform. This combination would have the advantage of providing easy access for coal vessels and the shipping of the produced hydrogen. It would also enable an easy CO_2 disposal, as the long ranch transport, necessary for land-based solutions, would not arise. No reference of such an idea has yet been found in the literature, but it seems as if it was the logical thing to do, if one has to use coal for hydrogen generation, as it is doubtful whether land-based CO_2 disposal facilities could be found nearby coal reservoirs[93].
Such a scheme could offer a combination of CO_2 disposal and ocean heat exploitation[94].

Marine Environment Impact

With respect to the question of what happens to the disposed CO_2, Teng *et al.* (1997, 773) think that the liquid CO_2 will neither lead to the creation of solid hydrates nor form a continuous liquid phase. Due to the hydrodynamic instability of liquid CO_2 and the rapid hydrate formation CO_2 droplets will form that will not coalesce to form a continuous phase but rather slowly diffuse. In deeper water the buoyancy of the CO_2 is large so that CO_2 will be surely captured, however at intermediate depths, that we do not consider here, the droplet size will have to be controlled carefully to ensure a long lasting stay in the ocean. Adams *et al.* (1995, 451) stress the need for a demonstration project to show environmental benignity of ocean disposal.

Carbonate Disposal

One of the most prominent features with texts dealing with CO_2 disposal by carbonate generation is that they stress its safe and environmentally friendly quality. Another that the raw materials to form stable carbonates should be abundant, which implies that this method could cope with the large amounts that necessarily will have to be disposed of. The basic idea is to make CO_2 react with other minerals in either a dry or an aqueous milieu. Insoluble carbonates are created that will not weather for a sufficiently long period and that therefore should be disposed of, *e.g.* as raw material for preparing street pavements[95].
Lackner *et al.* (1995) give a description of the kinds of rocks that can be used for this purpose. First of all some rocks, like limestone, dolomite and magnesite, have to be excluded, as they already are carbonated. So igneous rocks remain the rocks of choice. Examples are peridotites, serpentinite, gabbro and basalt, and those should be found in sufficient amounts over the World so that CO_2 absorption should be feasible on a large scale.
A variant of the industrial carbonate generation is to pump the CO_2 directly into underground caverns of porous magnesium or calcium bearing rocks (Lackner *et al.* 1995, 1166). The chemical reactions described before will then proceed slowly over several years, but it is not ensured that suitable and sufficient deposits can be found. They need to be mechanically stable and have to be sealed to the outside. It also has to be ensured that the injection well will not be cemented in and sealed by the carbonates.
Opposite to the creation of insoluble carbonates described before, Chohji *et al.* (1997) present a process that would create a solution, which may be comparatively easily discharged, as it should prove harmless to the natural environment (Chohji *et al.* 1997, 158). As they also rely on minerals found in soil, their process might be qualified for utilising the overburden from open coal mines. The basic idea is to saturate the soil solution with CO_2, to aerate it, whereby insoluble carbonates would be formed, and then to release the soil and insoluble carbonate into the environment. This process is technologically simple, but it requires large amounts of water, and so cannot be performed where water demand is high for other purposes. Chohji *et al.* (1997) therefore propose to use it near large dams.

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92 Although Riemer apparently has calculated with near-coast pipeline solutions.

93 Opposite to oil or gas reservoirs, the CO_2 generated could be applied in EGR or EOR schemes!

94 *Ocean heat technology* (OHT) exploits the heat difference between the upper, warmer layers of the oceans and the lower, colder water masses. They need as large heat difference between the water masses as possible, so they will have to be placed in tropical oceans. Yet physical efficiencies are very low, and the total capacity might not become large. Such platforms in principle are similar to the CO_2 disposal platforms, but generally not as sturdily dimensioned. The locations of these OHT is the same as the combined H_2 producing-CO_2 dispersing platfarms.

95 Where a gravel layer is used to stabilise the road construction.

If we assume surface mines, then the large amount of overburden, about twenty times the coal's weight, would seem to guarantee the extraction of a sufficient amount of minerals to perform the carbonate production. As it would be difficult to find large enough markets for the end products, even though their price should be low despitve the transport costs, the deposition of the carbonate will therefore occur at the location of the coal extraction (Lackner *et al.* 1995, 1167 f.). Alternatively the CO_2 has to be returned for EGR.
This method seems to be hampered by the same reasons that Lackner *et al.* (1995) have brought forward: the amount of the produced carbonates would be staggering. Therefore this method would only be employed in a few places, where environmental or agricultural concerns about the changed quality of the soil burden would not object.
Costs:
From an investigation of the typical economics of minerals and building materials, Lackner *et al.* (1995, 1165) conclude that the allowable cost of the CO_2 recovery will be the dominating factor for establishing the viability of the carbonate disposal method. For a cost of about $30 per tonne of CO_2 this translates into processing and mining costs that per tonne are $15 for the case of peridotite. For a comparison: cement sells at about $60 per tonne, but this material needs to be grounded twice and heated, which is not the case for the carbonate method. From their analysis Lackner *et al.* conclude that the CO_2 fixation budget is likely to be marginal for direct carbonates. The cost figure should look more optimistic for the direct injection, though.

Injection into Oil (EOR) or Natural Gas Reservoirs (EGR)

As we have stated before, separation of the CO_2 from SMR installations will offer the advantage of EOR and EGR solutions. One example for the feasibility of EGR is a study by Tontiwachwuthikul *et al.* (1996) for a Canadian location. That this method is economically sound has also been proven elsewhere (Blok *et al.* 1997), see the section on hydrogen production starting on page 73, so that we have chosen to assume that this technology will be used with all natural gas production, as we also assume sufficiently close sites to be identified for EOR.

CO_2 Disposal in Antarctic Ice Shield

Antarctica is the most hostile of the seven continents: its eternal ice shield[96] prevents easy access; its climatic conditions do neither welcome visitors nor economic activity. Besides some research projects in the austral summer or military bases durign the whole year, Antarctica is a remote ice-desert. In other words: ideal conditions for storing CO_2 as a solid[97].
This is the basic argument behind the idea of Honjou and Sano (1995) for using Antarctica as a kind of gigantic deepfreezer for frozen dry CO_2. Although average temperatures generally are not lower than the dry-ice point of CO_2, -78 °C[98], Honjou and Sanon argue that so low temperatures can be ensured by having artificial downward caves, with dimensions of about 100 m height and several kilometres length, resulting from excavating the ice. Basic convection would guarantee that the temperature of a block of dry-ice can be kept comfortably below the critical -78 °C, where it sublimates.
The low temperatures would ensure long solid residence times, before the CO_2 gets liberated to atmosphere. Hanjou and Sano (1995, 503) estimate annual sublimation rates of as low as 0.01 % yearly, a value supported by Seifritz (1994, 927), who mentions about 800 years by which half of a dry-ice dome with 200 m diameter will have sublimated.
The major mischief with the Antarctica solution is that this continent is very unapproachable for such kind of industrial activity. The cost question and reality of this solution therefore has not yet been treated in full. Furthermore current international regulations might exclude the region from the catalogue of feasible methods.

96 At least for the periods relevant to human experience.

97 This exploits that frozen CO_2 becomes so-called dry-ice.

98 For example in the austral summer the average temperature is -51 °C at the South Pole; although temperatures at the ice-core drilling site *Vostock* are even lower: -57 °C (Schwander and Stouffer 1984, 46).

Why Hydrogen ?

As can be seen in the technology description, hydrogen is the main energy carrier for providing end-use energy services. It seems artificial to produce hydrogen from the carbonaceous fuel sources. Furthermore, hydrogen has the reputation of being dangerous[99], so why this extra step? We shortly have to justify our choice.

Hydrogen itself is a very pure energy form, in that it does not contain any carbon[100], and so will not cause atmospheric CO_2 emissions when used[101]. Therefore it fits ideally in the general idea of an energy system where CO_2 emissions are reduced vastly. At the same time hydrogen also has advantages when the use of fuel cells is considered. Some fuel cells, like PAFC, can not handle even minor amounts of CO that act as catalysator poison and so destroy the fuel cells performance.

The advantages of hydrogen are then the fuel's lack of carbon content and a series of other factors presented below. If not mentioned otherwise the information was found in Morthorst *et al.* (1993), IR (10), or Wurster and Zittel (1994):

- When looking at the natural gas shift reaction, hydrogen's energy content is higher than that of natural gas (IR 10).
- Producing hydrogen allows off-gas cleanup at a centralised location, thus easing keeping tight air quality standards.
- Hydrogen burns without the creation of cancerogenous substances, like *e.g.* PACs from certain fuel resumes.
- In principle a similar infrastructure can be used for hydrogen as for natural gas, so hydrogen can be used in extension to existing natural gas pipelines and distribution systems (Town gas, for example, is a mixture of carbon monoxide and hydrogen. It has been used for decades without serious problems. In Denmark care has been taken to design the natural gas network so that it also would accommodate hydrogen in the future). As a starting point one could use a mixture of natural gas and hydrogen, called *hythane*.
- In the transport and off-road sector hydrogen via fuel cell solutions offers highly efficient fuel and overall system performance ratios compared to today's petrol or diesel fuelled vehicles.
- Hydrogen can act as a load management means in the electricity sector, if it is produced in times of low load. This enables a more optimal electricity generation. At the same time some fuel cell technologies can be used reversibly, *i.e.* both can feed on and produce hydrogen. This also could be done in a decentralised fashion.
- Stored hydrogen can even provide a seasonal energy storage and replace or supplement pumped hydrostorage.
- Hydrogen can be also stored in flushed caverns in salt domes. This strategy offers the advantage that similar technologies have already proved to be cost efficient and technically attractive for natural gas seasonal storage.
- A hydrogen system opens up for the generation of hydrogen from other energy sources. So in principle for electrolysis of water with electricity that can be provided for by hydropower, photovoltaics, wind converters; by gasification of biomass; or by thermochemical processes exploiting bundled solar radiation[102].

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[99] This stems mainly from the Hindenburg experience in the US in the 1920, when 39 people died during a zeppelin crash. What most people do not know, is that nobody actually suffered burns from the burning hydrogen. The fatalities exclusively were due to people jumping from the gondola, the flames seen in pictures of this event are actually those of burning diesel fuel from the engines (hydrogen burns without a flame) (IR 11).

[100] For example methanol does.

[101] We may in that respect neglect the small CO_2 impurities included in the hydrogen (page 77).

[102] For example the heliostat, or solar furnace, in Odeillo in the Pyrenes, where 4000 °C can be achieved at a capacity of about 1 MW. According to Hedley (1986, 171) even larger and more powerful ones have been developed.

- In air transport hydrogen offers less nitrogen-oxides and no sulphur, carbon or hydrocarbon emissions from the jet turbines compared to kerosene and jet-fuel driven ones. Furthermore cryogenic hydrogen would offer cooling of essential machine parts. Its high energy content offers weight advantages for air transport solutions.
- Hydrogen pipelines could replace long-distance transmission cables, and some analysts believe this method would be more efficient than conventional overhead power lines for long range transmission distances from about 1000 km upwards[103]. For example a hydrogen network has been proposed for Brazil, where distances between hydropower installations and electricity consumers are large (D'Ajuz 1989), another investigation for a frontier region has been present by Ouellette *et al.* (1997) for the less attainable Northwest territories in Canada. Another benefit could be the improved ability to control and direct the flow of energy.
- Hydrogen can be used directly as a feedstock in several chemical processes, it can directly be used in welding for steelmaking and other industrial applications.
- Due to its environmental benefits, hydrogen offers economic advantages, if externality pricing is introduced widely.

[103]The picture might change again, if we consider super-conducting transmission lines!

Discussion of Fuel Resources

In order for our CFS to be workable, we analyse shortly whether the necessary energy supply for the energy carriers that are included in it (Table 7) can be fulfilled.
We have to stress that the presented figures are not the results of the proper investigation (the bottom up analysis, which is described later on) yet, but more a cursory overview over, what a rough top-down analysis with some simplifying assumptions resulted in. Nevertheless those figures are important to look at, if we want to have a primary picture of, how viable the scenario is in the view of the resource situation. This plays an important role, as the energy carriers – with the exception of hydropower, which is not illustrated here as it is a renewable – all are fossil ones and therefore under the verdict of resource depletion.

Table 7 Principal primary energy inputs to the Clean Fossil Scenario

Energy Carrier	GWy/y	PJ/y	Mtoe/y	bn bl OE/y	RB/P
oil	2500	78840	1929	14	108
natural gas	3000	94608	2315	16	97
coal	8700	274363	6713	47	457

Note:
GWy: gigawattyear (*i.e.* one gigawatt constantly for one year),
PJ: petajoule, *i.e.* 10^{15} Joule,
Mtoe: million tonnes of oil equivalents,
bn bl OE: billion barrels of crude oil,
RB/P resource base_{1990} over production_{2050} ratio.

If we start with the aggregated overview that we have presented in the section on the global energy resource situation, then the resource base for all those energy carriers should allow a constant production of at least about a hundred years. However, we know that the current production of oil is higher than the value used in the scenario, and that the consumption of natural gas and coal is lower than assumed to be the case in the scenario. It is therefore not *per se* clear, whether the resource base and the current production levels will allow a steady production over a longer period that is necessary in order that the global energy system will not experience economic stresses.
One could imagine that a risk existed for the resource base to become exploited so fast already before the year 2050, the time of the scenario, that the peak production for any of those energy carriers would take place at around the same time. If before 2050, then the scenario was not viable at all, if afterwards, then it has to be ensured that this does not happen within the economical or technical lifetime, which ever is the longest, of the energy system's components.

Results

We start our analysis with a simple scaling of the presently estimated resource base by the current energy consumption for the fossils compared to oil's, see Table 8. This implies that our current consumption for all energy carriers becomes 22 billion barrels per year, and this enables us to use the production profiles for the future of Odell and Rosing (1983) directly. As the data in this source are given in billion barrels of oil, we have decided to use this unit in the following. Also we had to add the historic consumption to 1990 to the resource base values from IPCC II (1996, 87) to ensure that we can use this approach at all. This follows from the assumptions made by Odell and Rosing.
Also shown in Table 8 is the average annual growth rate for each energy carrier. This feature is important to estimate whether the peak production in any way could take place premature.

Table 8 Scaling of production and total resource base values

Energy Carrier	P_{1990}	RB+CS	(RB+CS)/P	(RB+CS)'	P_{1990}'	G-Rate
oil	22	2031	93	2031	22	-0.80%
natural gas	12	1870	154	3372	22	0.48%
coal	16	22419	1436	31534	22	1.89%

Notes:
P_{1990}: current production in billion barrels per year,
RB+CS: resource base from IPCC II (1996, 87) and historic consumption,
RB+CS': scaled total resource base (by the oil consumption),
P_{1990}': scaled 1990 consumption,
G-Rate: average annual growth rate in per cent to reach the 2050 consumption values from today's.

Now our interpretation of the data is not very accurate, as we do not have the resources and time to do a proper calculation. However, from a visual investigation of the figures presented in Odell and Rosing (1983, 164-170) we estimate that the about 2 per cent growth rate required on average for coal could pose some problems, as it seems the new discoveries and establishing of new mines might not keep pace with the increase in demand, foreseen in the scenario. However, we have to stress that the figures of Odell and Rosing do not allow an interpretation of a total resource base of more than 11000 billion barrels, and our equivalent amount for coal is about three times higher! The latter could probably allow an argument for a long lasting plateau.
Although the total resource base for natural gas is nominally equivalent to only about 3000 billion barrels, the 0.5 per cent growth rate should not pose any problems. This low growth rate would allow for a long plateau, especially if we consider that there is a large amount of unconventional natural gas that we have not taken account of so far.
In an analysis covering the period from the beginning of the 1990s to the year 2030 Maire and Bouchart (1995, 15) anticipate a growth in natural gas supply by between 0.9 and 1.5 per cent. This supports our belief that the 0.5 per cent growth necessary on average to reach production levels in the year 2050 could be realised.
The unconventional natural gas sources could become of more importance in the near future than thought of before, as the isotopic composition of Western Siberia natural gas is isotopically indistinguishable from much hydrate gas (Nisbet and Ingham 1995, 191), and parts of which already have been tried to exploit with some success (IV: Håland 1997)[104]. Furthermore, the importance of the non-traditional sources to expand the gas industry's feedstock has already been discovered (Gritsenko 1995).
The decline in oil consumption, which is related to the fact that this "energy carrier" only is assumed to be used for non-energy purposes, will probably not pose any problems as long as the current growth in demand will not perpetuate and total resources not be depleted too fast. But also here the argument given for natural gas applies, that any non-conventional sources could enable a long-lasting plateau. There is, however, the question whether economical constraints might make such a production profile difficult to achieve, as sunset industries generally would have difficulties in attracting private financing at a high gearing.

Other Factors to Consider

Judging from the present understanding of the reservoir geology and the resource estimates done so far for oil, in the future there will probably be a trend to exploit smaller reservoirs or if larger ones can be found then to a high degree probably in frontier locations. There will also be a trend towards oil with higher specific gravity (Masters *et al.* 1992), which could pose problems for using this resource as a petrochemical feedstock, but which could be solved by hydrocracking.
The likely development is towards generally higher exploration and development costs, which will be slightly abated by technological improvements. Generally speaking this should only mean about a doubling or tripling of prices for oil and natural gas, and not a ten-doubling that some have proposed.

[104] We should, however, be somewhat careful with some of those unconventional resources like submarine gas hydrates, that do not resemble economic hydrocarbon reserves as we presently know them (MacDonald 1997).

If, as appears to be probable, there will be new finds in today's less explored regions, then the supply pattern will likely change towards a reliance on smaller and geographically more diversified sources than is the case today[105]. This could mean a trend towards less concentration with the producing countries, but due to the increased financial demands might mean an increasing concentration in the downstream petroleum and natural gas industry, leading to enhanced market power of those companies compared to producers. This could, in the light of a situation like the 1960s lead to stable, and probably lower, prices than if supply rested on OPEC sources to a much higher degree[106].

With the changes in supply patterns as from the break up of the former Soviet Union and other Central European countries there will be an increase in the number of natural gas producing countries[107], but so too in the rights of passage costs, especially if the classical transit rights for pipeline transport are going to be maintained in the future (Hafner *et al.* 1995, 167). This could be counteracted by new international rules so that long distance gas transport by pipeline will not be penalised too much.

On the other hand, the large reliance of this scenario on coal as a primary energy source, allows for the forecast that a coal cartel could be enacted, if the supply situation becomes similar to the one with petroleum during the 1960s: *i.e.* if coal supply becomes concentrated in the hands of some large producers. Currently there is not much that supports this argument, coal reserves are more evenly distributed, and large producers are to be found amongst the industrialised countries.

A coal cartel, or in the terms of the scenario a hydrogen cartel, is only perceivable, if the market power of the integrated energy companies allows them to harvest a monopoly rent, *i.e.* if they control a major share of the total market. This would increase energy costs, but also lead to increased conservation efforts as experienced during the late 1970s. Whether the latter will provide for leeway to avoid part or all of the cost increases is difficult to answer presently.

Ways to increase their market share could be for the energy companies to use joint ventures similarly to the methods described in Bunker (1995) in the minerals extraction industry. While joint ventures sound very attractive, in that they offer some democratic right of the other parts involved in the project, in most cases a government organisation, they also bind this other part by economic constraints, like an agreement on development of related infrastructure. This can drain the government for economic means to do other investments and will lead to a loss of influence in arguments with the other part, in most cases a multinational company. Such a development would also ensure rather low energy prices.

Fossil Energy Carriers' Characteristics

High Energy Density ?

Fossil fuels have been used massively since the early days of the industrialisation. Their advantage is commonly assumed to be their storability and their high energy density, which however is an artefact of their geological life history. Counting the genesis of the carbon rich fossil fuels which is in the region of several decadal millions of years even a piece of high grade anthracite is only carrying a ridiculously small amount of the original solar radiation that was used to convert water and atmospheric carbon dioxide into carbohydrates by the plants of the Jurassic and Triassic periods. This material was later converted to carbon rich matter by emitting volatile matter, mainly methane and water, during the carbonisation process (Patterson, 1987).

The energy density of today's solar collectors and PV panels by measuring the harvest of solar energy is comparatively several orders of magnitude bigger, but the cliché of the high energy density of fossils is perpetuated in the public discussion. This seems to be a result of the engineering point of view, whereby the current energy demand of society shall be fulfilled by a rational exploitation of raw materials. In that sense coal, oil, or natural gas, measured in mass or volume, their availability, or handibility prove advantageous to renewable energy forms.

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[105] Although one has to acknowledge that this development currently seems to be likely, but surprises are, however, not to be excluded.

[106] However, the general market conditions might be different.

[107] For example Turkmenistan, Kazakstan, Uzbekhistan, Quatar, Abu Dhabi, Oman, Yemen, Egypt.

Sustainability of Fossils ?

The very physical limitation of the reserves of fossils impinges upon a sustainable development that is obeying the *hard* rule of sustainability: that the natural stock at any time is not delimited by any human generation and is perpetuated to the following ones in its true extent (definition given in lecture material by O. Hohmeyer, 1995).

To exemplify the hard definition each generation should leave the World in exactly the same state as it itself experienced when it came into being, so the exact number of trees, roads, houses, even humans. This definition does not seem to be workable in a dynamic society as ours, and it also can not be strictly applied to the Earth itself, as we know that there are some natural processes that are irreversible, like the continental drift, weathering and soil erosion, or dynamic patterns in ecosystems. The problem is also related to technological changes and changes in the perception of resources. For example oak trees were planted several hundred years ago to insure that the size of the Danish fleet could be maintained. Today, when the trees are full grown we do not need oak wood anymore to build ships[108].

One can argue that the development of mankind has made necessary the exploitation of fossil fuels, knowing that their reserves are limited, and that we eventually have to establish other energy systems better suited to the definition of *hard* sustainability. The relative ease with which we can fulfil our energy needs today means we can build up a stock of assets to help us in this conversion process. Therefore the exploitation of the fossils does not constitute a harm for mankind, as the necessity to change the energy system to make it more sustainable has been accepted. This is the definition of *soft* sustainability[109].

Nevertheless it is important to be clear about the final amount of fossil fuels there is in the World, and the problems that this might pose for future generations, once an energy system that is based on those limited resources feels the stresses of reserves dwindling and supplies stopping at some time. We have seen in the forgoing sections that for the immediate future this is probably not the case, but we know that this problem will become acute sometime in the next centuries. In that respect, any use of fossils is not sustainable, and one has to be clear about the necessity to eventually build up an energy system that does not have this drawback.

Environmental Effects of Fossil Fuels

Fossil fuels cause environmental impacts at the site of their production and conversion, the transport to the consumers, and the impacts from the resumes of the direct use. One should take all those aspects into consideration, but due to economical reasons we have to constrict every analysis to a practical basis. In this report we mention some of the environmental factors, but we can not be precise about them, as this is not the scope of the report.

For coal we have to mention that the reduction of the coal's ash content as a measure to reduce the transport demand will be of major importance for those cases where coal will not be gasified in-situ. This production of so-called *clean* or *ultra-clean* coal, depending on the final ash share and sulphur content, necessitates the application of large amounts of water, which restricts the use of this technology to regions with ample water supply. Dust can be liberated causing local environmental problems. The process also creates slag heaps near the coal mines, unless the ash can be used in the building sector. As environmental concerns are increasing, the latter is a likely development.

Likewise the mining of minerals, be it coal from surface mines or copper ores, is causing environmental impacts[110]. Those can be minimised by wise planning, but not all of them will be avoidable. How such large installations impact on the environment, the biodiversity of nearby otherwise undisturbed ecosystems, is a question that has to be answered. A first idea of the economic value of such services to mankind has been given by Costanza *et al.* (1997), although similar, more restricted attempts have been done before (Pearce and Moran 1994). This matter is of increasing interest today, and it could turn out to be a hot topic in the next years and decades.

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[108] Yet this wood might be important in the furniture industry, a more cultivated way of conquering market shares.

[109] As an aside: One of the leading ecological economists, David Pearce, has argued for Denmark leading a sustainable development, if the soft definition is applied.

[110] For surface mines the overburden averages ten times the thickness of the coal mined or about twenty times its weight (Lackner *et al.* 1995, 1167).

Back to fossil fuels' other environmental impacts: Today the emissions of SO_2 from fossil fuel burning, and from burning of large forest areas, are a source of concern with respect to the acid problematique. What is perhaps less well known is the contribution of SO_2 to regional climate change impacts. These are caused by aerosols that occur after SO_2 has been converted to sulphate particles, which have a direct effect, *i.e.* they reflect sunlight back into space, and an indirect one, *i.e.* they change clouds' qualities. Today the global sulphur load of about 96 million tonnes sulphur per year is about three times the pre-industrial one. Industrial emissions cause this increase, which has climatic consequences described in *e.g.* Feichter *et al.* (1997). Opposite to the greenhouse radiative forcing sulphur aerosols show large regional differences (Charlson *et al.* 1991).

In the CFS emissions of SO_2 and NO_x will be abated compared to the current situation, even though the primary energy input is larger than today's, simply by the filtering that is necessary to prevent catalyst poisoning with respect to fuel cells and as a result of the sulphur removal by processes related to CO_2 removal in the flue gases. This will mean that the aerosol load of the atmosphere will become smaller, a fact noteworthy to consider, when investigating climate change mitigation strategies (Wigley 1991).

7. CLEAN FOSSIL SCENARIO

Introduction

As has been explained before we have tried to calculate the consequences of introducing a so-called *Clean Fossil Scenario* into the World's energy system. The scenario is clean, because emissions to the environment are being reduced drastically compared to today's average applied technologies. It is fossil, as its primary energy nearly exclusively is being provided by fossil energy carriers. It is a scenario, in that it is a description of a possible future state of the global energy system. With respect to the latter, it should have become clear that it is not a deterministic forecast, and this was also not the intent of this paper.
We will now present the results of the scenario calculations. First we will present two methodologies that have been used. A simple one and a more elaborate one. The first requires manual distribution of supplies and demand to match both, the second can be performed automatically and consists of a series of mathematical instructions.
The description on the supply and demand balancing is actually on the most difficult part of such bottom-up analyses, as there are several degrees of freedom, and not all the parameters are defined in a stringent manner. For example, even though we have defined some thermal efficiencies for the cogeneration plants, it can be seen that those in many cases will not be fully exploited[1], as there will be too little demand for low temperature heat. Furthermore there are three technologies that provide this energy form: heat pumps, FC-CHP plants and IGCC plants. This means that one is free to choose some values for the distribution between these technologies and their contributions to the energy supply. To solve this problem in a satisfying way is not easy and requires some deliberations.
As has been described in the demand chapter, space heating has a very marked seasonal demand curve. We start with a description of the annual mean energy supply and demand, but we will also give an overview of the respective winter demand patterns. We will also present an extra maximum heat demand overview to show the global peak heat demands which will be the determining factor for the capacity calculations that lead over to the social and economic analysis of the scenario.

Simple Manual Optimisation

One could start to try to optimise the energy systems that the scenario results in by using some forgiven efficiencies for the various technologies and distributions between several competing technologies. In the case of space heating we have heat pumps and DH systems. How shall the demand for low temperature heat be divided between those two?
This can be done by arguing that if the space heating demand is high, its major share will be covered by DH systems and not by heat pumps[2]. Limit values can be chosen from calculated average per capita space heating demand, or may be found by setting some representative value, *e.g.* 300 W/cap for the heat intensive regions. The ratios are graduated between different limits, so that one ratio is used, when per capita heat demand is very high, another for middle demand, and third for low demand, reflecting assumptions on the technology shares in each region. In this way the share of the heat supply between DH and HPs is established.

1 Heat energy is assumed to be of less economic value. So oversupplying it will do only little harm. On the other hand the heat demand will have to be satisfied in any circumstance in the winter period as this in essential for society. Electricity supply will normally be matched much better to demand, as it would be an enormous economic waste to have an oversupply for that energy carrier.

2 This assumption is justified by the large efficiency that is assumed for the heat pumps, which can only be realised where the temperature difference between the heated space and the outside is not too large. Therefore we have to limit widespread heat pump applications to other regions.

The next question relates to the share of electricity versus heat production by the cogeneration plants. As electricity will be the most valuable energy form, the electrical efficiencies of the IGCC and FC-CHP plants will be predefined to be the largest value. Also these values and the distributions between the different power and heat stations' heat supply are made dependent on the average space heating demand, so that the FC share may not become lower than a certain limit. The argument again is that for low heating demand decentralised fuel cells will be more appropriate than DH from large IGCCs.
The problem then is to fit the thermal efficiencies and their respective shares of those cogeneration sources with the demands in each region by using globally uniform values for the heat efficiencies and distribution between the different energy technologies[3] for each class, so that heat supply is met in every region. This is necessary, as long range heat supply is not possible. It also implies that the populations are living sufficiently dense so that their space heating demand can be covered by DH systems.

Results of the Simple Optimisation

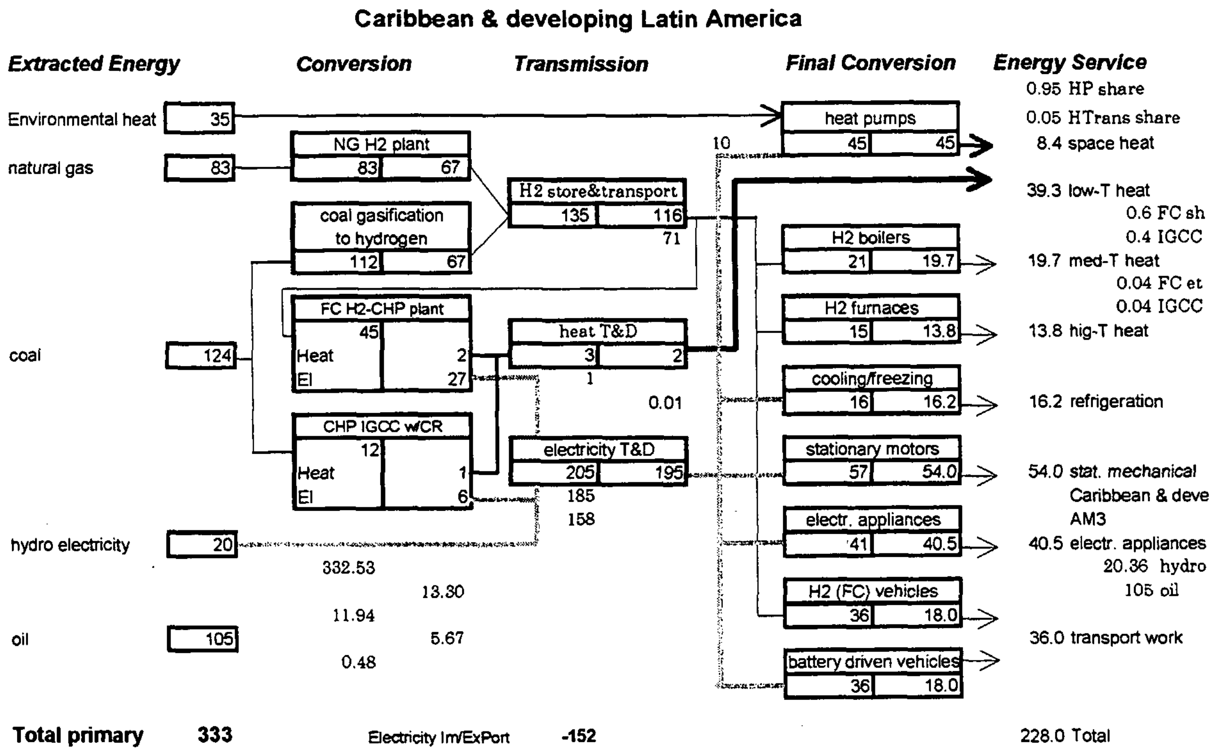
Globally the scenario assumptions lead to a heat demand that will be insignificant compared to the electricity demand. The reader may check with the average final energy demand, presented in the Demand Considerations chapter. On a global scale average heat efficiencies therefore will have to be very low. This also affects capacity costs: pure electricity stations have lower capacity costs than CHP installations, but we have chosen not to correct for this!
In some regions we end up with a regional undersupply of electricity, if thermal efficiencies are chosen as described before[4]. The electricity balance can be recreated by allowing electricity trade between the regions. This rests on an assumption of an increasing integration of the global power supply systems by intercontinental power lines, *e.g.* (Hafner 1995, 177) on an electricity line between Zaire[5] and Europe. Similarly one could imagine superconducting power lines between Asia and North America via the Bering Street, or that some South East Asian industrial centres will be connected to the rest of Asia. It would look more difficult with respect to Australia, New Zealand and the many, thinly spread, islands in the World's oceans, where economics probably would not argue strongly for such schemes.
A result of such an investigation is shown in Figure 1 for the annual average situation for the Caribbean and developing Latin America region. The values in that calculation result from choosing the same thermal efficiencies for countries lying in a group with the same kind of low temperature demands.

[3] For example the heat supply from FCs and IGCCs.

[4] This is even worse when the high values described in the section on technology are chosen, *i.e.* about 20 per cent for heat production.

[5] Today called: the democratic republic of Congo.

Figure 1 Example of a region's energy flow



Source: own calculations.
Note: **data are given in GWy**, 1 GWy = 8.76 TWh = 31.5 PJ.

In this case the region becomes an importer of electricity to the tune of 4800 PJ annually, whereas today it is about electricity autarkic and on top of this exporting petroleum products and coal. The latter would probably still be the case in the future, while the electricity import would result in a severe strain on the countries' payment balances.

Another interesting fact is that the internal electricity demand in some of the regions, as a result of efficiency and other assumptions, actually is so low that they will have an oversupply of electricity if they use thermal and fuel cell power stations to satisfy the heat demand. In those regions hydro-electricity will supply so much electricity that the region will automatically become an exporter of electricity, unless the heat efficiencies of the cogenerating plants are reduced. This is the case for Australia and New Zealand, where hydro-generation of 5 GWy is a major share of the calculated demand of only 24 GWy.

Conclusion

The application of globally uniform efficiencies and distributions for the three classes of regions depending on heat demand alone is not an optimal solution, although care has been taken to differentiate the values to optimise the global energy system. This points us to the need of at least to make a calculation, where distributions and efficiencies are optimised in each region. This has been done using some easy programming features.

Semiautomatic Optimisation

This method is fully manual in that it for every region and technology tries to optimise the energy system to match heat and electricity supply in every region. It will also mean looking more restrictively at the global electricity trade possibilities.

A series of assumptions have to be stated from the start. Some of them are obvious, some have arisen from preliminary modelling work with the data[6]:

- Primary energy input should be minimised.
- The electricity supply and demand should balance on a continental scale.
- Electrical efficiencies will be the maximum for each technology.
- Heat efficiencies will be chosen from a plausible range between zero and the maximum value identified in the technology description.
- Heat demand will be satisfied in each region, the distribution between HPs and DH, and the latter's contribution from FC or IGCC plants be optimised based on per capita heat demand calculations.
- With respect to electricity, for obvious reasons the Australia and Oceania groups will neither allow electricity import nor export. So electricity supply will have to match demand. The Caribbean group will suffer from the same problem to a much lesser degree, as it includes some of the larger, populous continental American states so that errors will not be pronounced here. This problem of island states, which in principle should be electricity autonomous can only be solved by a per country investigation, which is not a feasible approach[7].
- Fuel cells are thought to contribute at least 20 per cent to the cogenerated heat. This takes into account the cases where population densities are too small to justify large DH systems. The losses of those decentralised systems is assumed to be the same as in central DH systems: 20 per cent. This is a consequence of the fact that the model will generally not include fuel cells, and only uses IGCC to provide heat and electricity, when it shall minimise primary energy input alone[8].

When the global energy system is optimised under those assumptions, it can be seen, as expected, that the total, global energy consumption is about 10 per cent higher during the boreal winter than during the austral winter. The difference between the boreal winter and the average annual situation is about 8 per cent. This is not negligible and illustrates that one has to take into account the yearly variation in the space heating demand between summer and winter. The small difference between the yearly average and the boreal summer also supports the argument that the sharp increase in energy demand during the winter period simply is not expressed well by average annual assumptions.

A test has been made to evaluate the influence of the transcontinental optimisation of the electricity supply by allowing electricity imports between the three American regions. Although the total, boreal energy demand declined by roughly 6 per cent, it was decided not to continue in this direction. This kind of global optimisation would lead to the need of extraordinary large trans-continental electricity trade, which might not be justified, if we acknowledge that the poorest American region impossibly can import about 80 per cent of its total electricity supply.

It is very doubtful whether such large electricity amounts would be transported between the regions. Even with superconducting power lines and the expected increase in living standards, it would be unrealistic that the poorer regions were willing to pay for this kind of energy import. Therefore the transcontinental optimisation was not investigated further, despite the potentially large energy savings it leads to.

Also with this method the large oversupply of electricity in Europe and Russia during the boreal winter and the yearly average could not be avoided, as the heat demand gives a large electricity production as a by-product. If one allows a large share of heat pumps in the system, then the primary energy input can be reduced and the energy system optimised, however, as explained before this is not a realistic assumption.

With these considerations in mind we will now present the results of the more detailed calculations, where we present the three seasons separately. Finally we will analyse an artificial World, with winter on both hemispheres. The data from this run will be used to establish information on the maximum installed capacity that is needed to fulfil all services at all times.

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6 This has been done with the built-in solution finding option of one common spreadsheet program. It allows to optimise data with respect to some variables.

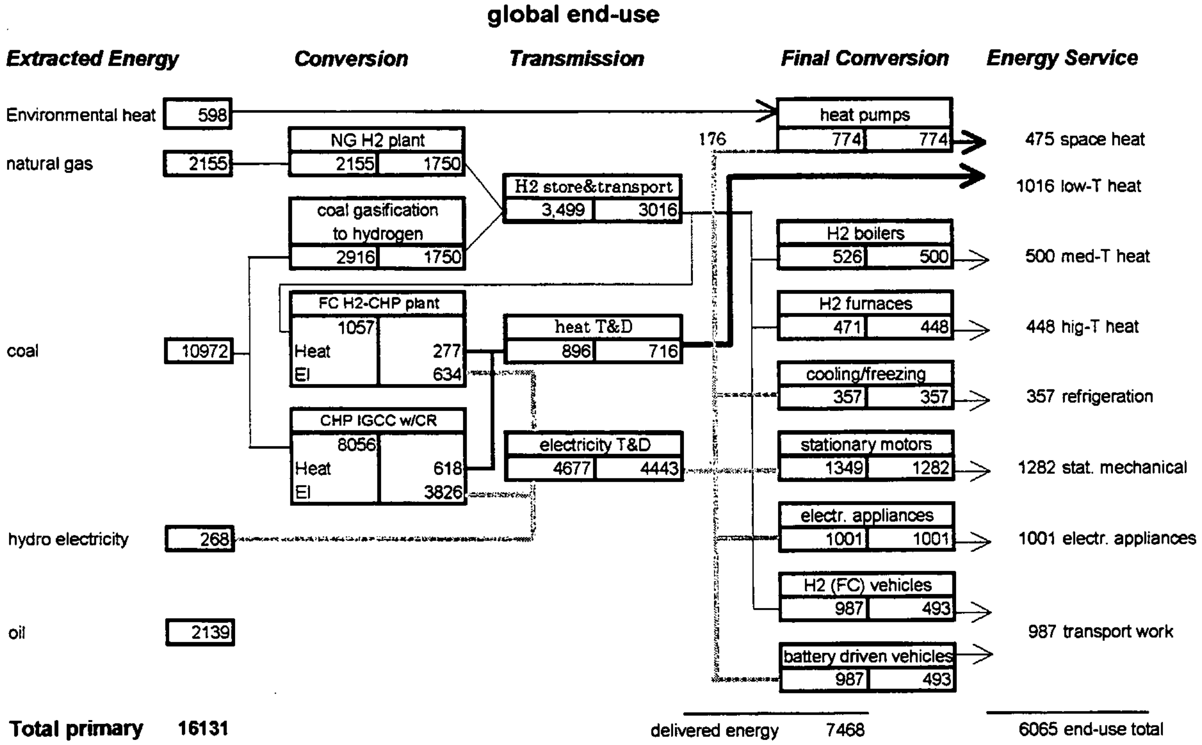
7 This is one weakness of bottom-up approaches.

8 FCs use hydrogen which is made at a loss, so that the interpolation scheme will discriminat against this technology.

Average Annual Energy Demands

With the average annual assumption we can calculate a primary energy demand of about 16000 GWy and an end-use total of about 6100 GWy, see Figure 2. This fits well with the original scenario sketch by Sørensen (1996), and the same is the case for the primary energy supply to the system. These agreements have to be seen on the background of some very dissimilar assumptions in both texts.
Knowledgeable are the differences in the distribution between the different energy carriers and technologies. With the demand assumptions in the CFS here, the energy end-use demand is generally somewhat higher, especially this is the case for electrical appliances and transport, where demand is higher by about 60, res. 40 per cent. The reason for this is that grouping the countries into only three groups depending on per capita income naturally smears out the spread in end-use demand that may arise from social, cultural or other reasons. As noted before, the climatic analysis resulted in a reduction of the space heating demand by a third.

Figure 2 Average global CFS energy supply and demand



Source: own calculations.

Also it can be seen that coal is the most prominent energy source, which from a resource base point of view can be justified easily. The input of natural gas is about a third less, which is a consequence of a much lower rate of hydrogen CHP. Electricity T&D is much more pronounced, stemming from the higher electricity share in the end-use demand.

Peak Boreal Winter Energy Demands

As stated before the global energy demand in the CFS peaks in the boreal winter due to the major amount of the human population living on the Northern hemisphere and the large space heating demand at that time. Table 1 shows the per capita end-use demand for the 17 regions, while Figure 3 gives an overview of the global energy system for the boreal winter period. The calculation has also been performed for each region separately with the Semiautomatic Optimisation method described before.

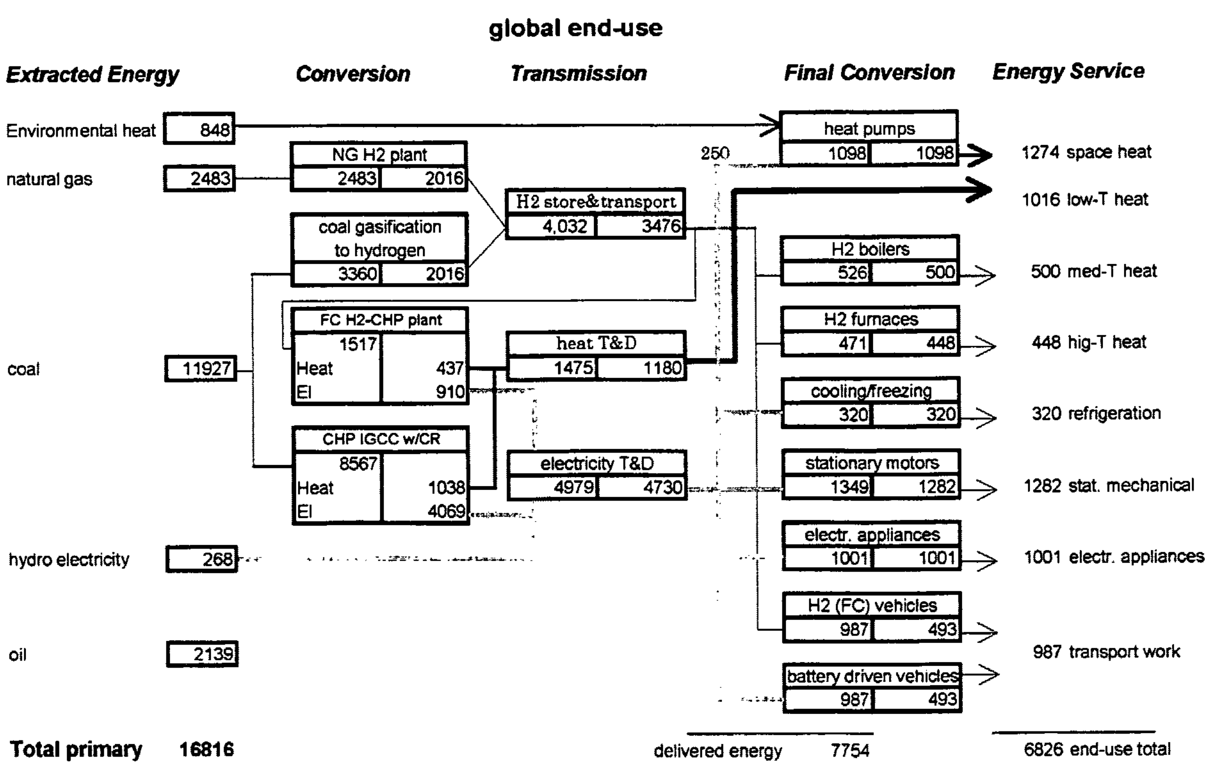
Opposite to the average situation the boreal winter peak can be clearly seen in the data for the regions in the middle latitude belt, with space heating demand surpassing the 800 W/cap for the riche and middle European region, topping in Russia with 900 W/cap. This group is followed by a group of regions where space heating on average is between 600 and 700 W/cap. For those regions total end-use energy demand tops at over 1200 W/cap, about three times the value in Sub-Saharan Africa!

Table 1 Boreal winter per capita end-use demands in 2050 for the 17 regions

REI	Geographical region	avg cool	avg space	avg lo	avg me	avg hi	avg stat	avg el	avg trp	Total
AF1	South Africa	42.7	0.0	114.8	58.4	53.7	161.0	114.5	108.6	653.6
AF2	Maghreb	17.0	50.0	110.0	55.0	35.0	150.0	115.0	100.0	632.0
AF3	Sub-Sahara Africa	34.0	6.3	73.8	37.1	22.5	93.7	85.6	70.7	423.7
AM1	North America	17.7	657.4	142.2	48.9	54.4	82.3	100.0	162.1	1265.0
AM2	Brazil, Argentina, Mexico	41.0	17.1	117.1	57.6	51.2	153.1	113.2	113.0	663.2
AM3	Caribbean & developing L. America	46.5	7.8	111.5	55.9	39.1	153.1	114.9	102.1	630.8
AS1	Japan and Four Tigers	29.2	689.8	140.0	45.0	43.4	74.4	100.0	158.5	1280.3
AS2	India group	55.1	0.0	113.6	60.5	60.2	161.0	114.8	107.2	672.4
AS3	China	17.0	50.0	116.0	64.0	75.0	172.0	115.0	111.0	720.0
AS4	Developing Asia	33.9	190.2	99.3	48.7	30.3	129.3	104.9	92.3	728.9
AS5	Oil rich countries	17.3	52.6	121.1	53.3	29.8	134.2	111.1	117.6	637.0
AU1	Australia - N Zealand	42.7	0.0	145.0	47.4	48.1	88.2	100.0	164.1	635.5
AU2	Oceania	36.4	2.6	113.5	53.9	33.5	147.1	113.9	105.4	606.2
EU1	Western Europe	12.0	897.8	140.1	43.3	35.1	73.3	100.0	157.4	1459.0
EU2	Central Europe, Turkey, Israel	11.5	813.4	121.2	49.7	28.4	121.8	109.5	120.5	1376.1
EU3	Developing Europe	13.8	558.1	108.5	54.5	40.0	149.5	113.4	100.0	1137.8
RUS	Russia	10.0	900.0	116.0	64.0	75.0	172.0	115.0	111.0	1563.0

Source: own calculations.

Figure 3 Boreal winter CFS energy supply and demand



Source: own calculations.

The increase in space heating is calculated to be served about equally by heat T&D and HPs, where the latter will have to be installed as heat recuperating units in the coldest areas reach the high performance factors that are assumed in the technical description. In the countries with milder winters this would probably not be necessary.

Peak Austral Winter Energy Demands

Clearly the austral winter, or boreal summer, period is globally the one where total energy end-use is lowest, as can be seen in Table 2.

Table 2 Austral winter per capita end-use demands in 2050 for the 17 regions

REI	Geographical region	avg cool	avg space	avg lo	avg me	avg hi	avg stat	avg el	avg trp	Total
AF1	South Africa	18.4	290.4	114.8	58.4	53.7	161.0	114.5	108.6	919.8
AF2	Maghreb	37.0	0.0	110.0	55.0	35.0	150.0	115.0	100.0	602.0
AF3	Sub-Sahara Africa	35.1	3.6	73.8	37.1	22.5	93.7	85.6	70.7	422.1
AM1	North America	44.5	11.2	142.2	48.9	54.4	82.3	100.0	162.1	645.5
AM2	Brazil, Argentina, Mexico	43.4	130.3	117.1	57.6	51.2	153.1	113.2	113.0	778.9
AM3	Caribbean & developing L. America	45.8	61.4	111.5	55.9	39.1	153.1	114.9	102.1	683.8
AS1	Japan and Four Tigers	52.1	0.0	140.0	45.0	43.4	74.4	100.0	158.5	613.5
AS2	India group	55.1	0.0	113.6	60.5	60.2	161.0	114.8	107.2	672.4
AS3	China	37.0	0.0	116.0	64.0	75.0	172.0	115.0	111.0	690.0
AS4	Developing Asia	43.9	0.0	99.3	48.7	30.3	129.3	104.9	92.3	548.8
AS5	Oil rich countries	38.3	0.0	121.1	53.3	29.8	134.2	111.1	117.6	605.5
AU1	Australia - N Zealand	16.6	235.9	145.0	47.4	48.1	88.2	100.0	164.1	845.4
AU2	Oceania	18.1	48.2	113.5	53.9	33.5	147.1	113.9	105.4	633.6
EU1	Western Europe	46.3	0.1	140.1	43.3	35.1	73.3	100.0	157.4	595.7
EU2	Central Europe, Turkey, Israel	42.3	0.0	121.2	49.7	28.4	121.8	109.5	120.5	593.4
EU3	Developing Europe	40.5	0.0	108.5	54.5	40.0	149.5	113.4	100.0	606.4
RUS	Russia	40.0	0.0	116.0	64.0	75.0	172.0	115.0	111.0	693.0

Source: own calculations.

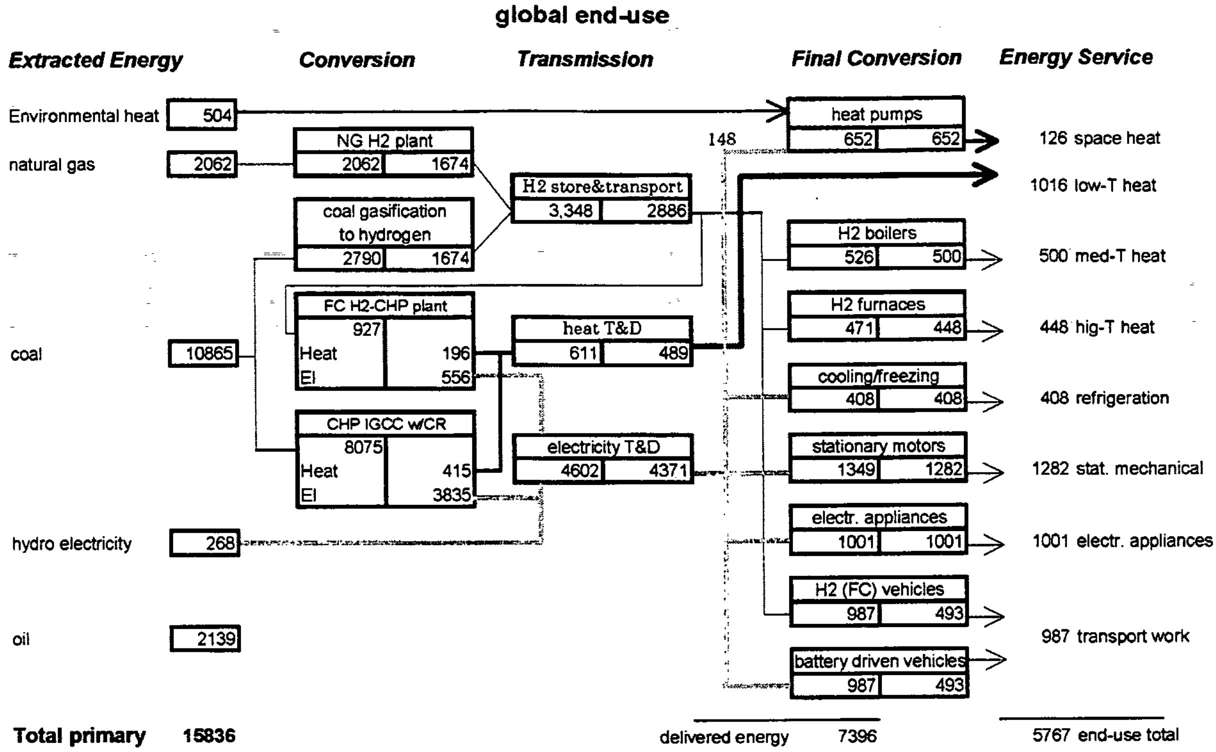
What is even more fascinating is that the countries on the Southern hemisphere are not exposed to the annual cycle to the same degree as their counterparts on the Northern hemisphere. This is related to the positions of the continents and the fact that the large land masses on the northern hemisphere enhance continentality[9], so that winters become more severe than at an equivalent location on the southern hemisphere, where the larger water masses work as temperature buffers. Therefore the peak end-use demands during the austral winters do not exceed the ones of the boreal winter hemisphere.

One may argue that some regions in the Southern hemisphere also become rather cold. This is correct, but it also has to be taken into consideration that the large share of the population in those countries will live near the coast and that the proximity of the levelling water masses reduces temperature ranges between the seasons. Another factor that makes demand peaks lower, of course, is the lower per capita income in most countries of the Southern hemisphere and related to this the activities by which energy demand is generated. The Southern Africa region in that respect is one exception as it is rather well-off, more developed than the rest of the southern hemisphere[10], and has raw materials extraction, which is one factor that influences energy end-use demand.

[9] Despite the fact that ocean currents, like the so-called Golf-stream tend to move heat northwards on the northern hemisphere.

[10] With the exception of the Australian group.

Table 3 Austral winter CFS energy supply and demand



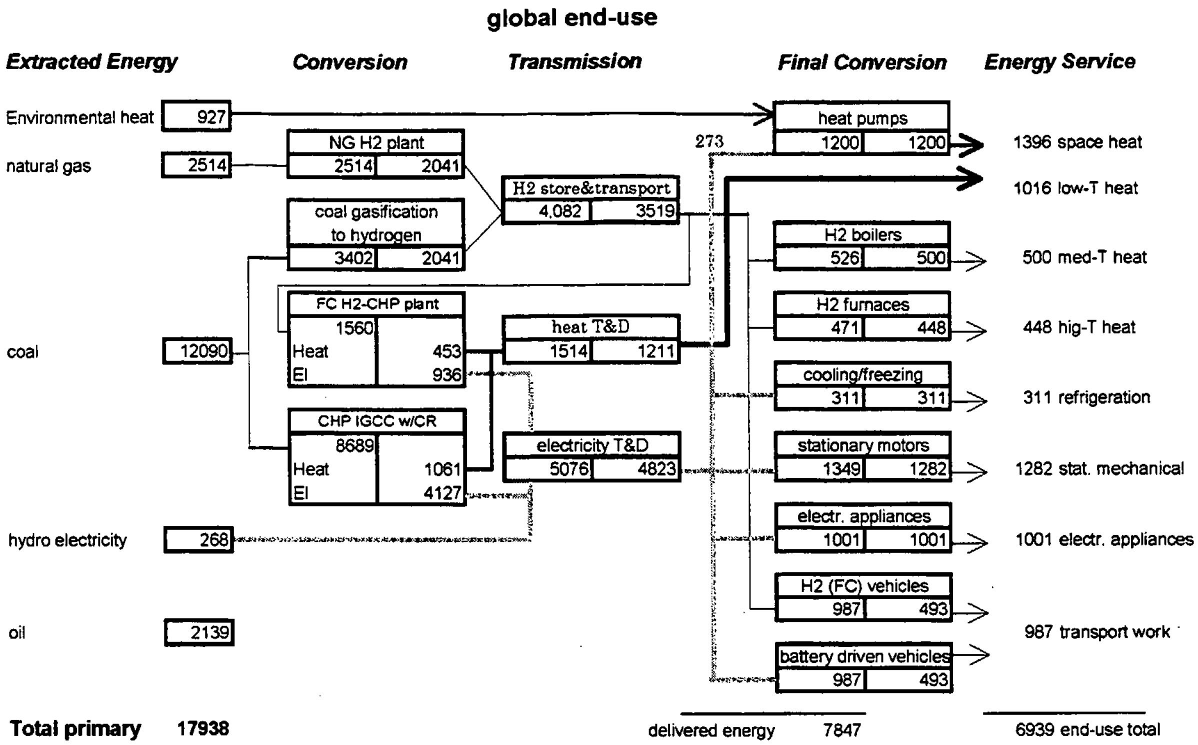
Source: own calculations.

Maximum Peak All-Winter Energy Demands

When we present Figure 4 we use it to lead over to an economic analysis of the CFS. What amount of capital will be necessary to realise it, or in other words, how much does it cost the global population?
The peak all-winter demand takes into consideration that space heating is the main fluctuating factor of the global energy demand, and that these fluctuations are causing problems in finding the right capacity and technology mix, as has been stated before. In an energy system as optimised as the CFS, where peak performing technologies with high efficiencies have been assumed to be used all over, variations of one specific demand will lead to imbalances, and it is difficult to optimise the total global energy system, when this occurs.
For example heat pumps will be a solution where winters are mild, or in locations where no DH system can be established, as economics do not favour this. If in one place there is a DH installation, it would be foolish also to install HPs to supply low temperature heat during the summer period as this would increase capital costs. Well, the kind of optimisation procedure that we have applied, only takes into consideration the primary energy input. Therefore a varying coverage of the heat supply patterns between summer and winter periods would arise. A result would be a massive use of heat pumps in winter and none during summer, which is not realistic. To prevent this from happening, limits were set for each technology's supply share. This prevented some of such peculiarities from happening, but only trying to minimise the primary energy input of the energy system, be it on a regional or global basis, will not necessarily lead to the economically most optimal system. This has, on the other hand, not been the main prerogative of this study. It only should investigate the technical feasibility of the CFS[11]. Therefore we will have to present the reader with a short economical analysis of the CFS, and try to answer what it would cost the World.

[11] This includes the availability of fossil resources to the degree that the CFS could be enacted for the period around the middle of the next century.

Figure 4 Peak all-winter CFS energy supply and demand



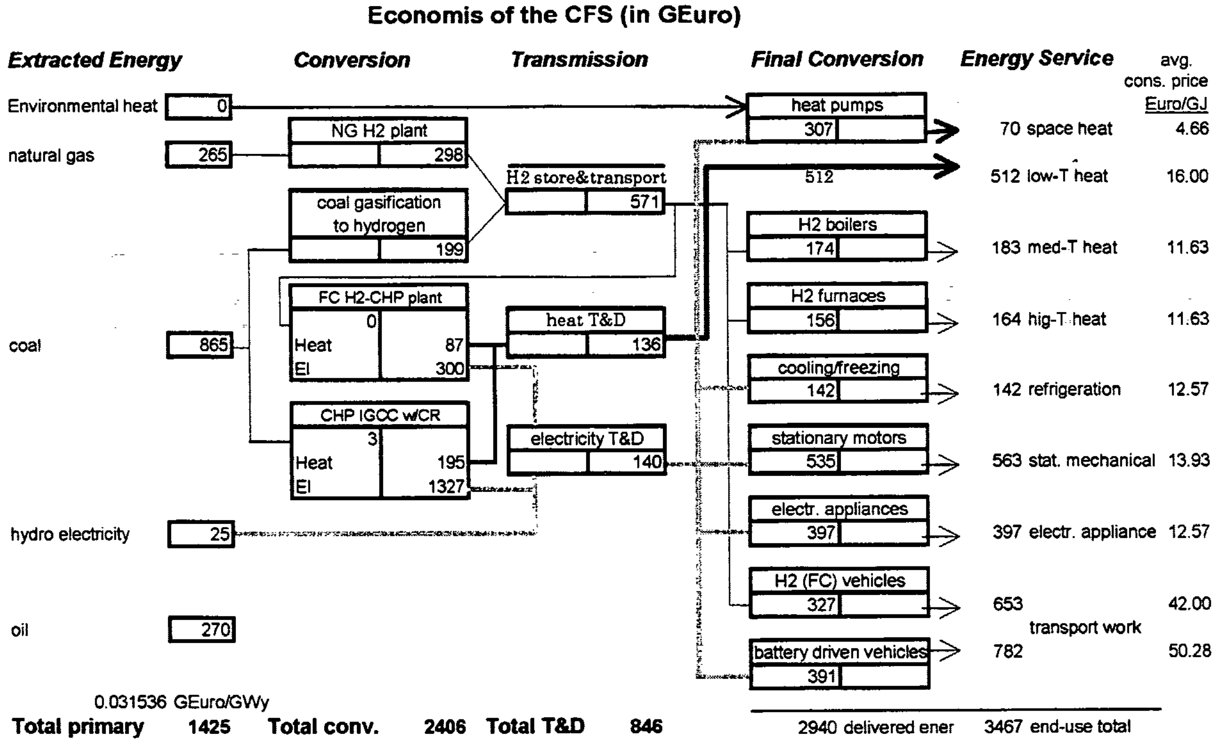
Source: own calculations.

Economics of the CFS

In the technical description some information was given on the costs of several energy technologies. No such data were given on the end-use technologies, where we may assume some AEEI leading to the required lower values, which ensure the viability of this scenario. For the other part, the conventionally so-called *energy system* (Scott 1995, 91), we have found or generated such data, so that we now can try to establish the global cost of the CFS. As we would like to investigate the peak capacity necessary for fulfilling global needs, we had to generate the all-winter peak data shown above.

Before we do the capacity cost analysis we present the average annual costs, and where they arise, Figure 5. Based on the calculated data on average costs of about 1.4 trillion Euro arise from the fuel costs alone, while conversion and T&D costs including fuel costs reach 2.4, respectively 0.8 trillion Euro (2.4 TEuro (=2.4 10^{12} Euro, 0.8 10^{12} Euro).

Figure 5 Annual average global energy costs of the CFS



Source: own calculations.

The last three columns in Figure 5 show the costs that arise on the consumer side. Here we have assumed that electricity from IGCC will still cost 11 Euro per GJ, while FC power plants deliver at 15 Euro per GJ to reflect the advantage of the cogenerated and marketed heat. Consumers would be billed for about 2.9 trillion Euro (*Final Conversion*). It is noteworthy to say that this amount is exclusive of any taxes or other fees.
But if we look at the *Energy Services*, then the energy units actually in most cases come a little bit more expensive, about 3.5 trillion Euro. This reflects the fact that due to imperfect conversion at the end-use side, services are still provided somewhat less effective than possible, although some of the potentials for extra efficiency will remain unobtainable due to economical or physical reasons.
In order to illustrate the energy service cost to the customers the last column gives the average consumer price for a unit of energy end-use service, measured in GJ. As can be seen heating with heat pumps is much cheaper than by a DH system, however, they can not be installed everywhere and therefore cannot penetrate the market completely. Most other end-uses have final costs in the range of 12 Euro per GJ with the exception of the transport sector, where costs are about four times as high. This also reflects a small price elasticity of transport demand, which has so far resulted in a rapid growth in this sector.

Peak cost analysis

As promised we shall now try a peak cost analysis, which is restricted to the capacity costs of maintaining the CFS, *i.e.* where we have assumptions on the technical lifetimes of the conversion technologies, the average utilisation, the capacity investments of each, and an interest rate, which together combine to the desired data. As interest rate we have here chosen ten per cent to reflect the fact that the energy sector after decades of deregulation more and more is acting like a private company and not like a state organisation, which would allow to choose a lower interest rate, perhaps 3 per cent. Also deregulation[12] and abolishment of subsidies would argue for higher rents than currently obtained by utilities. As an aside: profit potentials will be enhanced, too.

[12] For example in Southern Asia the previously strictly controlled ex-refinery prices are being deregulated (Dorian *et al.* 1996, 1010). This removes one typical market imperfection of current energy markets.

Table 4 Capacity costs of conversion technologies

Technology	Hydrogen production	Electricity		Hydrogen transport
NG H2 plant	8			
H2 store&transport				19
coal gasification to hydrogen	29			
FC H2-CHP plant		45		
CHP IGCC w/CR		483		
Total Conversion	**564**		**Total T&D**	**19**

Source: own calculations.

As can be seen the capacity costs then are about 600 billion Euro. This figure excludes the share of the energy extraction, *i.e.* the production of oil, natural gas and coal, but in the light of the small prices for those products they should not contribute vastly to the total capacity costs of the system. Also because it was not possible no data on the capacity costs at the end-use side are included. This could perhaps be much more important, as there lifetimes tend to be shorter than for the parts of the energy supply system, which would mean increased capacity costs compared to the power and hydrogen sector!
What seems to be a veritable flaw with this analysis is that does not yet contain information on the necessary reserve capacity, *i.e.* capacity only to be used in utmost peak situations or also as back-up, if other parts of the system break down. This is usually, what one terms “peak installed capacity”. This means that one should have more installed capacity that the previous analysis would make us think was necessary.
In light of the large utilisation times that we have assumed, ranging between 7500 and 8000 hours per year, and an assumed very even overall utilisation, *i.e.* with no prominant daily demand cycles due to better demand-side management, one could argue that the spare capacity does not need to be as large as the case is today. Maybe twenty per cent might be sufficient.
This would result in annual capacity costs of about 700 billion Euro in the energy sector.

Optimising the CFS

One technically obvious, but economically doubtful, method to further optimise the CFS is by allowing trans-continental electricity import and export, so that the total, global primary energy input is minimised. One option has been investigated.

Trans-Continental Electricity Import and Export

It has been noted before that so far our scenario is not literally optimised with respect to primary energy input. The lack of electricity trade between the regions that will have an over-supply of electricity and others that could minimise their primary energy consumption by substituting own capital costs with electricity import means that the latter also will use some energy to produce a surplus amount of electricity from a global point of view.
On the other hand, the regions that would profit from such a strategy are generally the poorest ones, so that their willingness to pay was rather low. If we abstract from this argument we may say that the CFS still can be optimised further. A calculation of the annual mean situation, where South Africa, the Brazil, Argentine and Mexico group, the richer oil exporting countries and the India group were all allowed to import electricity from North America, all European regions and Russia resulted in a decline of the primary energy input by (?) %.
fdasfdas

The CFS' Environmental and Climate Change Perspectives

Greenhouse Matters

One problem still left to be treated, is the elevated and increasing greenhouse effect leading to global warming, a phenomenon long ago described in the scientific literature (Arrhenius, 1896 !), and today still hotly debated – mainly because of the implied economic consequences of climate change or abatement strategies to mitigate its amplitude[13].

Today, or to be more exact during the 1980s[14], the situation is as described by Heimann (1996). Total anthropogenic CO_2 emissions are about 26 billion tonnes CO_2 annually[15], of which about 6 billion tonnes are due to so-called land-use changes, primarily by the clearing of tropical forests by non-sustainable slash-and-burn agriculture (Myers 1995, 113), and the rest, 20 billion tonnes, stem from fossil fuel use and cement making[16].

The seas are absorbing about 7 billion tonnes, the terrestrial ecosystems, mostly the boreal forests, 7 billion tonnes – the difference, c. 12 billion tonnes, is accumulating in the atmosphere. It is this difference, which is causing the rise of the greenhouse effect[17]. To stop this increase from occurring today, emissions would have to be reduced - and vastly. According to Enting *et al.* (1994, 32) the current CO_2 concentration can only be stabilised, if current CO_2 emissions are reduced by about 80 per cent[18].

A means to do this is to either drop fossil fuels, or prevent their CO_2 emissions from reaching the atmosphere directly and only with a time delay sufficient to prevent a too rapid growth of the greenhouse effect in accordance with the United Nation's *Framework Convention on Climate Change* (UNEP 1992): to "stabilise greenhouse gas concentrations at levels that would not inflict harm on natural or man-made systems". This is the basic idea behind this scenario.

One might argue what the advantage of a fossil scenario, like the CFS, is, if we know that fossil fuels are limited in extent, and that some day their production necessarily has to stop. The answer to this is that we today have an energy system that is based on fossil fuels as a result of a historic development.

In principle the hydrogen based CFS can be seen as a conversion from a truly fossil, and CO_2 emitting scenario, to a future energy system based on renewables. Important reasons for this would be problems in finding biofuel resources that are economically viable or ethically defensible.

The latter kind of problem might occur, if it turned out to become impossible to secure sufficient nutrition of the human population in the light of population forecasts ranging about 10 billions by the middle of the next century. In such a situation, it would be immoral to argue for biofuel solutions, even if they were economically viable. Or if moral ground told us first to ensure a decent nutrition, taking into use even marginal land for agri-

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13 The following texts can give a first overview of the diverging points of view on the necessity to reduce emissions the impacts and costs of climate change or the possibility to prevent it from occurring: Michaels and Stooksbury (1992), Wigley (1991), Woodwell and Mackenzie (1995), Anonymous (1995), Masood (1995), Hammit *et al.*, (1996, 1996a), Manne and Richels (1995).

14 Overall emissions have tended to rise, so the figures given are average for the 1980s and would be even higher today – and still rising.

15 Traditionally CO_2 emissions are given in GtC (billion tonnes of carbon), as biologists and geologists were the first to study the global carbon cycle. This has caused some confusion in the public, and not so seldom are figures of "total human emissions of 6 billion tonnes of CO_2" quoted –also by renowned people!

16 The latter source's contribution is a result of a chemical reaction when limestone is burned liberating CO_2.

17 The situation is similar for other greenhouse gases. The greenhouse effect was enhanced by about 2.6 Wm^{-2} in 1990 (IPCC 1996, 317). For a comparison: a doubling of the pre-industrial atmospheric CO_2 concentration is equivalent to about 4 Wm^{-2} (ibid.).

18 For stabilisation at 350 ppm, which is not so different from the present 360 ppm, cumulative fossil emissions are between 165 and 346 billion tonnes of carbon. Together with the land-use changes equivalent to 82 GtC, the average value is about 280 GtC. Stabilisation should occur in the year 2150, which gives an average total anthropogenic emission of about 1.7 GtC. Enting *et al.* (1994, 66) give values of 6.1 and 1.7 GtC for industrial and land-use change emissions for 1990, so that a reduction down to 22 per cent was necessary to reach stabilisation at 350 ppm. It has to be noted, however, that the industrial emissions so will have to be negative for several decades around the end of the 21 century (Enting *et al.* 1994, 102, fig. E.1)!

cultural production, until progress has been made to ensure a sufficient nutrition of the global population or population figures have started to decline after which state, land will become available for biofuel production. Looking back at the start of the industrialisation fossil fuels, with their high energy density per mass, enabled a vast extension of the physical production by industrialised processes. In those days the word "effective" meant mass production instead of more limited manufacturing schemes: Ford's conveyor belt produced T-model versus Rolls Royce's hand assembled Silver Shadow.
This evolution provided the market with cheap products for a, at that time, still growing population in the now industrialised countries. But it became soon clear that this kind of progress was bought with depraved working environment and living conditions (Baumbach 1994). And this led to the first environmental regulations.
When in the 1960s development was speeding, natural ecosystem's bearing limits were increasingly surpassed, and so initiatives were made to lessen the load on the environment by technical measures. This helped to abate pollution: Danish SO_2 emissions dropped to half their 1986 in the ten following years (Elsam 1995, 6); between 1980 and 1990 SO_2 emissions were cut by 17 per cent in the Czech Republic, by 23 per cent in the UK, by 24 per cent in the unified Germany, and by 56 per cent in the Netherlands (Dobris 1995, 238). Thereby the sulphur input into ecosystems was reduced. On the other hand over about the same period Hedin *et al.* (1994) have reported steep declines in atmospheric cation[19] concentrations, which has to some degree counteracted the SO_2 reductions.

Long-Range CO_2 Emissions of the CFS

If we recall that in the technology description it was mentioned that CO_2 emissions cannot be fully avoided then it is rewarding to shortly look at them and try to establish what the emissions predicted from the technology assumptions would mean for the level of the atmospheric CO_2 concentration.
To recall for SMR we have CO_2 emissions of 16.4 kg per GJ hydrogen, for hydrogen from coal 14 kg per GJ, and for IGCC we have 7 kg per GJ electricity. Furthermore there will be some emissions from the hydrogen, where 1 volume per cent (= 0.6 kg per GJ, Rosen 1996, 1083) might be a feasible assumption. Altogether this translates into emissions of about 2.6 billion tonnes CO_2 annually. Together with a worst case for the oil amount used in chemicals, see in the technology section, if we disregard complete recycling this ends up into 8.6 billion tonnes.
Thus, by enacting the CFS global CO_2 emissions to the atmosphere from fossil fuels in the real energy sector would be reduced to 2.6 billion tonnes annually in spite of a global primary energy input that is double the current one. This is one problem with CO_2 sequestration, it increases the total CO_2 production (Herzog 1996, 234), although it reduces atmospheric emissions, so that those for a 150 year period after all would stay below the limits described as necessary by *e.g.* Enting *et al.* (1994, 32) to stabilise atmospheric CO_2 concentrations at about 450 ppm. As the fossil fuel resources are sufficient to feed a global energy system as the one described in the CFS, no long term increase in the atmospheric CO_2 concentration would be caused by energy related emissions any longer for the forseeable future.
In the worst case, when also the "non-energy" oil products are being exploited, the total emissions will over a 150 year period mean a stabilisation at about 550 ppm, which means about a doubling of the CO_2 concentration compared to preindustrial values.

Social, Economic and Geopolitical Consequences of the CFS

The change from the current energy system to a clean one, *i.e.* where CO_2 emissions to the atmosphere are checked technologically offers some other environmental rewards but it also is not without complications. We will note some of those in this section.

Planning the CFS

First:
- it is not easy to realise the aims of our scenario. "The development of a new technology to a commercial product apparently takes some 30 years and another 20 years may be required to implement the technology on a large scale." (Sens *et al.*, 1994, 272), explains the most obvious restriction. This is caused by the large investments that will be necessary and makes necessary to shoulder the financial burdens by the market, manufacturers and governments or intra-national organisations in company (Serfass *et al.* 1994, 193).

[19] Cations can buffer the acidity from sulphuric acid, which is caused by SO_2 emissions.

When this text is written we are in the middle of 1997, and political initiatives should be taken very soon to ensure that the CFS becomes reality within the next 52 years[20]. On the other hand, if ongoing climate change research indicates that CO_2 emissions have to be lowered drastically sooner rather than later, then the CO_2 capture and sequestering should be regarded as a first relief, even though it would mean some higher costs compared to other solutions (Akai 1995, 803).
That long lead times may occur, can be seen in a warning by Blok *et al.* (1997, 167). Long planning horizons are required to exploit EGR made possible by CO_2 recovery, so that natural gas field depletion strategies have to be planned long before the actual hydrogen production begins. In other words, some parts of the CFS will have to be prepared long time before they actually will be implemented!
Implementing the hydrogen and fuel cell technologies, would in some areas probably happen by applying interim solutions. The fuel cell technology does need more development. The areas that are in need of more investigation and research have been described in *e.g.* a report of the "U.S. Department of Energy Advanced Fuel-cell Commercialisation Working Group" (Penner *et al.* 1995). The most critical step would be to ensure that a large enough market will open to attract investment in production capital, which could be achieved by using fuel cells in smaller applications first, where high-value applications can absorb the increased costs of new units[21]; this is not the case for large-scale utility-sized applications (ibid., p.385).
For example in the transport sector, one could imagine that methanol is being used, if hydrogen storage still proves a problem twenty, thirty years from now. The methanol could be produced from CO_2 and hydrogen, for example as one product that power stations will generate. Methanol is a liquid under normal conditions and could be used in *internal combustion engines* (ICEs) and in FCs[22] likewise. So it proves to be the first step into a FC and hydrogen future. The immediate advantage is that in the transport sector CO_2 emissions are being halved compared to the use of fossil liquid fuels (Eliasson 1994, 10).
Similarly the current trend towards a higher share of natural gas in the energy system is advantageous for the CFS. For example cryogenic NG transport by LNG vessels will become more widespread, if remote customers like Japan choose to import more NG on the cost of coal for power generation. This will advance gas handling technologies and infrastructure and give societies time to familiarise themselves with gaseous and cryogenic fuels (Rogner 1994, 859), important parameters for the hydrogen part of the CFS.
Then:
- many of our end-use assumptions are based on our current understanding of the services that we desire. For example washing clothes still requires traditional washing machines that have to use water based detergent solutions. If one imagines an ultrasound method in a slight fog of water droplets then the energy demand for heating the water will mostly disappear. Our end-use efficiency would have gained one dimension, and this would change our energy demand for this kind of activity.
Similarly it is impossible to forecast exactly what technologies or materials will be used, *i.e.* whether steel, concrete or some advanced fibre boards will be used in the construction and building sectors or for making power plants, etc.. Independent of this it will have to be ensured that those materials be produced sustainably, *i.e.* with a minimum of environmental damages.
The idea is to have some kind of *eco-restructuring* of the society by means of dematerialisation and the minimisation of resource use. But how can this be achieved? It can not easily be by command and control regulation, as this would encourage end-of-pipe solutions rather than improvement of the overall system efficiency (Rogner 1994, 854).
Such questions are relating to an energy system's *life cycle analysis* (LCA) and so are out of the scope of the present investigation.
Another open problem is the CO_2 sequestration. We did not explicitly choose between the different disposal methods, as it is too difficult to find data on them today. In the future, when more experience will have been collected, this would not have required as much work as it does today. One may argue that in places one solution will be more economical, even though it generally has higher costs than other solutions, but in that specific situation it is the optimal one. The important question, however, is how can the CO_2 sequestration part of the CFS be realised?

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20 Assuming that the reader will gain knowledge of this text already during 1998.

21 For example in telecommunications (Wells and Scott 1994).

22 For this purposes, the PEMFC will probably be the best solution, as development and deployment of this technology already has started and the advantages are: operation at low temperature and absence of hazardous materials (Penner *et al.* 1995, 338, 433 f.).

How Will CO_2 Disposal Be Enacted ?

Approaches to realise the reduction of CO_2 emissions directly into the atmosphere can be via normative legislation, simply prohibiting such emissions, or via creating economic incentives, to evade CO_2 taxation by the energy sector it will collect the CO_2 and store it in a lasting manner.

The obvious challenge with the CO_2 taxation model is that its revenue base would diminish with time. This can become a problem if the revenue of the CO_2 taxes have been used for other purposes, *e.g.* to reduce personal income taxes or other consumption taxes. In order to have a constant revenue base, the carbon taxes then should be increasing ever more, which in the end would make even the most expensive renewable technologies competitive, as their CO_2 externalities are much lower.

In that way a carbon tax can turn out to be not the optimal choice, but normative solution also in many instances are not optimal from an allocation point of view, as they tend to strain markets and create further market imperfections. In any way, rising energy costs, and the somewhat higher energy prices end-users would have to face in the case of an CFS are not the only problem. The very important question is, how can, apart from simple planning strategies, the World pay for the CFS?

Financing the CFS

We also need to look at the introduction phase of the more expensive CO_2 recovering technologies compared to the traditional CO_2 liberating electricity generation. How shall these methods be enacted, if economic arguments prevent them from taking place naturally? This point is also important if we look at the developing countries' situation. They can not be expected to pay a higher price for the energy services and conversion technologies, as they simply lack the means to do so.

It will, therefore, be necessary to have some means of transferring financial capital and know how to developing countries. As Dessus (1995, 38) has stated the leapfrogging of developing countries to reach high end-use efficiency is essential.

The financing might in fact turn out to be one of the most difficult subjects to treat. In order to realise the CO_2 free CFS everywhere an increasing share of the global investments will have to be going into developing regions. Globally total *foreign direct investments* (FDI) – investments and private bank-loans – are surpassing 4 trillion Euro[23] — but the DCs have attracted only a minuscule share of this: only 80 billion Euro in 1992 (Rohatyn 1994, 46 f.)[24]!

But the needs of the DCs are growing rapidly: according to Petroleum Economist (1993, 5) DCs desire investments of 80 billion Euro[25] yearly in the 1990s to add a total of 384 GW of capacity in the electricity sector alone! Of this amount about 40 per cent will have to be lent in foreign currency[26]. At a recent WEC conference it has been estimated that by the year 2000 between 480 and 880 billion Euro[27] will need to be spent globally per year for developments and investments in electric power generation.

Currently the global financing sector is treating an estimated 250 billion Euro every year (IR 19)[28], and as our economic analysis has shown, this has to be compared to a figure of about 700 billion Euro necessary to keep

[23] Original data 5 trillion dollar. For a comparison: total global trade was only about 3.2 trillion Euro (4 trillion dollar) (ibid.)! A large share of this trade, roughly 40 per cent, actually is between the subsidiaries and parent companies of TNCs (Hettne 1990, 188, citing Corbridge), which illustrates their large global trade influence!

[24] Original data: 100 billion dollars. The largest part of FDI circulates around the already industrialised nations! Its contribution to global development therefore is limited.

[25] Original data: $100 billion.

[26] In 1992 investments in all DCs made up an averaged 25 per cent of their gross national product. This share is supposed to grow to 27 in 1998 and to 35 per cent the end of the century. This would imply a growth of yearly investments by about 240 billion Euro (300 billion dollar) compared to current levels. It will necessitate an increased inflow of foreign capital into the DCs (Rohatyn 1994, 46).

[27] Original data: 600-1100 10^9 dollar

[28] Original data: 315 billion dollars. The direct investments are in fact only a small part of the global financial circulation. Daily the incredible amount of 100 billion dollars are being transmitted across the World (Thrift 1995, 25). This currency trading is catching the public attention, if international financial transactions are being scrutinised. A telling example is the case of Barings' Nigel Leeson, who by 27 February 1995 had

the major part of the CFS running. Even if we assume that the global economy will increase about fivefold[29] until 2050, so that the 700 billion in capacity costs should be compared to a global financial sector handling about 1250 billion Euro every year at that time, this amount is still staggering.
As can be seen the CFS will strain global financing as we know it presently, and the question arises, how such large sums will be provided in the future. Already the normal development process going on in Asia will very likely strain global financing; without doubt the need for new financing methods will arise, and it also has to be ensured that investors will be provided with the security needed for their investments if means shall be provided to continue the economic expansion in that region (Rohatyn 1994).even then financial crashes can not be excluded (Kruse 1994).
This challenge might be solved by introducing a universal energy or carbon tax, as has been proposed by *e.g.* Bach and Scheer (1990). The revenue from this source can then be used to finance the extra start-up costs that arise from choosing to buy the most efficient technology compared to less favourable ones. It will also be used to transfer means from ICs to the DCs, so that a global realisation of the scenario's ideas is ensured.
Also the price side needs some consideration: "In the future oil and gas will become more expensive, but gradually they will lose their role as price leaders. Energy prices will be determined by coal prices" (Sens *et al.*, 1994, 273). This means that a strong coal cartel could try to gain a large share of the global energy market by enacting an OPEC-like policy. Whether this is a reasonable assumption shall be seen. At least we have not explicitly calculated with much higher coal costs than at present.
One could fear that the increases in power station efficiency that we perceive possible can be eaten up by increased fuel costs. This would be a disincentive, if construction costs rise too much for rising efficiency. Today efficiency advantages would not be noted in the power prices for higher coal prices, as shown by Kobayasi (1994, 311). This unfortunately means that if coal prices are very volatile, efficiency efforts in the primary energy conversion could be curtailed, so that the total primary energy demand would rise.

Living in the CFS

Until now the reader may have got the impression that all the CFS is about is to solve some economical and technical problems, and that this study is a kind of Herman Kahn style optimistic projection into the future. But this will not be so in reality. Actually the economic challenges in enacting this scenario work are also very much related to social questions and refer to the distribution of scarce resources. As a last remark we therefore also have to look at those questions.
To realise the CFS demands a lot from the public. While some will welcome plans to minimise atmospheric CO_2 emissions by implementation of the CFS, some certainly will object about the real or imagined environmental impacts of the CO_2 sequestration. But we have to be aware that also today a major part of the CO_2 that is being released into the atmosphere will end up in the deeper layers of the oceans (Ohsumi 1995, 65). So the only difference between the CFS and the current situation is that in the CFS the public will be more aware of this fact.
In any case, if a strategy as described in this project is followed, it becomes essential to give the right signals to the energy industry. Economic incentives may be one way, but industry generally is better at anticipating the effect of legislative attractors (Scott 1995, 102) than at coping with economic restraints or attractors. In fact industry will normally be trying to prevent legislative restraints, while attractors will seldomly be noticed, and less energy is used to exploit them – "snags are more concrete, they are easier to understand" (do, p. 101).
This is certainly true for domestic politics, but it will be in an even higher degree valid for a global strategy that has to realise the targets of the CFS. It will therefore be necessary to have international agreements for imposing the CO_2 recovery on a global scale, with as little CO_2 leakage as possible[30]. This latter point might very well be the one that makes the total scheme impractical.

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caused the bank accumulated losses of some £830 million which led to the failure of Barings. Other problematic matters are the growing amount of derivatives that are being traded, and that might threaten global financial stability: over 12 trillion dollars (Rohatyn 1994).

[29] The average per capita GDP increases by a factor of about 2.4 and population will almost double, which together is about a factor of 5.

[30] The restriction of having to depose of the CO_2 will probably lead to drastic legislation against anyone who is trying to interfere with this process, *i.e.* power stations and CO_2 transport or disposal installations can become targets of civil action.

Another challenge is to ensure that efficient end-use technology is installed everywhere. If energy prices rise dramatically, *i.e.* over a short period, this will not necessarily become a problem, as AEEI will then be enhanced. If, on the other hand, prices only rise slowly, the public perception of efficiency advancements will be less acute, and this could translate into a much higher primary energy input than assumed here.
If efficiency can be bought only at the expense of higher up-front costs, then the lack of the necessary incremental investment will be a case of simple price discrimination. In the opposite case, chosing not the most efficient technology due to lack of adequate information will simply be a market imperfection.
How the technology transfer to the DCs shall be completed — and financed — is currently anohter doubtful matter. Development ais is today in most instances given for all other kinds of projects than for energy efficiency, or rational energy use. This means that the DCs have relatetively bad access to knowledge and financing of efficiency options due to its sometimes higher up-front costs.
Therefore technology transfer to invest efficiently in the DCs of adequate dimensions has to be ensured. This will by some be perceived as an unfair contribution to the DCs economic competitiveness, especially if we take into account their low wage levels, and will certainly caused public discussion. Nevertheless the major share of the global population will be living in the DCs, and to realise the CFS's elements there, too, will mean large money transfers from current, and upcoming (!), ICs.
However, this kind of development will also ensure large global markets, one could conclude that globalisation was maybe one first single step to ensuring environmentally proper options all over the World. But financing the CFS might in fact turn out to be a large problem.

8. SOURCES AND LITERATURE

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2	http://www.bp.com/bpstats/odata/orprfrm.html	Contains a chart over the R/P relationship of petroleum, *i.e.* the proven reserves over the annual production between 1969 and 1995.
3	http://www.bp.com/bpstats/ngdata/gprcfrm.html	Contains a chart on natural gas reserves in trillion m^3 between 1970 and 1995.
4	http://www.bp.com/bpstats/ngdata/grprfrm.html	A chart on natural gas' R/P ratios between 1969 and 1995.
5	http://www.eia.doe.gov/emeu/iea/iea95.html	Starting point for data on the World's energy supply and consumption by the Energy Information Administration of the *U.S. Department of Energy*. Indispensible information!
6	http://www.history.rochester.edu/	Starting point for data on some countries' district heating systems' data by the *University of Rochester*.
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10	http://www.cnie.org/nle/eng-4.html	Committe for the *National Institute for the Environment*: "Hydrogen: Technology and Policy"
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9. APPENDIX

Country Notes

Most of those country notes refer to developing countries, as we there had to experience the largest data gaps.

Antarctica

The data for oil resources of Antarctica are not considered.

Afghanistan

The petroleum heat content of Iran was used in the database.

Azerbaijan

The geothermal production has been extracted from the heat plant data for this country.

Brunei

The 'others' for data for natural gas and oil resources for the region 'Asia/Oceania' from Masters *et al.* (1992) are included in this country.

Bulgaria

The 'others' for data for natural gas and oil resources for the region 'Eastern Europe' from Masters *et al.* (1992) are included in this country.
The geothermal production has been extracted from the heat plant data for this country.

Canada

The geothermal production has been extracted from the heat plant data for this country.

Chad

The petroleum heat content of Yemen was used in the database.

Cook Islands

For this country population data for the year 1990 from Baratta (1995) were used.

Denmark

The 'others' for data for natural gas and oil resources for the region 'Western Europe' from Masters *et al.* (1992) are included in this country.

Eritrea

For this country population data for the year 1990 from Baratta (1995) were used.

Gibraltar

For this country population data for the year 1990 from Baratta (1995) were used.

Greenland

For this country population data for the year 1990 from Baratta (1995) were used.

Hungary

The petroleum refinery heat consumption for this country has been excluded from the head plant data.

India

According to Johansen (1997) in 1995 there was an installed wind power capacity of 0.550 GW, and in 1995 alone were some more 300 MW installed. This would pose for about 250 MW installed in 1994. In an article received for publication at the beginning of 1994 Gupta *et al.* (1995) mention approximately 43 MW of wind power being generated in India, and that another 100 MW were being planned for the following years.
Both figures would make sense, if the 43 MW were the average of the installed peak capacity of the 250 MW, this interpretation does however only allow an average utilisation factor of about 17 per cent, or equivalent to 1500 hours production. This would be somewhat lower than the about 2000 hours that one normally would assume to be the case, but could be the result of slightly worse maintenance records in developing countries compared to industrialised regions.

Jordan

The 'others' for data for natural gas and oil resources for the region 'Middle East' from Masters *et al.* (1992) are included in this country.

Lithuania

The geothermal production has been extracted from the heat plant data for this country.

Mexico

According to Bronicki (1994) in the Mexico there were installed about 0.7 GW of geothermal electricity capacity.

Montserrat

For this country population data for the year 1990 from Baratta (1995) were used.

Nauru

For this country population data for the year 1990 from Baratta (1995) were used.

Niue

For this country population data for the year 1990 from Baratta (1995) were used.

Neutral Zone

The data for natural gas and oil resources of the Neutral Zone are included in the database but not considered for the reserve allocation. The data for Saudi Arabia was used for heat content of the products.

Philippines

According to Bronicki (1994) in the Philippines there were installed about 0.98 GW of geothermal electricity capacity, equivalent to about 15 per cent of the country's total electricity generation capacity.

Poland

The petroleum refinery heat consumption for this country has been excluded from the head plant data.

Puerto Rico

No data could be found for this country's final energy consumption, although the EIA database does give data for extraction and conversion.

Romania

The petroleum refinery heat consumption for this country has been excluded from the head plant data.

Russia

The 'others' for data for natural gas and oil resources for the Former Soviet Union from Masters *et al.* (1992) are included in this country.
The geothermal production has been extracted from the heat plant data for this country.

Somalia

The petroleum heat content of Yemen was used in the database.

Tuvalu

For this country population data for the year 1990 from Baratta (1995) were used.

Ukraine

The geothermal production has been extracted from the heat plant data for this country.

USA

According to Bronicki (1994) in the United States there were installed about 2.8 GW of geothermal electricity capacity in 1991. This was equivalent to 45 per cent of the global geothermal power production.

World

According to Bronicki (1994) in 1991 there was a total of 6 GW of geothermal electricity capacity installed in the World. Furthermore 2 GW were planned or under construction, and if those became operational by 1995/96, this would mean an annual average growth of 4 per cent.
There was also installed some 14 GW of thermal geothermal capacity, which according to Bronicki (1994) had saved some 5.5 Mtoe.

OECD Fuelwood Data

FIPS	Country	OECD	Fuelwood PJ	Waste PJ	Waste.OT	Waste.IND	Waste.TR	Diff
AS	Australia	1	26.35	188.42	77.88	110.54	0.00	162.06
AU	Austria	1	31.81	116.82	93.79	22.61	0.42	85.01
BE	Belgium	1	5.37	5.02	0.00	0.00	5.02	-0.34
CA	Canada	1	67.31	383.95	80.39	303.56	0.00	316.63
DA	Denmark	1	4.73	19.68	15.49	4.19	0.00	14.95
FO	Faroe Islands	1		0.00	0.00	0.00	0.00	
FI	Finland	1	40.03	145.71	34.33	111.37	0.00	105.68
FR	France	1	95.65	467.69	465.59	2.09	0.00	372.04
GM	Germany	1	37.04	54.85	49.83	5.02	0.00	17.81
GC	Germany, East	1		0.00	0.00	0.00	0.00	
GE	Germany, West	1		0.00	0.00	0.00	0.00	
GR	Greece	1	14.83	23.03	21.77	1.26	0.00	8.20
GL	Greenland	1		0.00	0.00	0.00	0.00	
GQ	Guam	1		0.00	0.00	0.00	0.00	
HQ	Hawaiian Trade Zone	1		0.00	0.00	0.00	0.00	
IC	Iceland	1		0.00	0.00	0.00	0.00	
EI	Ireland	1	0.59	2.51	0.84	1.67	0.00	1.93
IT	Italy	1	53.49	46.06	39.36	6.70	0.00	-7.44
JA	Japan	1	1.35	91.70	3.35	88.35	0.00	90.35
LU	Luxembourg	1		0.00	0.00	0.00	0.00	
MX	Mexico	1	149.06	316.54	246.20	70.34	0.00	167.47
NL	Netherlands	1	1.99	2.51	2.09	0.42	0.00	0.52
NZ	New Zealand	1	0.49	41.87	5.86	36.01	0.00	41.38
NO	Norway	1	4.59	41.03	22.19	18.84	0.00	36.45
PO	Portugal	1	4.88	41.87	19.26	20.94	1.67	36.99

FIPS	Country	OECD	Fuelwood PJ	Waste PJ	Waste.OT	Waste.IND	Waste.TR	Diff
RQ	Puerto Rico	1		0.00	0.00	0.00	0.00	
SP	Spain	1	22.82	28.05	0.00	28.05	0.00	5.23
SW	Sweden	1	37.09	209.77	41.87	167.90	0.00	172.68
SZ	Switzerland	1	11.25	27.63	14.65	12.98	0.00	16.38
TU	Turkey	1	74.51	0.00	0.00	0.00	0.00	-74.51
VQ	Virgin Islands, U.S.	1		0.00	0.00	0.00	0.00	
UK	United Kingdom	1	2.24	18.42	12.98	5.44	0.00	16.18
US	United States	1	853.52	968.87	583.25	385.62	0.00	115.35

Regions Abbreviations

Short Form	Explicit Form	Abbr.
NAFTA	Canada and United States	AM1
Mexico group	Mexico, Brazil and Argentina	AM2
Latin America	Caribbean, Central and South America	AM3
Australia - N Zealand	Australia and New Zealand	AU1
Oceania	Oceania without AUS or NZ	AU2
South Africa	Republic of South Africa	AF1
Maghreb	North Africa at Mediterranean	AF2
Sub-Saharan Africa	Africa, except RSA and MAG	AF3
Western Europe	EU and Norway, Switzerland	EU1
Central Europe	Most Central European Countries, Turkey, Israel	EU2
Developing Europe	Poorer European Countries of Europe	EU3
Russia	Russia	RUS
China	China	CHI
Japan and Tigers	Japan and Hong Kong, Singapore, Taiwan, South Korea	AS1
India group	India, Pakistan , Malaysia, Philippines, Thailand, Indonesia	AS2
Oil rich countries	Middle East Oil States	AS3
Developing Asia	Asia, rest of	AS4

Regional Country Groupings

RE1	Country	Climate Class	Income 1990	Income 2050	Pop. 2050	W/cap 2050
AF1	Seychelles	tropical, arid	high	high	106	574
AF1	South Africa	special mixed	middle	middle	91466	741
AF2	Algeria	tropical, arid	middle	middle	58991	612
AF2	Egypt	tropical, arid	middle	middle	115480	612
AF2	Libya	tropical, arid	middle	middle	19109	612
AF2	Morocco	tropical, arid	middle	middle	47276	612
AF2	Tunisia	tropical, arid	middle	middle	15907	612
AF2	Western Sahara	tropical, arid	middle	middle	558	612
AF3	Angola	tropical, arid	middle	middle	38897	612
AF3	Benin	tropical, humid	middle	middle	18095	620
AF3	Botswana	tropical, arid	middle	middle	3320	612
AF3	Burkina Faso	tropical, arid	low	middle	35419	612
AF3	Burundi	tropical, humid	low	low	16937	183
AF3	Cameroon	tropical, humid	middle	middle	41951	620
AF3	Cape Verde	tropical, humid	middle	middle	864	620
AF3	Central African Republic	tropical, humid	middle	middle	8215	620
AF3	Chad	tropical, arid	low	low	18004	179
AF3	Comoros	tropical, arid	middle	middle	1876	612
AF3	Congo	tropical, humid	middle	middle	8729	620
AF3	Cote d'Ivoire(IvoryCoast)	tropical, humid	middle	middle	31706	620
AF3	Djibouti	tropical, humid	middle	middle	1506	620
AF3	Equatorial Guinea	tropical, humid	middle	middle	1144	620
AF3	Eritrea	tropical, humid	middle	middle	8808	620
AF3	Ethiopia	tropical, arid	low	low	212732	179
AF3	Gabon	tropical, humid	middle	high	2952	583
AF3	Gambia, The	tropical, humid	middle	middle	2604	620

AF3	Ghana	tropical, humid	middle	middle	51205	620
AF3	Guinea	tropical, humid	middle	middle	22914	629
AF3	Guinea-Bissau	tropical, humid	low	low	2674	183
AF3	Kenya	tropical, humid	middle	middle	66054	620
AF3	Lesotho	tropical, arid	middle	middle	5643	612
AF3	Liberia	tropical, humid	middle	middle	9955	620
AF3	Madagascar	tropical, humid	low	low	50807	183
AF3	Malawi	tropical, humid	low	low	29825	183
AF3	Mali	tropical, arid	low	middle	36817	612
AF3	Mauritania	tropical, arid	middle	middle	6077	621
AF3	Mauritius	tropical, arid	middle	middle	1654	612
AF3	Mozambique	tropical, arid	low	low	51774	179
AF3	Namibia	tropical, arid	middle	middle	4167	612
AF3	Niger	tropical, arid	low	middle	34576	612
AF3	Nigeria	tropical, humid	middle	middle	338510	620
AF3	Reunion	tropical, arid	middle	middle	1033	612
AF3	Rwanda	tropical, humid	low	low	16937	183
AF3	Saint Helena	tropical, arid	middle	middle	10	612
AF3	Sao Tome and Principe	tropical, arid	middle	middle	294	612
AF3	Senegal	tropical, humid	middle	middle	23442	620
AF3	Sierra Leone	tropical, humid	low	low	11368	183
AF3	Somalia	tropical, humid	low	low	36408	183
AF3	Sudan	tropical, arid	low	middle	59947	612
AF3	Swaziland	tropical, arid	middle	middle	2228	612
AF3	Tanzania	tropical, humid	low	low	88963	183
AF3	Togo	tropical, humid	middle	middle	12655	620
AF3	Uganda	tropical, humid	low	low	66305	183
AF3	Zaire	tropical, humid	low	low	164635	197
AF3	Zambia	tropical, arid	middle	middle	21965	635
AF3	Zimbabwe	tropical, arid	middle	middle	24904	612
AM1	Canada	polar	high	high	36352	1809.2
AM1	Greenland	polar	high	high	72	1730.2
AM1	United States	special mixed	high	high	347543	740
AM2	Argentina	middle latitudes	high	high	54522	902
AM2	Brazil	tropical, humid	middle	middle	243259	680
AM2	Mexico	tropical, arid	middle	middle	154120	651
AM3	Antigua and Barbuda	tropical, humid	middle	middle	99	620
AM3	Aruba	tropical, arid	middle	middle	109	612
AM3	Bahamas, The	tropical, arid	high	high	435	574
AM3	Barbados	tropical, arid	high	high	306	574
AM3	Belize	tropical, arid	middle	middle	480	612
AM3	Bermuda	tropical, arid	middle	middle	79	612
AM3	Bolivia	tropical, arid	middle	middle	16966	612
AM3	Cayman Islands	tropical, arid	middle	middle	67	612
AM3	Chile	middle latitudes	middle	middle	22215	917
AM3	Colombia	tropical, humid	middle	middle	62284	620
AM3	Costa Rica	tropical, humid	middle	middle	6902	620
AM3	Cuba	tropical, humid	middle	middle	11284	620
AM3	Dominica	tropical, arid	middle	middle	97	612
AM3	Dominican Republic	tropical, arid	middle	middle	13141	612
AM3	Ecuador	tropical, humid	middle	middle	21190	620
AM3	El Salvador	tropical, humid	middle	middle	11364	620
AM3	Falkland Islands	middle latitudes	middle	middle	3	885
AM3	French Guiana	tropical, arid	middle	middle	353	612
AM3	Grenada	tropical, arid	middle	middle	134	612
AM3	Guadeloupe	tropical, arid	middle	middle	634	612
AM3	Guatemala	tropical, humid	middle	middle	29353	620

AM3	Guyana	tropical, humid	middle	middle	1239	620
AM3	Haiti	tropical, arid	middle	middle	17524	612
AM3	Honduras	tropical, arid	middle	middle	13920	612
AM3	Jamaica	tropical, arid	middle	middle	3886	632
AM3	Martinique	tropical, arid	middle	middle	518	612
AM3	Montserrat	tropical, arid	middle	middle	14	612
AM3	Netherlands Antilles	tropical, arid	middle	middle	259	612
AM3	Nicaragua	tropical, humid	middle	middle	9922	620
AM3	Panama	tropical, humid	middle	middle	4365	620
AM3	Paraguay	tropical, arid	middle	middle	12565	612
AM3	Peru	tropical, humid	middle	middle	42292	652
AM3	Puerto Rico	tropical, humid	high	high	5119	583
AM3	Saint Kitts and Nevis	tropical, arid	middle	high	56	574
AM3	Saint Lucia	tropical, arid	middle	middle	235	612
AM3	Saint Pierre and Miquelon	tropical, arid	middle	middle	8	612
AM3	Saint Vincent/Grenadines	tropical, arid	middle	middle	174	612
AM3	Suriname	tropical, arid	middle	high	711	594
AM3	Trinidad and Tobago	tropical, arid	middle	high	1899	574
AM3	Turks and Caicos Islands	tropical, arid	middle	middle	32	612
AM3	Uruguay	tropical, arid	middle	middle	4027	612
AM3	Venezuela	tropical, humid	middle	middle	42152	668
AM3	Virgin Islands, U.S.	tropical, arid	middle	middle	158	612
AM3	Virgin Islands, British	tropical, arid	middle	middle	37	612
AS1	Hong Kong	tropical, humid	high	high	5618	583
AS1	Japan	middle latitudes	high	high	109546	952
AS1	Korea, South	tropical, humid	high	high	52146	614
AS1	Singapore	tropical, humid	high	high	4190	583
AS1	Taiwan	tropical, humid	high	high	22	604
AS2	India	tropical, humid	low	middle	1532674	699
AS2	Indonesia	tropical, humid	middle	middle	318264	638
AS2	Malaysia	tropical, humid	middle	high	38089	583
AS2	Pakistan	tropical, humid	middle	middle	357353	620
AS2	Philippines	tropical, humid	middle	middle	130511	643
AS2	Thailand	tropical, humid	middle	middle	72969	620
AS3	Afghanistan	tropical, arid	middle	middle	61373	612
AS3	Azerbaijan	middle latitudes	middle	middle	10881	885
AS3	Bangladesh	tropical, humid	low	middle	218188	620
AS3	Bhutan	middle latitudes	low	middle	5184	885
AS3	Brunei	tropical, humid	middle	middle	512	620
AS3	Burma	tropical, humid	middle	middle	80896	620
AS3	Cambodia	tropical, humid	low	middle	21394	620
AS3	East Timor	tropical, humid	middle	middle	1415	620
AS3	Georgia	middle latitudes	middle	high	6028	902
AS3	Jordan	tropical, arid	middle	middle	16671	612
AS3	Kazakstan	middle latitudes	middle	high	22260	902
AS3	Korea, North	tropical, humid	middle	middle	32873	646
AS3	Kyrgyzstan	middle latitudes	middle	middle	7182	885
AS3	Laos	tropical, humid	low	middle	13889	620
AS3	Lebanon	tropical, arid	middle	middle	5189	612
AS3	Macau	tropical, humid	middle	middle	547	620
AS3	Mongolia	tropical, humid	middle	middle	4986	620
AS3	Nepal	middle latitudes	low	middle	53621	885
AS3	Oman	tropical, arid	high	high	10930	594
AS3	Sri Lanka	tropical, humid	middle	middle	26995	620
AS3	Tajikistan	middle latitudes	middle	middle	12366	885
AS3	Turkmenistan	middle latitudes	middle	middle	7916	885

AS3	Uzbekistan	middle latitudes	middle	middle	45094	885
AS3	Vietnam	tropical, humid	low	low	129763	183
AS3	Yemen	tropical, arid	middle	middle	61129	612
AS4	China	tropical, arid	middle	middle	1516664	700
AS5	Bahrain	tropical, arid	high	high	940	594
AS5	Iran	tropical, arid	middle	middle	170269	621
AS5	Iraq	tropical, arid	middle	middle	56129	632
AS5	Kuwait	tropical, arid	high	high	3406	594
AS5	Qatar	tropical, arid	high	high	861	594
AS5	Saudi Arabia	tropical, arid	high	high	59812	594
AS5	Syria	tropical, arid	middle	middle	34463	612
AS5	United Arab Emirates	tropical, arid	high	high	3668	594
AU1	Australia	tropical, arid	high	high	25286	662
AU1	New Zealand	middle latitudes	high	high	5271	902
AU2	American Samoa	tropical, arid	high	high	139	574
AU2	Cook Islands	tropical, arid	high	high	29	574
AU2	Fiji	tropical, arid	middle	middle	1393	612
AU2	French Polynesia	tropical, arid	high	high	403	574
AU2	Guam	tropical, arid	high	high	250	574
AU2	Kiribatia	tropical, arid	middle	middle	165	612
AU2	Maldives	tropical, arid	middle	middle	830	612
AU2	Nauru	tropical, arid	high	high	25	574
AU2	New Caledonia	tropical, arid	high	high	295	574
AU2	Niue	tropical, arid	high	high	1	574
AU2	Papua New Guinea	tropical, arid	middle	middle	9637	621
AU2	Solomon Islands	tropical, arid	middle	middle	1192	612
AU2	Tonga	tropical, arid	middle	middle	128	612
AU2	Tuvalu	tropical, arid	high	high	16	574
AU2	Vanuatu (New Hebridies)	tropical, arid	middle	middle	456	612
AU2	Western Samoa	tropical, arid	middle	middle	319	612
EU1	Austria	middle latitudes	high	high	7430	909
EU1	Belgium	middle latitudes	high	high	9763	919
EU1	Czech Republic	middle latitudes	middle	middle	8572	902
EU1	Denmark	middle latitudes	high	high	5234	902
EU1	Faroe Islands	middle latitudes	high	high	51	902
EU1	Finland	middle latitudes	high	high	5172	902
EU1	France	middle latitudes	high	high	58370	938
EU1	Germany	middle latitudes	high	high	69542	931
EU1	Gibraltar	tropical, arid	high	high	28	574
EU1	Iceland	polar	high	high	363	1730.2
EU1	Ireland	middle latitudes	high	high	3809	902
EU1	Italy	special mixed	high	high	42092	706
EU1	Luxembourg	middle latitudes	high	high	461	902
EU1	Netherlands	middle latitudes	high	high	14956	938
EU1	Norway	middle latitudes	high	high	4694	921
EU1	Spain	special mixed	high	high	31755	706
EU1	Sweden	middle latitudes	high	high	9574	918
EU1	Switzerland	middle latitudes	high	high	6935	902
EU1	United Kingdom	middle latitudes	high	high	58733	938
EU2	Bosnia and Herzegovina	middle latitudes	high	high	3789	902
EU2	Croatia	middle latitudes	high	high	3991	902
EU2	Cyprus	tropical, arid	high	high	1029	574
EU2	Estonia	middle latitudes	middle	middle	1084	885
EU2	Gaza Strip (Palestina)	tropical, arid	high	high	4426	574
EU2	Greece	special mixed	high	high	9013	679
EU2	Hungary	middle latitudes	middle	middle	7715	885
EU2	Israel	tropical, arid	high	high	9144	574

EU2	Latvia	middle latitudes	middle	middle	1891	885
EU2	Lithuania	middle latitudes	middle	middle	3297	885
EU2	Malta	middle latitudes	high	high	442	902
EU2	Poland	middle latitudes	middle	middle	39725	911
EU2	Portugal	special mixed	high	high	8701	679
EU2	Slovakia	middle latitudes	middle	middle	5260	902
EU2	Slovenia	middle latitudes	high	high	1471	902
EU2	Turkey	special mixed	middle	middle	97911	699
EU3	Albania	middle latitudes	middle	middle	4747	885
EU3	Armenia	middle latitudes	low	low	4376	232
EU3	Belarus	middle latitudes	middle	middle	8726	885
EU3	Bulgaria	middle latitudes	middle	middle	6690	885
EU3	Macedonia	middle latitudes	middle	middle	2646	885
EU3	Moldova	middle latitudes	middle	middle	5138	885
EU3	Romania	middle latitudes	middle	middle	19009	892
EU3	Serbia and Montenegro	middle latitudes	high	high	10979	902
EU3	Ukraine	middle latitudes	middle	middle	40802	885
RUS	Russia	middle latitudes	middle	middle	114318	973

REI: means the region's abbreviation code.
Economic region: means the grouping from IPCC II (1994) that we have applied for that country.

Changes in Countries' Income Classing

Income Class 1990	Income Class 2050	Number Countries
high income	high income	62
low income	low income	15
low income	middle income	10
middle income	high income	7
middle income	middle income	125

As can be seen 10 countries, today in the poor group, will reach the middle income group, and 7, today of middle per capita income, will reach the rich group.

Regional Population and per capita GDP Indexes for the Year 2050

Type	Global Region	Regions	POP-50	GDP-50
Population	USA	NAF	1.19	3.00
Population	OECD-W	WEU	1.05	3.08
Population	OECD-A	AUS	1.06	3.77
		JAP	1.06	3.77
		OCE	1.06	3.77
Population	CPASIA	CHI	1.52	9.43
Population	M-EAST	OIL	3.59	2.49
Population	L-AMER	CAM	1.84	3.28
		BAX	1.84	3.28
Population	CPEUR	CEU	1.21	2.62
		RUS	1.21	2.62
		PEU	1.21	2.62
Population	AFRICA	AFR	3.44	3.03
		MAG	3.44	3.03

		RSA	3.44	3.03
Population	SEASIA	ASI	2.03	5.83
		NIC	2.03	5.83
Population	Total	OTH	1.90	2.43

Source: IPCC II (1994).
The table shows how we have used the IPCC information on the population development until the year 2050. The index for 1990 is, of course, 1.00.
Global Region: this is the IPCC definition of the global regions.
Note: *OTH* can be assumed to be a global mean.

Average GDP in the geographical regions 1990 and 2050

REI	Geographical region	avgGDP 1990	avgGDP 2050
AF1	Southern Africa	2821	8545
AF2	Maghreb	1003	3063
AF3	Sub-Sahara Africa	338	980
AM1	North America	21928	65725
AM2	Brazil, Argentina, Mexico	3264	10734
AM3	Caribbean & developing Latin America	1505	4650
AS1	Japan and Four Tigers	21269	75155
AS2	India group	458	2596
AS3	China	317	2993
AS4	Developing Asia	796	3681
AS5	Oil rich countries	3145	8776
AU1	Australia - N Zealand	16516	62098
AU2	Oceania	2385	7746
EU1	Western Europe	19039	58786
EU2	Central Europe, Turkey, Israel	3097	7561
EU3	Developing Europe	2739	7174
RUS	Russia	3780	9920

Source: own calculations.

Regional Population Development

code	Geographical region	Sum 1990	Sum 2050	Difference
AF1	Southern Africa	37066	95711	58645
AF2	Maghreb	118206	269263	150848
AF3	Sub-Sahara Africa	480561	1776382	1295821
AM1	North America	277770	401786	124016
AM2	Brazil, Argentina, Mexico	265535	472872	207337
AM3	Caribbean & developing Latin America	174190	375098	200908
AS1	Japan and Four Tigers	174837	179459	4622
AS2	India group	1289636	2563551	1273915
AS3	Asia	391927	897066	505139
AS4	Oil rich countries	110209	344841	234632
AU1	Australia - N Zealand	20244	31975	11731

code	Geographical region	Sum 1990	Sum 2050	Difference
AU2	Oceania	6120	15842	9721
CHI	China	1155305	1587048	431743
EU1	Western Europe	366295	352716	-13579
EU2	Central Europe, Turkey, Israel	154648	208119	53471
EU3	Developing Europe	117725	107898	-9827
RUS	Russia	148309	119623	-28686
Total		5288583	9799250	4510458

Data in thousands.
Source: own calculations based on SOFA (1996), IPCC II (1994) and Baratta (1995).

Pre-Defined Scenario Assumptions

High Income Groupings' Industrial End-Use Energy Rates

Activity / Energy	Process heat <100 C	Process heat 100-500 C	Process heat >500 C	Stat. mech. energy	Electrical appliances	Transport. work
Construction				20		10
Agriculture	5			6	2	6
Manufacturing	10	5	10	30	12	10
Raw mats.&energy	5	5	5	8	11	9
TOTAL	**20**	**10**	**15**	**64**	**25**	**35**

Middle Income Groupings' Industrial End-Use Energy Rates

Activity / Energy	Process heat <100 C	Process heat 100-500 C	Process heat >500 C	Stat. mech. energy	Electrical appliances	Transport. work
Construction				25		8
Agriculture	8			4	2	4
Manufacturing	22	30	20	30	38	9
Raw mats.&energy	5	5	15	86	20	9
TOTAL	**35**	**35**	**35**	**145**	**60**	**30**

Low Income Groupings' Industrial End-Use Energy Rates

Activity / Energy	Process heat <100 C	Process heat 100-500 C	Process heat >500 C	Stat. mech. energy	Electrical appliances	Transport. work
Construction				5		4
Agriculture	4			3	1	3
Manufacturing	5	4	2	5	13	4
Raw mats.&energy	1	3	3	8	6	4
TOTAL	**10**	**7**	**5**	**21**	**20**	**15**

High Income Groupings' Residential and Services End-Use Energy Rates

Activity / Energy	Process heat <100 C	Process heat 100-500 C	Stat. mech. energy	Electrical appliances	Transport. work
Surroundings					
Food and water	15	5			
Security			0.5		0.5
Hygiene / Health	95	25		0.5	0.5
Relations, leisure				52.5	64
Services & trade	10		5.5	20	30
Education				2	
Commuting					25
TOTAL	**120**	**30**	**6**	**75**	**120**

Middle Income Groupings' Residential and Services End-Use Energy Rates

Activity / Energy	Process heat <100 C	Process heat 100-500 C	Stat. mech. energy	Electrical appliances	Transport. work
Surroundings					
Food and water	15	5			
Security			0.5		0.5
Hygiene / Health	55	15		0.5	0.5
Relations, leisure				37.5	34
Services & trade	5		4.5	15	20
Education				2	
Commuting					15
TOTAL	**75**	**20**	**5**	**55**	**70**

Low Income Groupings' Residential and Services End-Use Energy Rates

Activity / Energy	Process heat <100 C	Process heat 100-500 C	Stat. mech. energy	Electrical applicances	Transport. work
Surroundings					
Food and water	5	2			
Security			0.5		0.5
Hygiene / Health	10	6		0.5	0.5
Relations, leisure				18.5	4
Services & trade	5		3.5	10	7
Education				1	
Commuting					8
TOTAL	**20**	**8**	**4**	**30**	**20**

Climatic macroregions based on bioclimatic classification

Climatic Region	Food chilling demand	Air conditio. demand	Space heating demand
tropical, humid	15	40	0
tropical, arid	12	15	20
middle latitudes	10	10	300
polar climate	9	0	1001
special mixed	12	15	100

Climatic Extreme Demands

Climatic Region	Peak space heating demand	Minimal space heating demand	Minimal air conditio. demand	Peak air conditio. demand
tropical, humid	0	0	40	40
tropical, arid	50	0	5	25
middle latitudes	900	0	0	30
polar climate	3000	100	0	0
special mixed	300	0	5	30

Table 1 Average yearly per capita end-use demands in 2050 for the 17 regions

REI	Geographical region	avg cool	avg space	avg lo	avg me	avg hi	avg stat	avg el	avg trp	Total
AF1	South Africa	28.1	96.8	114.8	58.4	53.7	161.0	114.5	108.6	735.9
AF2	Maghreb	27.0	20.0	110.0	55.0	35.0	150.0	115.0	100.0	612.0
AF3	Sub-Sahara Africa	34.6	4.0	73.8	37.1	22.5	93.7	85.6	70.7	421.9
AM1	North America	28.5	219.3	142.2	48.9	54.4	82.3	100.0	162.1	837.5
AM2	Brazil, Argentina, Mexico	41.5	50.3	117.1	57.6	51.2	153.1	113.2	113.0	696.9
AM3	Caribbean & developing L. America	45.8	23.9	111.5	55.9	39.1	153.1	114.9	102.1	646.3
AS1	Japan and Four Tigers	36.8	229.9	140.0	45.0	43.4	74.4	100.0	158.5	828.1
AS2	India group	55.1	0.0	113.6	60.5	60.2	161.0	114.8	107.2	672.4
AS3	China	27.0	20.0	116.0	64.0	75.0	172.0	115.0	111.0	700.0
AS4	Developing Asia	37.9	64.1	99.3	48.7	30.3	129.3	104.9	92.3	606.8
AS5	Oil rich countries	27.8	21.0	121.1	53.3	29.8	134.2	111.1	117.6	616.0
AU1	Australia - N Zealand	28.6	82.0	145.0	47.4	48.1	88.2	100.0	164.1	703.4
AU2	Oceania	27.2	20.3	113.5	53.9	33.5	147.1	113.9	105.4	614.8
EU1	Western Europe	24.0	299.4	140.1	43.3	35.1	73.3	100.0	157.4	872.6
EU2	Central Europe, Turkey, Israel	22.3	271.3	121.2	49.7	28.4	121.8	109.5	120.5	844.7
EU3	Developing Europe	23.6	186.0	108.5	54.5	40.0	149.5	113.4	100.0	775.5
RUS	Russia	20.0	300.0	116.0	64.0	75.0	172.0	115.0	111.0	973.0

Source: own calculations based on various data.

Notes on abbreviations:

avg cool: average refrigeration and air conditioning end-use demand,
avg space: average space heating end-use demand,
avg lo: average low (<100°C) temperature end-use demand,
avg me: average medium (100-500°C) temperature end-use demand,
avg hi: average high (>500 °C) temperature end-use demand,
avg stat: average stationary motors end-use demand,
avg el: average electrical appliances end-use demand,
avg trp: average transport end-use demand.

Table 2 Boreal winter per capita end-use demands in 2050 for the 17 regions

REI	Geographical region	avg cool	avg space	avg lo	avg me	avg hi	avg stat	avg el	avg trp	Total
AF1	South Africa	42.7	0.0	114.8	58.4	53.7	161.0	114.5	108.6	653.6
AF2	Maghreb	17.0	50.0	110.0	55.0	35.0	150.0	115.0	100.0	632.0
AF3	Sub-Sahara Africa	34.0	6.3	73.8	37.1	22.5	93.7	85.6	70.7	423.7
AM1	North America	17.7	657.4	142.2	48.9	54.4	82.3	100.0	162.1	1265.0
AM2	Brazil, Argentina, Mexico	41.0	17.1	117.1	57.6	51.2	153.1	113.2	113.0	663.2
AM3	Caribbean & developing L. America	46.5	7.8	111.5	55.9	39.1	153.1	114.9	102.1	630.8
AS1	Japan and Four Tigers	29.2	689.8	140.0	45.0	43.4	74.4	100.0	158.5	1280.3
AS2	India group	55.1	0.0	113.6	60.5	60.2	161.0	114.8	107.2	672.4
AS3	China	17.0	50.0	116.0	64.0	75.0	172.0	115.0	111.0	720.0
AS4	Developing Asia	33.9	190.2	99.3	48.7	30.3	129.3	104.9	92.3	728.9
AS5	Oil rich countries	17.3	52.6	121.1	53.3	29.8	134.2	111.1	117.6	637.0
AU1	Australia - N Zealand	42.7	0.0	145.0	47.4	48.1	88.2	100.0	164.1	635.5
AU2	Oceania	36.4	2.6	113.5	53.9	33.5	147.1	113.9	105.4	606.2
EU1	Western Europe	12.0	897.8	140.1	43.3	35.1	73.3	100.0	157.4	1459.0
EU2	Central Europe, Turkey, Israel	11.5	813.4	121.2	49.7	28.4	121.8	109.5	120.5	1376.1
EU3	Developing Europe	13.8	558.1	108.5	54.5	40.0	149.5	113.4	100.0	1137.8
RUS	Russia	10.0	900.0	116.0	64.0	75.0	172.0	115.0	111.0	1563.0

Source: own calculations.

Table 3 Austral winter per capita end-use demands in 2050 for the 17 regions

RPI	Geographical region	avg cool	avg space	avg lo	avg me	avg hi	avg stat	avg el	avg trp	Total
AF1	South Africa	18.4	290.4	114.8	58.4	53.7	161.0	114.5	108.6	919.8
AF2	Maghreb	37.0	0.0	110.0	55.0	35.0	150.0	115.0	100.0	602.0
AF3	Sub-Sahara Africa	35.1	3.6	73.8	37.1	22.5	93.7	85.6	70.7	422.1
AM1	North America	44.5	11.2	142.2	48.9	54.4	82.3	100.0	162.1	645.5
AM2	Brazil, Argentina, Mexico	43.4	130.3	117.1	57.6	51.2	153.1	113.2	113.0	778.9
AM3	Caribbean & developing L. America	45.8	61.4	111.5	55.9	39.1	153.1	114.9	102.1	683.8
AS1	Japan and Four Tigers	52.1	0.0	140.0	45.0	43.4	74.4	100.0	158.5	613.5
AS2	India group	55.1	0.0	113.6	60.5	60.2	161.0	114.8	107.2	672.4
AS3	China	37.0	0.0	116.0	64.0	75.0	172.0	115.0	111.0	690.0
AS4	Developing Asia	43.9	0.0	99.3	48.7	30.3	129.3	104.9	92.3	548.8
AS5	Oil rich countries	38.3	0.0	121.1	53.3	29.8	134.2	111.1	117.6	605.5
AU1	Australia - N Zealand	16.6	235.9	145.0	47.4	48.1	88.2	100.0	164.1	845.4
AU2	Oceania	18.1	48.2	113.5	53.9	33.5	147.1	113.9	105.4	633.6
EU1	Western Europe	46.3	0.1	140.1	43.3	35.1	73.3	100.0	157.4	595.7
EU2	Central Europe, Turkey, Israel	42.3	0.0	121.2	49.7	28.4	121.8	109.5	120.5	593.4
EU3	Developing Europe	40.5	0.0	108.5	54.5	40.0	149.5	113.4	100.0	606.4
RUS	Russia	40.0	0.0	116.0	64.0	75.0	172.0	115.0	111.0	693.0

Source: own calculations.

Greenhouse Gas Budgets

Atmospheric CO_2 Budget 1980-89 (IPCC 1994)

Sources and Sinks	range	standard values	standard Gt CO_2 / yr.
Fossil fuel and cement production		5.5±0.5	20.2
Observed atmospheric increase		3.2±0.2	11.7
Ocean uptake (model calculated)		2.0±0.8	7.3
based on O_2/N_2 ratio trend	1.9±0.8		
based on observations of $^{13}C/^{12}C$ ratio	2.1±1.5		
Net balance of terrestrial biosphere		0.3±1.0	1.1
Land use change emissions		1.6±1.0	5.9
Regrowth of temperate latitude forests		0.5±0.5	1.8
CO_2 uptake by other terrestrial processes		1.4±1.5	5.1

Fluxes in GtC per year (middle column) and billion tonnes CO_2 per year (right column).
Uncertainty ranges represent estimated 90 % confidence intervals.
Source: Heimann (1996); extended with own calculations.

Energy Costs and other Economic Factors

Considered Energy	Cost in $/GJ	Cost in Euro/GJ	Source
coal	1.93	1.5	Audus (1996, 840)
coal	2	1.6	Kjær (1996, 900)
coal	85.5 (£45/t)	2.7	Sens *et al.* (1994, 279)
natural gas	4.84	3.9	Audus (1996, 840)
natural gas	3 HHV	2.4 HHV	Blok (1997, 165)
oil	5.1	4.1	$30/bl estimated
hydro electricity		3	estimated
environmental heat		0	estimated
social interest rate		3 % p.a.	
private interest rate		10 % p.a.	

Source:.
Note: Audus $\$_{1996}$, Kjær $\$_{1995}$,
Coal cost from Sens *et al.* not taken, as overseas prices have to be assumed!

CO_2 Emissions from Extracted Primary Energy

Considered Energy	Extracted Energy (GWy)	Extracted Energy (EJ)	CO_2 Emission Factors (Mt / EJ)	CO_2 Emissions (Mt)
environmental heat	1700	54	0	**0**
natural gas	3000	95	57	**5383**
coal	8700	274	95	**26065**
hydro electricity	220	7	5	**35**
oil	2500	79	73	**5755**
total	16120	508	-	**37238**

Note: Primary energy assumptions from the original scenario description by Sørensen (1996).
Conversion factors for CO_2 emissions have been taken from Anderson and Trier (1995, 154).
For hydro electricity recalculated values for high energy density dams from Rosa and Schaeffer (1994).

Chemical Data

Hydrogen Datasheet

Kind of data	Numeric value
Symbol	H
Atomic weight	1.0079
Atomic volume	14.4 cm^3 / mol
Density @ 293 K	0.0000899 g / cm^3
Specific heat	14.304 J / g K
Melting point	14.06 K
Boiling point	20.4 K
Heat of fusion	0.05868 kJ / mol
Heat of vaporisation	0.44936 kJ / mol
HHV	284.6 kJ / mol
1Nm^3	0.0886 kg
1GJ (Nm^3)	7.0 kg
Volume energy density (Nm^3)	0.013 GJ / Nm^3
Mass energy density	˜ 140 MJ / kg
Density @ 20 K	0.0709 t m^{-3}
Volume energy density @ 20 K	9.926 GJ / m^3

Sources: based mostly on data from MIT, http://setec-astronomy.mit.edu/chemicool/hydrogen.html;
Giacomazzi 1989, 603;
IR (10).

Methane Datasheet

Kind of data	Numeric value
Symbol	CH_4
Ionic weight	c. 16 g/mol
Ionic volume	
Density @ 293 K	
Specific heat	
Melting point	
Boiling point	113 K
Heat of fusion	
Heat of vaporisation	
HHV	887.2 kJ / mol
LHV	
Volume energy density (Nm^3)	0.040 GJ / Nm^3.
Density @ 113 K	0.47 t m^{-3}
Volume energy density @ 113 K	c. 26 GJ / m^3

Source: based on various sources. a.o. Steinberg (1995), Giacomazzi (1989).

Carbon Dioxide Datasheet

Kind of data	Numeric value
Symbol	CO_2

Kind of data	Numeric value
Ionic weight	
Ionic volume	
Density @ 293 K	
Specific heat	
Melting point	
Boiling point	195 K
Heat of fusion	
Heat of vaporisation	
Density @ c. 190 K	1 t / m^3

Source: based on various sources. a.o. Skovholt 1993,

Fundamental Reaction Kinetics

Reaction	Enthalpy	Description
$C + \frac{1}{2} O_2 = CO$	-123.1 kJ / mol	partial combustion
$C + O_2 = CO_2$	-405.9 kJ / mol	complete combustion
$C + CO_2 = 2\ CO$	159.7 kJ / mol	Boudouard reaction
$C + H_2O = CO + H_2$	118.9 kJ / mol	water gas reaction
$C + 2\ H_2 = CH_4$	-87.4 kJ / mol	hydrogasification reaction
$CO + H_2O = H_2 + CO_2$	-40.9 kJ / mol	water-gas shift reaction
$CO + 3\ H_2 = CH_4 + H_2O$	-206.3 kJ / mol	methanation
$CaO + CO_2 = CaCO_3$	- 179 kJ / mol	
$MgO + CO_2 = MgCO_3$	-118 kJ / mol	
$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$	-68 kJ / mol	
$Mg(OH)_2 + CO_2 = MgCO_3 + H_2O$	-37 kJ / mol	

Source: mostly based on Kristiansen (1996), Lackner *et al.* (1995).
Note: values for the same reactions might differ depending on the temperature considered.

Table 4 Some data for CR

Species	Value	Source
CO_2 absorption	5 GJ/ton CO_2	Hendriks *et al.* 1989, 127 ff.
CO_2 compression and pumping	90 kWh/ton CO_2	Hendriks *et al.* 1989, 127 ff.

Note: Arbitratrily chosen data.

Natural Gas Components

Component	Hexane	Propane	Butane	Pentane	Nitrogen	Methane	Carbon dioxide	Ethane
Formula	C_6H_{14}	C_3H_8	C_4H_{10}	C_5H_{12}	N_2	CH_4	CO_2	C_2H_6
Molecular weight	86.17	44.09	58.12	72.15	28.01	16.04	44.01	30.07
LHV, kJ/gram	45.1	46.36	45.72	45.35	0	50.01	0	47.49
HHV,	46.68	50.35	49.50	49.01	0	55.50	0	51.88

Component	Hexane	Propane	Butane	Pentane	Nitrogen	Methane	Carbon dioxide	Ethane
kJ/gram								

Source: http://gatorpwr.che.ufl.edu/cogen/measurements/reports/nat_gas.html

Glossary of Units, Explanations and Abbreviations

Abbreviated Units

Abbreviation	Verso	Explanation
kg	kilogram	one kilogram is today defined by a quantum effect in the old days by a standard mass stored in Paris
m	metre	one metre is today defined as the number of wavelengths of light of a specific frequency
s	second	one second is today defined via the metre
N	Newton	one Newton is equivalent to a mass of one kilogram that is accelerating at one metre per second squared
J	joule	one joule is equivalent to a mass of one kilogram moving one metre while accelerating at one metre per second squared
W	watt	one watt is one joule per second
kWh	kilowatthour	one kilowatthour is the power of one watt over one hour, *i.e.* 3.6 10^6 joule
W / cap	watt per capita	one W/cap is equivalent to an average energy consumption of one watt, resulting in 8.76 kWh or 31.536 MJ per year.
GWy	gigawattyear	one GWy is the power of 1 GW over the period of 1 year, *i.e.* is equivalent to: 8.76 TWh, 31.536 PJ, 7.53 Pcal, or 753.2 ktoe.
K	Kelvin	Kelvin is the basis of the so-called absolute (or physical) temperature scale. 0 °C is equivalent to 273.15 K, 100 °C to 373.15 K.

Typical Non-SI Values

Abbreviation	Verso	Numero
toe	tonne of oil equivalent	41.87 GJ
tce	tonne of coal equivalent	29.18 GJ
tce	tonne of coal equivalent	0.697 toe
	energy content of one barrel crude oil	5.83 GJ
	energy content of one tonne charcoal	28.90 GJ
	energy content of one tonne charcoal	0.986 tce
	energy content of one tonne wood@2 5%rH	13.46 GJ
	energy content of one m^3 wood	9.76 GJ
	weight of one m^3 wood	0.725 t
	energy content of one tonne <u>dry</u> wood	18.3 GJ
DWT	dead weight tonne	
NWT	net weight tonne	
BRT	brutto registered tonnage	
bl	barrel	0.159 m^3
cal	calorie	0.239 J
Btu	British thermal unit	1055 J
quad	quad (quadrillion Btu)	$1.055 \cdot 10^{18}$ J
bar	Bar	c. 100 kPa
knot	one nautical mile per hour	1.852 km h^{-1}
nm	nautical mile (=equator / 360·60')	1.852 km
GtC	gigatonne Carbon	3.67 Gt CO_2
mile	international mile	1.609 km

Notes:
Wood: at a moisture content of 20 to 30 per cent.

Affixes and Suffices

Abbreviation	Verso	Numero	Normal English Expression
k	kilo	10^3	thousand
M	mega	10^6	million
G	giga	10^9	billion
T	tera	10^{12}	trillion
P	peta	10^{15}	quadrillion
E	exa	10^{18}	quintillion
m	milli	10^{-3}	one thousandth
μ	micro	10^{-6}	one millionth
n	nano	10^{-9}	one billionth
p	pico	10^{-12}	one trillionth
f	femto	10^{-15}	one quadrillionth
a	atto	10^{-18}	one quintillionth
da	deca	10^1	ten
h	hecto	10^2	hundred
d	deci	10^{-1}	one tenth
c	centi	10^{-2}	one hundredth

Note: The old English expression for 10^9, "milliard", has been neglected and surpassed by the "billion" stemming from US American.

General Abbreviations

Abbreviation	Verso
$	reads: US Dollar, base year about 1990
3-D	Three (3) Dimensional
ABB	Asea Brown Boveri
AC	Alternating Current, symbol: ~
AEEI	Autonomous Energy Efficiency Index
AEEI	Autonomous Energy Efficiency Improvement
ANS	Alaska North Slope
ANWR	Arctic National Wildlife Refuge
AO/P	Additional Occurrences to Production ratio (in years)
AS	Air Separation
ASU	Air Separation Unit
austral	refering to the Southern Hemisphere
boreal	refering to the Northern Hemisphere
BRT	brutto registered tonnage
CC	Combined Cycle
CFL	Compact Fluorescent Lamp
CFS	Clean Fossil Scenario
CH_4	methane (a greenhouse gas, but also making up natural gas)
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide (one important greenhouse gas)
CR	CO_2 Recovery
DC	Direct Current, symbol: –
DC	Developing Country
DEA	Danish Energy Agency
DME	Direct Market Economies
dollar	reads: US Dollar, base year about 1990

Abbreviation	Verso
DWT	Dead Weight Tonne
EC	European Communities (until 1994)
ECU	European Currency Unit
EGR	Enhanced Gas Recovery
EOR	Enhanced Oil Recovery
EU	European Union (from 1995 onwards)
Euro	Successor of the ECU, about 1.25 $
ExternE	Research project of the EU on Externalities of Energy Systems
FC	Fuel Cell
FCCC	Fuel Cell Combined Cycle
FCCC	UN Framework Convention on Climate Change
FDI	Foreign Direct Investment
FGD	Flue Gas Desulphurisation
GATT	General Agreement of Tariffs and Trade
GBS	Gravity Base Structure
GDP	Gross Domestic Product
GHE	GreenHouse Effect (radiative forcing of the climate system)
GHG	GreenHouse Gas (able to absorb infrared radiation)
GNP	Gross National Product
GT	Gas Turbine
GtC	GigaTonnes Carbon (=3.67 billion tonnes of CO_2)
HAT	Humid Air Turbine
HHV	Higher Heating Value (taking into account the latent vapour heat)
HP	Heat Pump
HRSG	Heat Recovery and Steam Generation
HTG	High Temperature Gas Cleaning
HVAC	Heating, Ventilation And Cooling
I	electrical Current (Ampere)
IAEA	International Atomic Energy Agency
ICG	In situ Coal Gasification
ICs	Industrialised Countries
IEA	International Energy Agency
IGCC	Integrated coal Gasification Combined Cycle
IGMCFC	Integrated Gasification MCFC power station
IGO	Inter-Governmental Organisation
IIASA	International Institute for Applied Systems Analysis
ILO	International Labour Organisation
IPAT	Impact = Population · Affluence · Technology
IPCC	UN&WMO International Panel on Climate Change
IV	Interview
LCA	Life Cycle Analysis
LCO_2	Liquid CO_2
LCC	Large Crude Carrier
LDC	Less Developed Country
LH_2	Liquefied Hydrogen
LHV	Lower Heat Value (*i.e.* without water vapour's latent heat)
LNG	Liquefied Natural Gas
MCFC	Molten Carbonate Fuel Cell
MEA	MonoEthanolAmine
MOIP	Mandatory Oil Import Program
NCW	Non-Communist World
NG	Natural Gas
NGL	Natural Gas Liquid
NGO	Non-Governmental Organisation
NIC	Newly Industrialised Country

Abbreviation	Verso
NIE	Newly Industrialised Economy
Nm^3	Normal cubic metre (@ 293 K, 1013 hPa)
NWT	Net Weight Tonne
OAPEC	Organisation of Arab Petroleum Exporting Countries
OCS	Outer Continental Shelf
OE	Oil Equivalents
OECD	Organisation for Economical Co-Operation and Development
OHT	Ocean Heat Technology
OPEC	Organisation of Petroleum Exporting Countries
PAT	Population · Affluence · Technology
PEMFC	Proton Exchange Menbrane Fuel Cell
PF	Pulverised Coal
PFB	Pressurized Fluid Bed
PPCR	Power Plant with CO_2 Recovery
PPP	Purchasing Power Parity
R&D	Research and Development
R/P	Reserve over annual Production ratio (in years)
RB/P	Resource Base to Production ratio (in years)
ROW	Rest of the World
SMR	Steam-Methane Reforming
T&D	Transmission and Distribution
TEMAPS	Theoretical Maximum Physical Stock
TLP	Tension Leg Platform
U	electrical Voltage (Volt)
UCG	underground coal gasification
UN	United Nations
USC	Ultra Super-Critical steam cycles
VLCC	Very Large Crude Carriers
VSP	Vertical Seismic Profiles
WEC	World Energy Council
WMO	World Meteorological Organisation (Geneve)
WPC	World Petroleum Congress
WRI	World Resources Institute Washington, DC/US
WTO	World Trade Organisation (the sequel of GATT)

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af: Peder Voetmann Christiansen

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af: Maria Hermannsson, Sebastian Horst, Christina Specht

Vejledere: Jeppe Dyre og Peder Voetmann Christiansen

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Et matematisk modelprojekt

af: Claus Dræby, Michael Hansen, Tomas Højgård Jensen

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af: Glenn Møller-Holst, Marina Johannessen, Birthe Nielsen og Bettina Sørensen

Vejleder: Jesper Larsen

302/95 KOMPRESSORER - Analyse af en matematisk model for aksialkompressorer

Projektrapport sf: Stine Bøggild, Jakob Hilmer, Pernille Postgaard

Vejleder: Viggo Andreasen

303/95 Masterlignings-modeller af Glasovergangen

Termisk-Mekanisk Relaksation

Specialerapport udarbejdet af:

Johannes K. Nielsen, Klaus Dahl Jensen

Vejledere: Jeppe C. Dyre, Jørgen Larsen

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304b/95 STATISTIKNOTER Simple normalfordelingsmodeller

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304c/95 STATISTIKNOTER Simple Poissonfordelingsmodeller

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af: Marianne Wilcken Bjerregaard,
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Vejledere: Peder Voetmann Christiansen og
Petr Viscor

309/95 Tiden og Tanken
En undersøgelse af begrebsverdenen Matematik
udført ved hjælp af en analogi med tid

af: Anita Stark og Randi Petersen

Vejleder: Bernhelm Booss-Bavnbek

310/96 Kursusmateriale til "Lineære strukturer fra
algebra og analyse" (E1)

af: Mogens Brun Heefelt

311/96 2nd Annual Report from the project
LIFE-CYCLE ANALYSIS OF THE TOTAL DANISH
ENERGY SYSTEM

by: Hélène Connor-Lajambe, Bernd Kuemmel,
Stefan Krüger Nielsen, Bent Sørensen

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by: B. Booss-Bavnbek, K.P.Wojciechowski

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THE OPENNESS OF THE FUTURE
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By: Helmut Pape, University of Hannover

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Cardiovascular System

By: Johnny T. Ottesen

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et manuskript til en fjernsynsudsendelse
+ manuskript

af: Gunhild Hune og Karina Goyle

Vejledere: Peder Voetmann Christiansen og
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Specialerapport af: Peter Meibom, Mikko Østergård
Vejledere: Jeppe Dyre & Jørn Borggreen

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af: Ulla Rasmussen
Vejleder: Anders Madsen

318/96 Modelling the Respiratory System
by: Tine Guldager Christiansen, Claus Dræby
Supervisors: Viggo Andreasen, Michael Danielsen

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Impacts

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325/96 Retorik eller realitet ?
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Specialerapport af Helle Pilemann
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326/96 Bevisteori
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af: Gitte Andersen, Lise Mariane Jeppesen,
Klaus Frovin Jørgensen, Ivar Peter Zeck

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