

**THE LONG TERM
POTENTIAL
OF FUSION POWER IN
WESTERN EUROPE**
MARKAL scenarios until 2100

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Preface

ECN Policy Studies has carried out the present study under a contract of the European Union, DG XII, the Dutch Ministry of Economic Affairs, and the Dutch Ministry of Education, Culture and Science. The ECN project number is 7.7119.

We were encouraged by the stimulating discussions and comments, especially at the SEO Workshop on 25-26 May 1998 at ECN, Petten, attended by P.V. Gilli, P.E. Grohnheit, G. Kolb, J. Lemming and B. Villeneuve.

Abstract

The present study focuses on the potential of fusion power in Europe in the 21st century. The study includes two scenarios and more than 60 scenario variants. In the scenario variants the assumptions with respect to CO₂ policy, fossil fuel availability, discount rates, and characteristics of fusion power and competing technologies have been varied. The model used is a MARKAL model of the Western European energy system.

Fusion power is not cost effective in the absence of CO₂ policy, as its generating costs are higher than those of coal-fired power and fission power. Fusion power comes out as a cost-effective option in case of CO₂ reduction policies. Under such circumstances coal-fired power loses market share. Fusion power starts to become economically attractive at marginal cost levels between 32 and 67 ECU/tCO₂. The economic potential of fusion power appears to be relatively insensitive to changes in assumptions with respect to competing technologies and fusion power itself, as well as availability of natural gas, and discount rate. Fusion power is not indispensable to obtain substantial CO₂ reduction, if need would be.

However, it is difficult to indicate alternatives to fusion power. Experience with fission power as we know it today has been troublesome. Technical breakthroughs that would simultaneously solve the issues of safety, hazards of actinides, and risk of proliferation are to be awaited. Coal-fired power with CO₂ separation and geological sequestration is not yet a full-grown option. Due to depletion of fossil fuel resources and scarcity of cheap geological CO₂ sequestration, it will not be a lasting alternative to fusion power.

Renewables - hydro, biomass, wind, photovoltaic power - could make substantial inroads in the power generation market. However, wind and solar energy are intermittent energy sources, which cannot substitute base-load power options like fusion power.

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SUMMARY

The European Commission wishes more insight in the potential role of fusion power in the second half of the 21st century. Therefore, several scenario studies are carried out in the so-called macro task Long Term Scenarios (SE0) to investigate the potential of fusion power in the energy system. The main contribution of ECN to the macro task Long Term Scenarios is to perform a long term energy scenario study for Western Europe with special focus on the role of fusion power, and based on two main scenarios until 2100.

There are various reasons for constructing new energy scenarios (in addition to existing scenarios) to analyse the prospects of fusion power. First, the existing long term scenarios have not been designed with the aim to analyse fusion power. Instead, the objective of those studies was to explore future developments of the entire energy system, and in part of these studies fusion power has been considered as only one of many power generation options. Second, the existing long term scenario studies only included scenarios with a limited range of values for a number of vital inputs. Preferably, scenarios/variants should be analysed in large numbers and for a range of conditions. Third, existing long term scenario studies have focused too much on the entire world and they provided too little detail on 'regional' energy systems (Europe).

This study of the economic potential of fusion power in Western Europe in the 21st century is based on a technology oriented model for Western Europe. The contents of the study are as follows:

1. methodology and scenario design,
2. key parameters of scenarios,
3. results of two scenarios without CO₂ constraints,
4. results of scenario variants with CO₂ policy and various discount rates,
5. additional sensitivity analysis,
6. discussion,
7. conclusions and recommendations.

First focus is on the methodology. For this study the technology oriented optimization model MARKAL-EUROPE has been used. This model covers the period 1990-2100 and it includes over 400 demand technology applications and approximately 100 supply technologies. Special attention has been given to methodological issues related to the time horizon until the year 2100:

1. Technology assumptions are primarily based on detailed estimates, learning effects, and expert opinions included in studies of colleague institutes and other studies.
2. The issue of discounting has been dealt with in the following way:
 - A discount rate based on the social rate of time preference for inter-generational decisions. A relatively low discount rate of 2.5% per year governs the depletion of fossil fuel resources and cumulative CO₂ emissions from 1990 to 2100.
 - A higher interest rate is considered appropriate for energy investment decisions, viz. from 5 to 8 and 10% per year for power generation.
 - One scenario applies end-use specific discount rates (between 10 and 25%) to account for hurdles in the uptake of energy conservation measures.
3. Climate change is driven by the increased concentration levels of greenhouse gases. With a cumulative emission budget the timing of emission reduction can be optimised. Stabilisation levels for CO₂ in the year 2100 (e.g. 450, 550, 650 and 750 ppm) can be translated into cumulative CO₂ emission budgets for Western Europe.

It should be noted that investment decisions at one moment in time are mainly governed by the discount rate of 5, 8 or 10% used for the depreciation of the investment cost of a power generation technology. For the total period 1990-2100 the low discount rate of 2.5% per year governs the depletion of fossil fuels and - if applicable - the CO₂ emission (if it is constrained).

Secondly, the study addresses key parameters of scenarios. One parameter is the fossil fuel resource base: proven, probable and possible reserves. For conventional and unconventional oil the reserve/production ratio is 130 years, for gas 190 years and for coal (only reserves) 220 years. It is assumed that 10.5% of global fossil fuel resources is available to Western Europe (Table S.1). In the ‘high demand’ scenario this figure is 15%.

Table S.1 Reference fossil fuel availability for Western Europe, 1990-2100 [EJ]

	Conv. Oil	Tar sands and extra heavy oils	Oil shale	Conv. Gas	Unconv. Gas	Coal
Indigenous	353	46	54	552		1,682
Import	576	601	131	560	606	648
Total	929	647	185	1,112	606	2,330

Another key parameter is fossil fuel prices. Price trends for heavy crude oil are determined for two scenarios (Figure S.1). These prices have been translated into natural gas prices for power generation. The price trends are based on a number of considerations:

- Imported hard coal rises with 0.35% per year until 2050, and stabilises after that¹.
- Prices of heavy crude oil differ for the two scenarios. *Rational Perspective* (RP), which has a low energy demand, shows an oil price ending up at \$ 25/bbl in 2100.
- Scenario *Market Drive* (MD), the ‘high demand’ scenario requires higher oil prices. After a peak in 2050, heavy crude oil ends up at \$ 29.5/bbl in 2100.

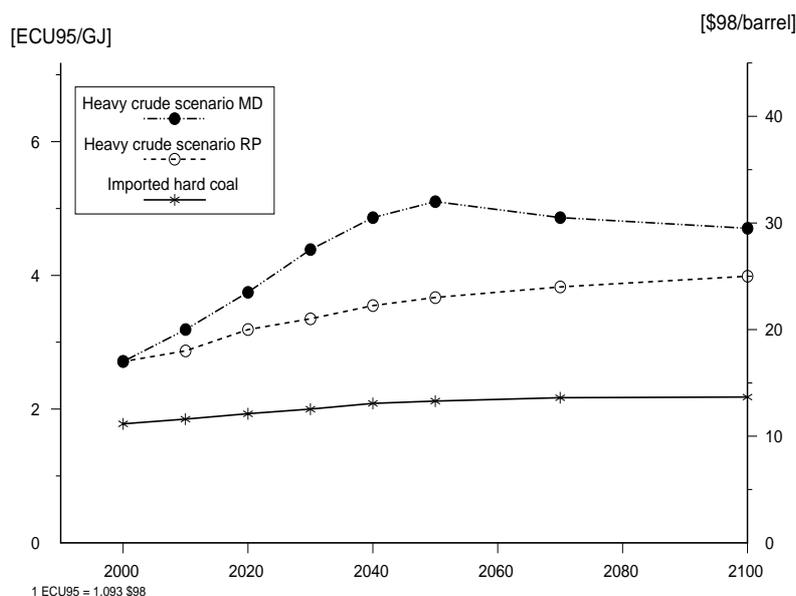


Figure S.1 Heavy crude oil prices and coal price for two scenarios

As the third step, the two scenarios used throughout this study are addressed. Table S.2 presents characteristic differences in key parameters of these scenarios.

¹ Such low coal prices can only occur if coal demand is low, e.g. due to CO₂ policies.

Table S.2 *Key differences between scenarios Rational Perspective and Market Drive*

	Rational Perspective (RP)	Market Drive (MD)
Decision criteria	Uniform 5% discount rate for all energy decisions across all sectors	8% discount rate for power generation, higher discount rates for end use
Energy demand	Generally lower than in MD	Generally higher than in RP
Availability of fossil fuels for Western Europe	10.5% of world's resources of coal, oil, and natural gas	15% of world's resources of coal, oil, and natural gas
Energy prices	Oil price increases slowly until 2100, \$ 25/bbl in 2100	Oil price increases fast, peaking in 2050, \$ 29.5/bbl in 2100
Fission power	Maximum capacity declining to 70% of current capacity in 2070 and declining further after that	Maximum capacity declining to 80% of current capacity in 2070 and declining further after that

Further, foresights have been made of the development with respect to cost and performance of fusion power and other technologies for power generation. The investment cost of fusion power is about ECU 300/kW in 2100, as comes up from one of the studies contributing to macro task SEØ.

Rational Perspective can be characterised as the ecologically driven scenario of the two. The process of politically driven global economic integration will lead to more collective public action in this scenario. International co-operation will be more efficient in order to deal with complex shared problems. Strong penetration of new, more efficient demand and supply technologies is facilitated. This strong penetration will be achieved by setting efficiency standards, removing existing barriers for the introduction of efficient technologies and active energy service companies carrying out cost-effective efficiency improvements for end-users.

Market Drive is the market driven scenario. In this scenario the market mechanism is seen as the best way to generate prosperity and handle complexity in uncertainty. The penetration of new, more efficient demand and supply technologies totally depends on market forces and the behaviour of the actors involved. The environmental protection agenda is also set by the market and thus not by public policy. Moreover, energy policy is driven by the desire to minimise government control and to maximise efficient operation of free markets. Barriers will persist in the uptake of efficient equipment. Efficiency gains will only be made for competitive reasons.

The two main scenarios are first analysed without CO₂ constraint (base case). The resulting power generation mix for both base case scenarios is shown in Figure S.2.

In the absence of CO₂ reduction policies, fossil fuels are favoured for power generation. In both scenario's gas-fired power grows strongly until 2040. From 2030 onwards coal gets a competitive edge over gas-fired power in scenario MD, due to relatively high gas prices. In scenario RP this transition occurs in 2050. Fission energy declines slowly until 2050 in scenario RP (this scenario has a uniform discount rate of 5%). Under the more severe conditions of scenario MD (discount rate for power generation is 8%), fission power is almost phased out in 2030. A recovery occurs not earlier than in 2070. New renewables - wind, biomass, PV - show a modest market share under these circumstances. This is because part of them (offshore, wind, PV in central and northern Europe) is not competitive under these circumstances.

As fusion power is rather costly, it cannot compete with alternative base-load power options in the absence of CO₂ policies. Therefore, irrespective of the discount rate used, fusion power needs some incentive such as a cumulative CO₂ constraint in order to become competitive to coal-fired power. Total CO₂ emissions for both scenarios are shown in Figure S.3.

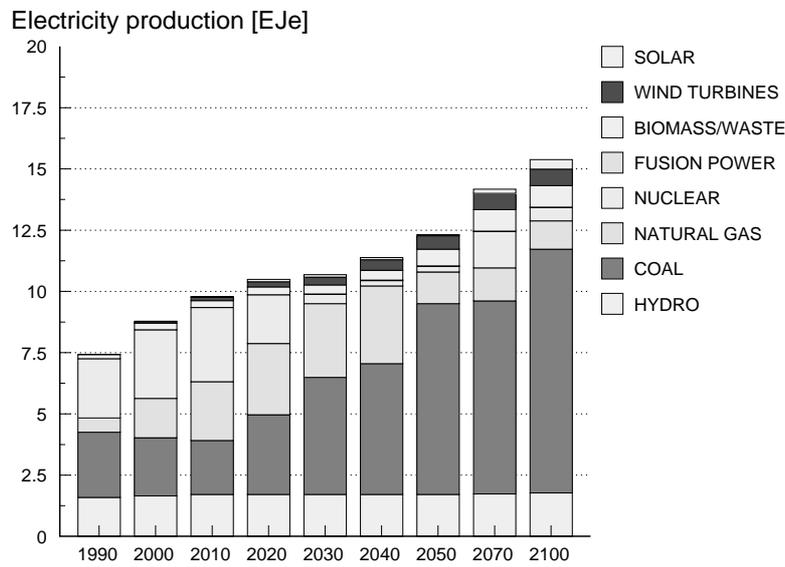
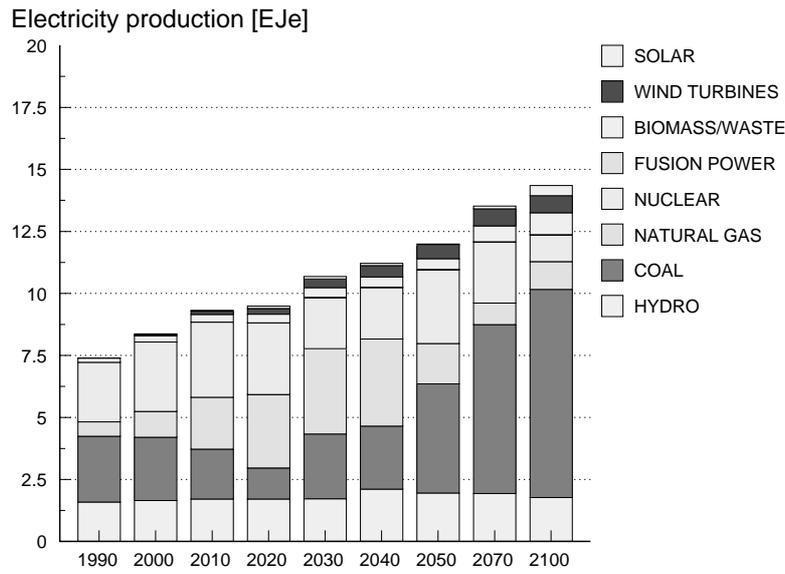


Figure S.2 Power generation by source for the base cases of Rational Perspective (top) and Market Drive (bottom)

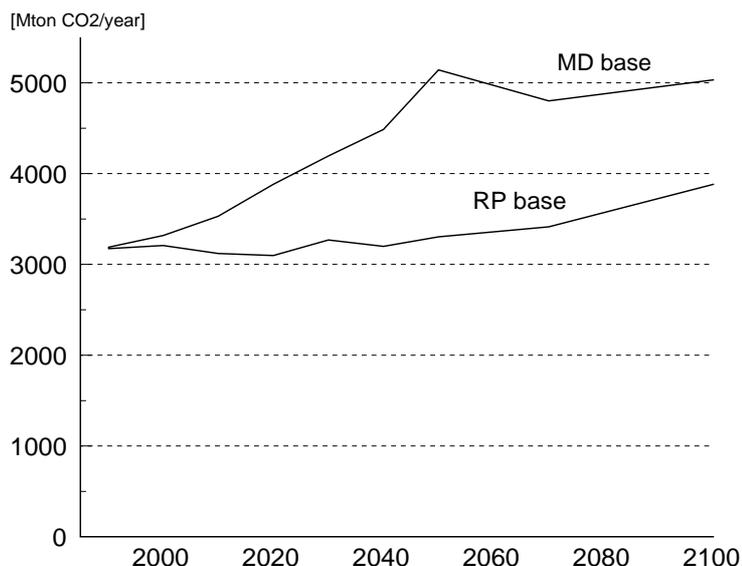


Figure S.3 *Western European CO₂ emissions, base case scenarios Rational Perspective (bottom) and Market Drive (top)*

CO₂ emissions are closely related to fossil fuel consumption. In scenario RP fossil fuel consumption is stable and changes in the fossil fuel mix are small until 2050. Therefore, CO₂ emission remains stable until 2050 (Figure S.3). After 2050, coal consumption increases at the expense of oil use. Consequently, CO₂ emission increases slowly after 2050. In 2100 CO₂ emission is 20% higher than in 1990.

In scenario MD fossil fuel consumption rises until 2050. After that date, fossil fuel consumption declines, whereas the contribution from new renewables increases. Fission power shows a (second) peak around 2070. Coal consumption surges from 2020. Therefore, the CO₂ emission increases until 2050, and remains more or less stable after that date. In 2100 the CO₂ emission is 60% higher than in 1990.

The fourth step is the analysis of CO₂ reduction variants. In order to analyse the potential of fusion power under circumstances of constrained CO₂ emission, several cumulative CO₂ emission budgets for Western Europe have been defined that correspond to various levels of global stabilisation of CO₂ concentration, viz. from 450 ppm to 750 ppm (Figure S.4).

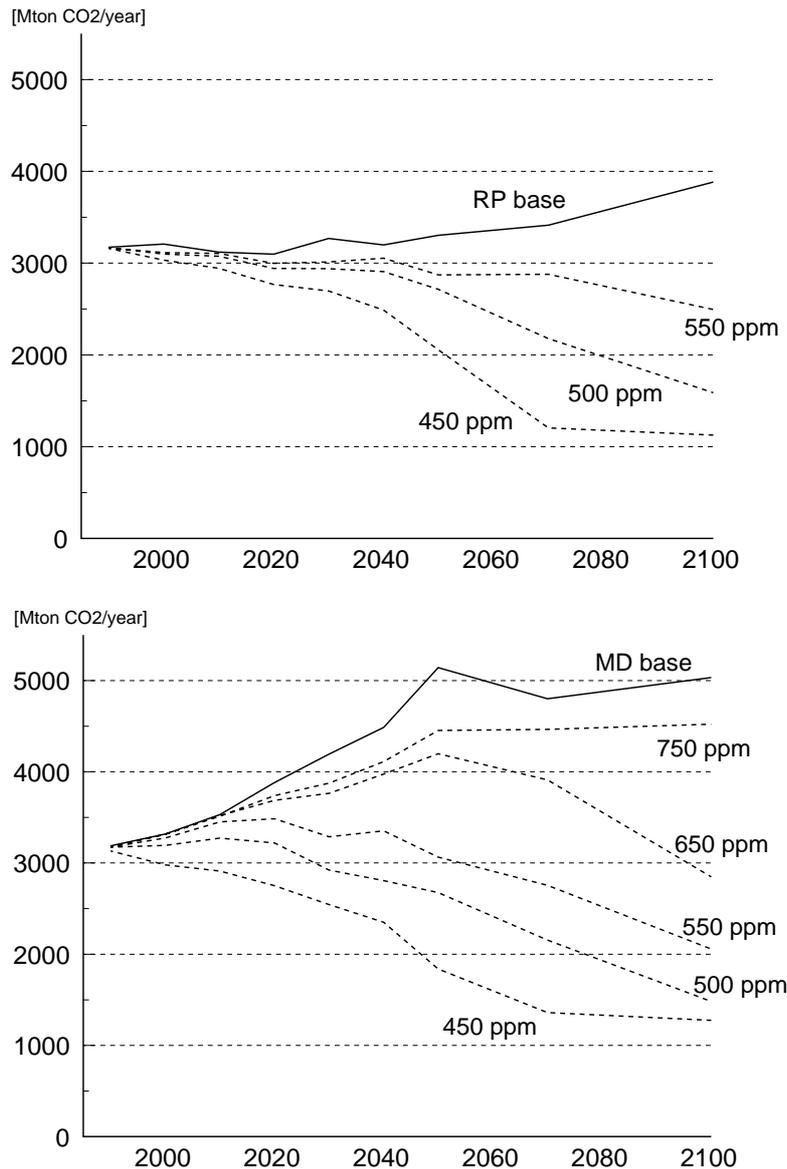


Figure S.4 *Western European CO₂ emissions, CO₂ variants scenarios Rational Perspective (top) and Market Drive (bottom)*

As the unconstrained CO₂ emission of scenario RP is almost equal to the 650 ppm level, only the CO₂ reduction cases 550 ppm, 500 ppm, and 450 ppm are shown. CO₂ emission in the unconstrained MD scenario is higher than any of the emission levels contemplated. Figure S.5 shows the consequences of increasing CO₂ constraints for the power generation mix in 2100 in case of scenario RP and scenario MD respectively.

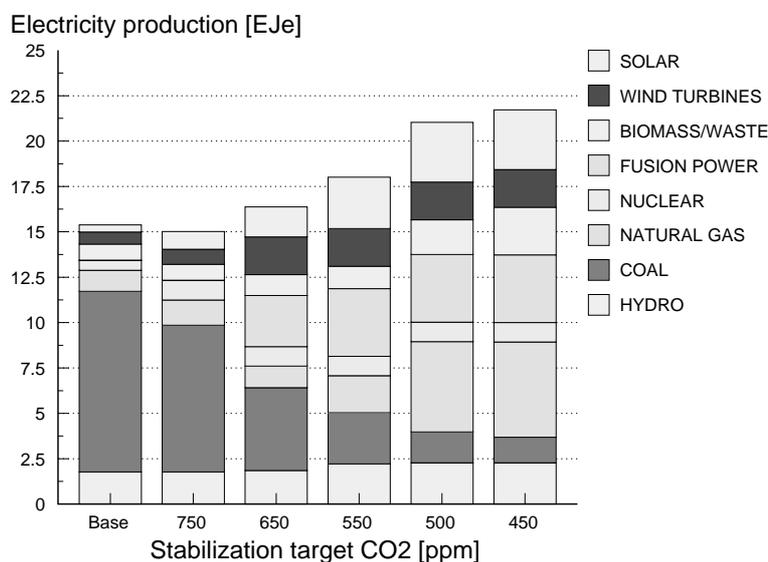
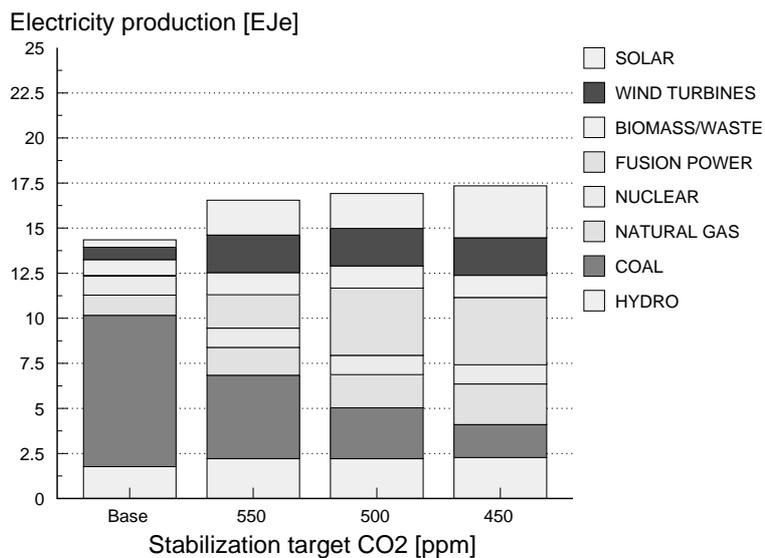


Figure S.5 Power generation by source for the CO₂ variants of scenario *Rational Perspective* (top) and *Market Drive* (bottom), year 2100

Starting with scenario RP, and going from 550 ppm down to 450 ppm, the following trends can be noted:

- At 550 ppm (slightly decreasing CO₂ emission in Western Europe) fusion power obtains a share in power generation which is somewhat larger than that of fission energy (which is at its upper bound), biomass-fuelled power, and gas-fired power, and comparable with the share of solar power, wind power and hydro power (including wave energy and tidal energy). Coal-fired power remains the main power source.
- At 500 ppm fusion power is maximised to about 160 GW at the expense of coal-fired power.
- At 450 ppm fusion power remains at its maximum level, whereas gas-fired power and solar power show increased output at the expense of coal-fired power. The remaining coal-fired power in case of stringent CO₂ reduction is equipped with CO₂ separation and geological sequestration.

In case of the CO₂ variants of scenario MD the following trends can be observed:

- At 650 ppm (slightly increasing CO₂ emission in Western Europe) fusion power gets a share in power generation which is twice the share of fission energy, biomass-fuelled power, and gas-fired power, and larger than that of solar power, hydro power and wind power. Coal-fired power remains the main power source.
- At 550 ppm fusion power is maximised at the expense of coal-fired power. Also tidal power, solar power, and gas-fired power show some increase.
- At 500 and 450 ppm fusion power remains at its maximum, whereas gas-fired power and solar power show increasing output at the expense of coal-fired power.

Generally, fusion power starts to be introduced at a marginal CO₂ reduction cost of some ECU 30/t CO₂. Only if a larger potential is assumed for fission power (see below) the marginal CO₂ reduction cost is higher than ECU 30/t CO₂.

As the fifth and last step, a sensitivity analysis was carried out for the following cases:

- Scenario RP with discount rate 8% (the set of discount rates of scenario MD),
- Scenario RP with discount rate 10%,
- Scenario RP with phase-out of fission energy,
- Scenario RP with high availability of fossil fuels (15% of global resources, like MD),
- Scenario MD with discount rate 5% (as in scenario RP),
- Scenario MD with high investment cost of fusion power (20% higher),
- Scenario MD with a high potential of renewable energy,
- Scenario MD with high upper limit for fission energy (200 GW).

The installed fusion power capacity for the sensitivity cases as well as for the 'normal' CO₂ variants for the years 2070 and 2100 is shown in Table S.3 and S.4 respectively.

Table S.3 *Installed fusion power, CO₂ variants and sensitivity cases, year 2070 (GW)*

Scenario	Case	650 ppm	550 ppm	500 ppm	450 ppm
RP		×		12.8	57.4
RP	Disc. Rate 8%	×		12.8	57.4
RP	Disc. Rate 10%	×	9.5	47.6	58.9
RP	Phase out of fission	×	1.9	12.8	57.4
RP	High Fossil Fuel Avail.	×		1.9	57.4
MD		1.9	47.8	57.4	58.9
MD	Disc. Rate 5%		12.8	57.4	58.9
MD	High cost fusion		37.0	57.4	58.9
MD	High Potent. Renew.			1.9	12.8
MD	High Potential Fission		12.8	57.4	58.9

¹ × means the unconstrained RP scenario is roughly comparable with the 650 ppm level.

Table S.4 *Installed fusion power, CO₂ variants and sensitivity cases, year 2100 (GW)*

Scenario	Case	650 ppm	550 ppm	500 ppm	450 ppm
RP		×	78.4	157.5	157.5
RP	Disc. Rate 8%	×	102.3	157.5	157.5
RP	Disc. Rate 10%	×	140.3	157.5	157.5
RP	Phase out of fission	×	119.3	157.5	157.5
RP	High Fossil Fuel Avail.	×		119.3	157.5
MD		119.3	157.5	157.5	157.5
MD	Disc. Rate 5%	69.8	157.5	157.5	157.5
MD	High cost fusion	56.5	157.5	157.5	157.5
MD	High Potent. Renew.		83.0	119.3	157.5
MD	High Potential Fission	8.3	157.5	157.5	157.5

¹ × means the unconstrained RP scenario is roughly comparable with the 650 ppm level.

The main results from the scenario variants and sensitivity cases are as follows:

1. Scenario MD is more demanding from the point of view of CO₂ reduction than scenario RP. Therefore, fusion power capacity is higher in case of a 'moderate' CO₂ emission level of 550 ppm in scenario MD than in scenario RP.
2. In the 550 ppm CO₂ reduction case of RP, fusion power capacity is 78 GW in 2100, about half the maximum level in the most stringent CO₂ reduction cases. If the discount rates of scenario MD (8% discount rate for power generation) are substituted for the 5% discount rate of RP, fusion power capacity rises to 102 GW. If the discount rate is increased to 10%, the capacity rises further to 140 GW. This is because some renewable options - notably solar power in the northern part of Western Europe - have a high capital cost component in their generation cost, whereas fusion power has both high capital cost and high replacement cost (diverter, blanket, and first wall). Capital costs depend on the discount rate used, but replacement costs not. The variation of discount rates shows that fusion power is able to compete at both 5% and 8% discount rate, presuming there is some cumulative CO₂ constraint.
3. A 20% higher level of investment cost for fusion power (thus 20% more than the default of ECU 3000/kW) does not mean a large difference in competitiveness. In the 'normal' 650 ppm CO₂ reduction case of MD, fusion power capacity in 2100 is 119 GW. In case of 20% higher investment cost fusion power capacity shrinks to 56 GW in 2100. This case shows that a somewhat higher investment cost level is not very detrimental to the economic potential of fusion power.
4. If scenario RP is combined with the ample availability of fossil fuels of scenario MD (15% of global fossil fuel resources), fusion power loses competition with gas-fired power in the 550 ppm CO₂ reduction case of RP. However, it remains an economically viable option at 500 and 450 ppm. This case shows that availability of oil and natural gas to a certain extent affects the competitiveness of fusion power.
5. If a high potential of renewables is assumed for MD, fusion power is not competitive in the 650 ppm CO₂ reduction case. In the 550 and 500 ppm CO₂ reduction cases fusion power loses 47% and 24% respectively of its original market share in 2100. However, a high potential of renewables is more threatening to coal- and gas-fired power than to fusion power (at stringent CO₂ reduction targets).
6. The potential of fusion power is rather insensitive to the development of fission power. In case of an RP scenario variant with a phase-out of fission power, fusion power profits in the 650 ppm case (from 78GW to 119 GW in 2100). In the MD scenario variant with an upper bound of 200 GW for fission power, fusion power only suffers in the 650 ppm case (from 119 GW to 8 GW). In that case fusion power is introduced at a cost of ECU 67/t CO₂, which clearly indicates that competition is fierce.

Another set of calculations concerns scenario variants in which it is assumed that fusion power is not available. Equal CO₂ stabilisation levels can be attained in that case, albeit at higher costs. As the CO₂ bound is a cumulative constraint, deeper CO₂ reductions in the first half of the 21st century (when fusion power is not available anyhow) would make natural gas available for gas-fired power as a substitute for fusion power.

It is difficult to indicate clear alternatives to fusion power. Experience with fission power as we know it today has been troublesome. Technical breakthroughs that would simultaneously solve the issues of safety, hazards of actinides, and risk of proliferation are to be awaited. Compared to the IIASA-WEC study (1995), the present study gives less credit to a careless future for fission power. Coal-fired power with CO₂ separation and geological sequestration is not yet a full-grown option. Due to depletion of fossil fuel resources and scarcity of cheap geological CO₂ sequestration opportunities, it will not be a lasting alternative to fusion power, certainly not in the 22nd century.²

² CO₂ sequestration in the Atlantic Ocean has not been taken into account due to lack of information and presumed lack of public acceptance.

Renewables - hydro, wind, biomass fuelled power, photovoltaic power - are able to make substantial inroads in the power generation market. However, wind and solar energy are intermittent energy sources that cannot substitute base-load power such as fusion power. In addition to renewables, fusion power is one of the few CO₂ free and virtually inexhaustible energy options that could become available. Fusion power could become an economically viable power generation option under conditions that could prevail in 21st century.

1. INTRODUCTION

1.1 Background

Fusion energy research has made remarkable but not always widely noticed progress in the last forty years. Such progress is very important because of the enormous long term potential (beyond 2050) of fusion power. However, it is a prerequisite, not a warrant for commercial fusion power. During the next decades, substantial investments are needed in order to develop, demonstrate and eventually commercialise fusion power, starting with the next experimental fusion reactor ITER. If decisions with large financial consequences are at stake, it could be worthwhile to reconsider the motives for the development of fusion power. Under these circumstances a programme of socio-economic research on fusion energy (SERF) has been adopted by the European Union (DG XII). The European Commission requests an analysis of the potential role of fusion energy in the second half of the 21st century. Within this programme the following Macro tasks are carried out:

- Long term scenarios (SE0)
- Production costs (E1)
- External costs and benefits (E2)
- Fusion as a large technical system (S1)
- Fusion and the public opinion (S2).

This report of ECN serves as a kind of synthesis and is the follow-up of an interim report on the role of fusion power in energy scenarios (April 1998) [1]. In that report the method for analysing fusion power's economic potential is also presented. Both the present study and the interim report contribute to Macro task SE0, as do the (ensuing) studies from the following institutes:

- Arge Wärmetechnik, Graz, Austria [2]
- FZ Jülich, Germany
- Risø, Denmark
- CEA-Lemme, Toulouse.

The present study is considered to be a synthesis, as it draws on the ideas and insights of the interim report and on the results of studies of other institutes, such as the above mentioned. Both a comprehensive analysis of all SE0 contributions as well as a vision of and conclusions based on that analysis are due for publication in early 1999, similar to reports covering the other Macro tasks and an executive summary of the whole SERF programme.

1.2 Rationale

A main issue is how fusion power could fit in the whole group of future energy options. The history of fusion energy research goes back as far as 1958 [3]. Despite impressive progress in scientific and technical respect since that early date, this highly complex technology will need another fifty years of research, development and demonstration before it could eventually transit to the commercial stage. After having passed that trajectory successfully, fusion power could gradually displace established power generation options like coal-fired power and fission power (Light Water Reactor, LWR). The uncertainties and long time scale involved in the development of fusion energy could explain why fusion power is not always contemplated in long term energy scenarios. However, in energy scenarios with a time horizon of 2100 from reputed institutes like IASA (1995) [4] and IPCC (1996) [5] fusion power gets little attention as well, as set out in the interim report of ECN. The limited attention is mainly due to the fact that it has to be demonstrated that fusion power is technically feasible. Other technologies such as fuel cells and solar cells are technically proven. It is no longer questioned whether these technologies could become commercially available, merely when and to what extent they could capture the market.

Focusing on long term energy scenario studies, one could wonder what type of questions are addressed by those studies. Growth of world population is a key issue. Population growth in developing countries will remain high for decades. The world population will increase from 6 billion people in 1999 to 8 billion in 2025 and about 11 billion in 2050 and beyond (probably within a range of 8 to 13 billion). Population growth and economic growth are important driving forces for global energy demand. The most pressing environmental issue in the long term could be the risk of global warming due to large scale fossil fuel combustion. Next to global warming is the issue of the depletion of fossil fuel resources.

Depletion of fossil fuel resources is more urgent for oil and gas than for the world's abundant coal resources. Oil and gas production could be at risk for a number of reasons:

- Development of unconventional oil and gas resources could require massive investments. In this period of 'rock-bottom' oil prices, the problems that should be anticipated in case of a relatively rapid drain of cheap oil and gas resources are often overlooked.
- A shift in oil production from industrialised countries to countries in the Middle East in the course of the next century could result in significant political risks. The same could eventually hold for natural gas, which is also unevenly distributed over the globe.
- The issues of global warming and depletion of oil and gas resources are concerned with the same time scale (21st century) and are also interrelated. On the one hand, firm CO₂ reduction policies could slow down the growth of fossil fuel consumption and at the same time temporarily postpone depletion of fossil fuel resources. On the other hand a substantial switch from coal to natural gas as power station fuel, due to concern about global warming, could result in supply problems and price escalation for natural gas.

Some trends are particularly strong. The world population will increase considerably in the next century. Energy demand will continue to grow due to population growth and economic growth. In view of these pervasive trends, world-wide demand for fossil fuels, particularly the most versatile fuels of oil and gas, will remain high, at least for a number of decades.

Because of a threatening climate change due to heavy reliance on fossil fuels, the world arrives at a crossroad. Either the pattern of fossil fuel consumption remains unchanged and CO₂ emissions rise to levels incurring serious risks for mankind, or firm policies are adopted aiming at energy conservation and the development and application of CO₂ free energy sources. Governments tend to opt for the latter strategy, in agreement with the Protocol of the Kyoto Conference. However,

policies and measures aimed at the CO₂ reduction targets agreed upon are still to be implemented in the industrialised world³ [6].

What is more, governments are focused on near-term solutions in order to fulfil their obligations from the Kyoto Protocol. Energy conservation and renewable energy are important in the medium term, although photovoltaic power (PV, solar cells) will not capture the market at short notice. It is evident that fission power as we know it today (LWR) has its issues and limitations. Technical breakthroughs that would simultaneously solve the issues of safety, hazards of actinides, and risk of proliferation are to be awaited. Therefore, long term options such as fusion power also need careful consideration. In addition to being a CO₂ free energy source, fusion power is considered virtually inexhaustible due to the ample availability of Deuterium and Lithium (the source of Tritium). Fusion power cannot help in the medium term, but its commercial introduction could coincide with the time scale in which climate change policies should become effective.

One could wonder whether fusion power is not too speculative. However, a technology such as the fast breeder reactor, although technically feasible, would lead to serious risks of proliferation. Fusion power could be considered as a technology entailing both sufficient long term potential and possible public acceptance for inclusion in a scenario study until 2100. Public acceptance can be related to issues such as safety and hazards of long living radio active waste. In both respects fusion power shows favourable profiles.

Now that the rationale for inclusion of fusion power in long term energy scenarios has been given, the outlook for fusion power will be addressed shortly. Distinct steps are required in order to warrant the steady progress of fusion power in scientific and technical respect. At the moment, focus is on ITER. This experimental fusion reactor should demonstrate ignition in a fusion reactor based on magnetic confinement; it is not meant to produce electricity. The successor of ITER, called DEMO, would indeed be the first fusion power plant to produce electricity in the period of 2020-2030. After that, prototype fusion power plants would pave the way for commercial fusion power. Just as the past forty years of fusion energy research have been characterised by major technical problems and breakthroughs (e.g. the invention and development of the so-called Tokamak, the technology of choice for ITER), the road towards commercial fusion power will be filled with (unforeseen) technical problems and solutions. The development of fusion power appears to be more or less unpredictable for a number of reasons:

- There are various ways to reach the goal of a commercial fusion power plant. Our ideas of a commercial fusion reactor will almost certainly prove to be wrong. Yet, we have to rely on cost studies of a commercial fusion reactor based on magnetic confinement, as this way of confinement (like in ITER) is most advanced today.
- Due to the relatively large investments needed for ITER and its successors, close international co-operation and co-ordination of energy research budgets are needed. This makes the outcome of the process of RD&D even more unpredictable.

³ A good example is the US. In October 1997 a three-stage proposal on climate change was introduced, in anticipation of an international agreement to be negotiated 2 months later in Kyoto. One of the comments on stage 1 is: 'Because stage 1 lacks a quantitative goal for reducing greenhouse gas emissions, does not have a specific performance plan, and contains incomplete information on expected outcomes and links to the protocol's target, stage 1 may not provide a firm foundation for stages 2 and 3'.

We cannot escape from this lack of predictability. Nevertheless, the economics of some commercial fusion power plant assumed available from 2050 could be analysed. Different routes towards commercial fusion power are beyond the scope of this study. The study will focus on the economic potential of fusion power under various conditions. The motives for the development of fusion power can be formulated as follows:

- fusion power is a CO₂ free energy source,
- it is virtually inexhaustable,
- it is a base load option (not intermittent),
- it is presumably not much more costly than other CO₂ free power generation options.

1.3 New long term scenarios

On the one hand fusion power is one of the main CO₂ free options with a large energy potential, albeit with distinct uncertainties and with a time horizon beyond 2050. On the other hand R&D on fusion energy demands substantial financial commitments in order to further progress in its engineering issues and plasma physics. This is in a nutshell the background of our assessment of the potential economic benefits of fusion power. The benefits of fusion power will primarily originate from the contribution of fusion power to the power generation system in the long term⁴. A structured way to assess the future contribution from fusion power to the energy system is via energy scenario analysis. Such an analysis should give a robust answer to the question of how fusion power ranks under various conditions.

If its RD&D programme would prove to be successful, fusion power could become available as a commercial power generation option by the year 2050. Most likely, it would take several decades more before the share of fusion power in total power production would have become substantial. Therefore, energy scenarios that analyse the economic potential of fusion power need a time horizon of some 100 years from now.

The development of the energy system is driven by changes in energy demand, technical innovation, changes in (relative) energy prices, the practical potentials and public acceptance of energy technologies, future decision criteria for investment decisions, government policies, etc. It is hard to predict how these factors will change over time during the next century. Thus, there are many uncertainties regarding the driving factors that determine the further development of the energy system.

Energy outlooks with a time horizon until 2100 are relatively scarce. Most scenarios with such a time horizon have been developed for the analysis of greenhouse gas mitigation strategies [1]. Unfortunately, the most recent IIASA [4] and IPCC [5] studies did not pay much attention to fusion power. Some scenarios in the IIASA study are highly optimistic with respect to fission power. However, due to the difference in time scale between fission and fusion power, such scenarios cannot be readily applied. Therefore, we need new scenarios that will enable us to analyse the potential of fusion power in depth.

If one develops scenarios with a time horizon of 100 years, it seems appropriate to express some hesitations. If we go back 100 years, could anyone have foreseen the technical innovations that shaped our electrical power system today? Or 50 years ago could anyone have foreseen the advance of computers today? Can breakthrough developments be expected the next century? How erroneous have most energy outlooks from the early seventies for the year 2000 proven to be? Can we accurately envisage future energy demand? How many additional oil and gas reserves will be discovered? What will be the institutional context within which decisions concerning the energy system will be taken? Will concern about environmental issues change, and to what extent?

⁴ It is noted that secondary benefits are also expected as a result of technology spin-off effects towards other sectors (e.g. superconductors).

These questions show that one has to be modest with regard to the predictive value of scenarios with a very long time horizon. All kinds of future developments cannot possibly be foreseen. However, it remains valuable to structure energy scenarios that enable an analysis of various developments of the energy system and an evaluation of the potential of fusion power. Energy scenario analysis is an appropriate way to discern the main factors that determine the contribution of fusion power to the energy system. Due to the large uncertainties, a range of conditions has to be considered. Scenarios and their variants need to cover a wide range of developments for the key driving factors. This requirement can only be met by constructing a significant number of scenario variants.

Moreover, it is deemed important that the study should have an appropriate geographical scope. Since world regions differ substantially with respect to energy demand level, availability of energy resources, technological skills, and environmental policy, the economic potential of technologies like fusion power can also differ widely per region⁵. Scenarios that meet all of these requirements are not readily available. Therefore, new scenarios for one region, viz. Western Europe⁶, have been constructed in the present study with the aim to analyse the economic potential of fusion power.

The present study applies the MARKAL model for Western Europe as its key tool. Such a model for Western Europe with a time horizon until 2050 was developed in the framework of another project and it has been adjusted for this study to cover the period 1990-2100. The MARKAL model and the model's database underwent several important modifications in order to make it suitable for analysis of such a long period of time.

1.4 Overview of the report

This report contains 8 chapters. In Chapter 2 methodology and scenario design are addressed. Chapter 3 provides background information on key parameters of scenarios. This includes information on energy demand, reserves and prices of fossil fuels, developments for energy technologies with respect to efficiency, cost and availability and policies to reduce emissions of carbon dioxide (CO₂). Results of scenarios without CO₂ constraints are presented in Chapter 4. Chapter 5 shows results of various scenario variants. These variants consider different CO₂ emission targets and different discount rates. Further sensitivity analyses are presented in Chapter 6. Finally, Chapter 7 and Chapter 8 contain a discussion and conclusions and recommendations respectively.

⁵ The resources and availability of several key energy sources varies widely between different world regions. North America has e.g. large reserves of coal and substantial reserves of oil and natural gas, the US has sites with high solar radiation without large seasonal differences which is favourable for solar PV. Western Europe has much more limited reserves of natural gas, oil and coal and the region is less suitable for solar PV as annual insolation per square meter is more limited and seasonal fluctuations of solar energy are larger than in the US. Japan has a different situation. Due to such differences in regional circumstances, fusion power should preferably be analysed on a regional level.

⁶ Western Europe is defined as the 15 EU member states, Norway, Iceland, and Switzerland.

2. METHODOLOGY AND SCENARIO DESIGN

2.1 General approach

The approach for the analysis of the economic potential of fusion power in Western Europe can be described as follows. Point of departure is that fusion power might become available as a power generation option with its specific characteristics, e.g.:

- High investment cost,
- High operation and maintenance cost,
- Long construction schedule,
- Large unit size,
- Base-load operation,
- Possibly long lifetime.

It is noted that assessment of the probability that fusion power will or will not become available as a technical option is beyond the scope of this study. For the larger part of the scenario calculations it has been assumed that fusion power is available as a commercial technology. As fusion power is presumably rather costly compared to current base-load options (coal-fired power, LWR, gas-fired combined cycle), its economic attractiveness depends on factors other than its pure financial costs: fusion power is a CO₂ free power generation option, and it is regarded as virtually inexhaustible. Other factors, related to the entire energy system and competing energy technologies, can be divided in factors that enhance the prospects of fusion power and factors that reduce its prospects. In the modelling part of this study the factors that enhance or reduce the prospects of fusion power are combined. The resulting balance of factors results in either no, a small, or a large potential for fusion power.

An existing dynamic energy system model has been adjusted and used for this study. Inside the model, decisions with respect to the configuration of the energy system are simulated by a straightforward cost-minimising approach. Constraints resulting from e.g. the future potential of technologies, existing energy infrastructure, fossil fuel resources, electricity load characteristics, and environmental considerations are taken into account.

Since all factors affecting the prospects of fusion power have significant uncertainties, factors need to be varied in scenario variants. What is more, varying of factors in scenario's gives answers to questions such as :

- how important is the CO₂ free character of fusion power,
- how important is the fact that fusion power is inexhaustible,
- are the costs of fusion power indeed not much higher than those of other CO₂ free power generation options?

Therefore, several scenario variants and sensitivity analyses have been investigated (Chapters 5 and 6). Section 2.2 of this chapter briefly describes the energy modelling approach. Section 2.3 highlights issues related to the very long time horizon of the study and Section 2.4 presents lists of scenario variants.

2.2 Modelling approach

The energy scenarios have been calculated with the widely used MARKAL model [16]. MARKAL is a model that simulates decisions to invest in and utilise energy technologies. The objective of a MARKAL scenario is to minimise the cost of the entire energy system covering energy supply, energy distribution and energy use. A user of the MARKAL model defines a database for a selected region. This database includes information about:

- the level and pattern of the demand for energy services over time,
- energy technologies that satisfy this energy demand and their development over time (current technologies and future technologies),
- availability and prices of energy carriers over time,
- constraints or taxes for emissions (notably CO₂) from energy use,
- discount rates.

When a calculation is performed, MARKAL selects a least cost mix of energy technologies to satisfy the demand for energy services. MARKAL takes numerous constraints into account e.g. related to the load patterns of electricity demand, the intermittent character of some renewable energy sources, growth constraints for technologies, maximum capacity turn over rates, etc. When a constraint is varied in a sensitivity analysis, the optimal mix of technologies will be changed.

The database and results of the Western European MARKAL model have been described in detail in [14, 15]. For the present study the database has been extended to the year 2100. The MARKAL database for Western Europe has 350 end use technology applications (households, services, transport), 58 power generation technologies (including combined heat and power) and 120 other conversion technologies (including processes for biomass conversion, refinery processes, industrial processes).

2.3 Long time horizon issues

Energy scenario analysis with a very distant time horizon is not straightforward. Assumptions on technological innovation are different for scenarios with various time horizons. Other issues which need further clarification as a result of a long time horizon are discounting and climate change. These three issues will be discussed below.

Technological change

Most energy scenarios with a relatively short time horizon assume some kind of technological innovation, but the technological innovation is assumed to be exogenous. In the present study technological innovation is assumed to be exogenous too. This more or less pragmatic choice is based on the following considerations:

- Little is known about the driving forces of technological innovation, e.g. the relation between cumulative sales of a technology, cumulative RD&D investments and the progress in cost and performance.
- It would be difficult to maintain internal consistency if a large number of power generation options would be used and learning curves would be available only for some of them.
- The transparency of the technology assumptions could be reduced if technology development were endogenised.

Some recent long term scenario studies, e.g. studies by Shell [7], IIASA [4], Mattson [8] and Poles [9], endogenise technological innovation. In each of these studies a simple relationship is assumed between the cumulative world-wide sales of an energy technology and the investment costs of the technologies. With each doubling of the cumulative sales of a technology the investment cost drops a certain percentage. The cost reduction per doubling of sales is estimated between 0% and 30%

[10], although a range of 10-20% cost reduction for each doubling is more common. The cost reduction is believed to result from several learning mechanisms. In some of the studies this approach produced feed-forward effects in the results of energy system models, with one technology gaining the entire market while continuously becoming cheaper.

Our understanding of the dynamics of technology in the long term is limited. How will current technologies have evolved? Which energy technologies will become available in the next 100 years? It may well be that technologies emerge that have not or hardly been envisaged today. Technology forecasting is increasingly receiving attention. Some relationships between technology driving factors, conditions required for technology development and innovation, are under investigation. The notion that technologies which at first seem most promising for technical reasons are not always the ones adopted by the market, is getting through. Lock-in and lock-out effects are also considered important factors. The dynamic development of relation networks between research institutes, industries, funding agencies, etc. is also deemed relevant. However, a grand theory to give robust forecasts of technology development is not available. What is more, the exogenous technological innovation which we assume is sufficiently transparent and consistent.

The approach chosen for this study is to make use of exogenous estimates of technology development processes. Technology assumptions are primarily based on detailed estimates, learning effects, and expert opinions included in studies of our colleague institutes that contribute to the SERF programme. Other sources of data are several other studies [11, 12, 13, 14, 15], that include forecasts of the development of energy technology.

Discount rates

The following two sections are mainly derived from the aforementioned IPCC study [5]:

1. The discount rate allows economic effects occurring at different moments in time to be compared. It plays a vital role in public policy analysis of actions with varying time paths of costs and benefits. It is particularly important for issues with a long time horizon. Then the choice of a discount rate strongly affects the net present value of alternative actions.
2. Two main approaches are used to determine appropriate discount rates for climate change analysis. On one hand, the social rate of time preference (or prescriptive approach) is linked with normative questions such as 'How should impacts on future generations be valued?'. The social rate of time preference is derived from the rate of growth of consumption per capita and the greater distance we feel to generations further away from us. On the other hand, the descriptive discount rate derives the discount rate from interest rates which are common on the capital market. The social rate of time preference tends to be relatively low (between 2 and 3%). The descriptive approach (or opportunity cost approach) tends to generate higher discount rates which may also differ per country, sector and as a function of the risks involved in the investment. Economists continue to debate which of the two approaches is right.

Many quantitative studies pay attention to discount rates. Frequently, it was decided to take an intermediate discount rate which amounts to 4-7% [16]. In several studies sensitivity analyses have been performed with higher and lower discount rates (e.g. ETSU, [12]).

The present analysis on the prospects of fusion power has a slightly different approach, with two different kinds of discount rates being applied simultaneously:

- A discount rate based on the social rate of time preference, taking into account the greater distance we feel to generations further away from us. This relatively low discount rate governs the depletion of fossil fuel resources and the emission of CO₂ over time, presumed some cumulative emission of CO₂ is allowed for the period 1990-2100. For inter-generational issues a discount rate is chosen of 2.5% per year.
- A higher interest rate is applied to energy investment decisions. For the power generation sector this discount rate ranges from 5 to 8 and 10% per year.

Climate change

For near-term analysis of strategies to reduce emissions of greenhouse gases it is common to consider annual emission targets. This is considered most practical, as until recently international climate change also focused on emission targets for specific years.

However, the characteristics of the climate change issue are different. Climate change is driven by the increased concentration levels of greenhouse gases, and thus, what really matters are the cumulative emissions over a long period of time. Another consideration is that if annual targets would be assumed, timing of emission reduction would not be optimised. With a cumulative emission budget the timing of emission reduction can be optimised, under the condition that the energy model is capable of including cumulative emission constraints. The MARKAL model can handle such constraints.

Environmental targets for climate change in terms of stabilisation levels for CO₂ in the year 2100 (e.g. 450, 550, 650 and 750 ppm) can be linked directly to global cumulative emission limits. Assuming some way to differentiate commitments between developing countries and the developed countries, a cumulative emission budget for Western Europe for the period until 2100 can also be calculated.

2.4 Selection of scenarios and sensitivity analysis

Two main scenarios are used (to be described in Chapter 3, Section 3.1), called Rational Perspective (RP) and Market Drive (MD). Table 2.1 summarises scenario RP, its variants with CO₂ constraints and different discount rates, and its sensitivity cases (see footnotes).

Table 2.1 *Scenario RP variants and sensitivity cases*

Scenario	CO ₂ level [ppm]	Disc. Rate [%]	Fusion	Fission	Fossil res.	Renewable
RP	-	5	yes	declining	default	default
	550	5	yes	declining	default	default
	500	5	yes	declining	default	default
	450	5	yes	declining	default	default
RP08	-	8	yes	declining	default	default
	650	8	yes	declining	default	default
	550	8	yes	declining	default	default
	500	8	yes	declining	default	default
RP10	450	8	yes	declining	default	default
	-	10	yes	declining	default	default
	650	10	yes	declining	default	default
	550	10	yes	declining	default	default
RPHFR ¹	500	10	yes	declining	default	default
	450	10	yes	declining	default	default
	-	5	yes	declining	high	default
	550	5	yes	declining	high	default
RPFPO ²	500	5	yes	declining	high	default
	450	5	yes	declining	high	default
	-	5	yes	phase out	default	default
	550	5	yes	phase out	default	default
RPNFP ³	500	5	yes	phase out	default	default
	450	5	yes	phase out	default	default
	550	5	no	declining	default	default
	500	5	no	declining	default	default
	450	5	no	declining	default	default

¹ RPHFR = Rational Perspective, High Fossil Resources.

² RPFPO = Rational Perspective, Fission Phase Out (in 2080).

³ RPNFP = Rational Perspective, No Fusion Power.

In the same way Table 2.2 summarises scenario MD, its variants with CO₂ constraints and different discount rate, and its sensitivity cases (see footnotes).

Table 2.2 Scenario MD variants and sensitivity cases

Scenario	CO ₂ level [ppm]	Disc. Rate [%]	Fusion	Fission	Fossil res.	Renewable.
MD	-	8	yes	declining	high	default
	750	8	yes	declining	high	default
	650	8	yes	declining	high	default
	550	8	yes	declining	high	default
	500	8	yes	declining	high	default
	450	8	yes	declining	high	default
MD05	-	5	yes	declining	high	default
	750	5	yes	declining	high	default
	650	5	yes	declining	high	default
	550	5	yes	declining	high	default
	500	5	yes	declining	high	default
	450	5	yes	declining	high	default
MDHRP ¹	-	8	yes	declining	high	high
	750	8	yes	declining	high	high
	650	8	yes	declining	high	high
	550	8	yes	declining	high	high
	500	8	yes	declining	high	high
	450	8	yes	declining	high	high
MDHCF ²	650	8	high cost	declining	high	default
	550	8	high cost	declining	high	default
	500	8	high cost	declining	high	default
	450	8	high cost	declining	high	default
MDHFP ³	-	8	yes	high pot.	high	default
	750	8	yes	high pot.	high	default
	650	8	yes	high pot.	high	default
	550	8	yes	high pot.	high	default
	500	8	yes	high pot.	high	default
	450	8	yes	high pot.	high	default
MDNFP ⁴	650	8	no	declining	high	default
	550	8	no	declining	high	default
	500	8	no	declining	high	default
	450	8	no	declining	high	default

¹ MDHRP = Market Drive, High Renewables Potential.

² MDHCF = Market Drive, High Cost Fusion.

³ MDHFP = Market Drive, High Fission Potential (up to 200 GW).

⁴ MDNFP = Market Drive, No Fusion Power.

3. BACKGROUND INFORMATION ON KEY PARAMETERS OF SCENARIOS

This chapter gives background information on key parameters. It starts with scenario assumptions (Section 3.1). In Section 3.2 fossil fuel resources are addressed and in Section 3.3 fossil fuel prices. Power generation technologies are described in Section 3.4, and constraints to technologies in Section 3.5. The last Section (3.6) deals with CO₂ reduction policies.

3.1 Scenario assumptions for energy demand and discount rates

Two main energy demand scenarios have been developed for this study. The two scenarios are named *Rational Perspective* and *Market Drive* and they are somewhat modified from an earlier scenario study⁷. The differences between the two scenarios relate to their perspective towards decision criteria on energy investments by individual actors (represented by different discount rates), the level of energy demand, availability of fossil fuels for Western Europe and energy price projections (see Table 3.1). Assumptions regarding the cost and performance of technologies are the same for the two scenarios. The maximum and minimum potentials of supply technologies are also the same for the two scenarios, except for the maximum bound of fission power.

Table 3.1 *Key differences between scenarios RP and MD*

	Rational Perspective (RP)	Market Drive (MD)
Decision criteria	uniform 5% discount rate for all energy decisions across all sectors	8% discount rate for power generation, higher discount rates for end use
Energy demand	In most sectors lower than in MD	In most sectors higher than in RP
Availability of fossil fuels for Western Europe	10.5% of world's resources of coal, oil and natural gas	15% of world's resources of coal, oil and natural gas
Energy prices	Oil price increases slowly until 2100, \$ 25/bbl in 2100	Oil price increases faster than in RP, \$ 29.5/bbl in 2100
Fission power	Maximum capacity decreases to 70% of current capacity around 2070, with further decline towards 2100	Maximum capacity decreases to 80% of current capacity around 2070, with further decline towards 2100

General scenario background

Rational Perspective can be characterised as the ecologically driven scenario of the two. The process of global economic integration will lead to more collective public action in this scenario. International co-operation will be more efficient in order to deal with complex shared problems. Heavy polluters and energy intensive industries will decline in comparison to more environmentally friendly sectors like services. Strong penetration of new, more efficient demand and supply technologies is facilitated. This strong penetration will be achieved by setting efficiency standards, removing existing barriers for the introduction of efficient technologies, and active energy service companies which carry out cost-effective efficiency improvements for end-users. The above mentioned policy shifts are driven by

⁷ Since the time horizon of the MARKAL model for Western Europe has been extended from 2050 to 2100, energy demand projections have been extrapolated and in some cases reconsidered.

environmental concerns and concerns about efficiency throughout society. The base case of Rational Perspective does not assume a specific policy for reducing CO₂ emissions.

Market Drive is the market driven scenario. In this scenario the market mechanism is seen as the best way to generate prosperity and handle complexity in uncertainty. The penetration of new, more efficient demand and supply technologies totally depends on market forces and the behaviour of the actors. The environmental protection agenda is also set by the market and thus not by public policy. Moreover, energy policy is driven by the desire to minimise government control and to maximise efficient operation of free markets. Barriers will persist in the uptake of efficient equipment. Efficiency gains will only be made for competitive reasons. The base case of Market Drive does not assume a specific policy to reduce CO₂ emissions.

Discount rate

A discount rate is required to annualise the capital cost in order to compare the costs of alternative technologies with different ratios of initial capital expenditure to annual running costs. The formulation of the MARKAL model allows to choose one uniform discount rate applied to all technologies or different discount rates applied to the different sectors.

In scenario *Rational Perspective* a single discount rate is applied. By applying a uniform rate, all technologies at the demand side of the energy system are allowed to compete with energy supply technologies like in a perfect market. In other words, scenario Rational Perspective assumes a market that works rational without barriers and with perfect information so that any difference in pay back opportunities will automatically be removed. The discount rate in Rational Perspective amounts to 5% per year, which is typical of a low-risk investment climate.

Scenario *Market Drive* acknowledges that in reality more stringent investment criteria apply for many energy related decisions and that hidden cost and market barriers do play a role. This scenario assumes different discount rates per type of sector. The discount rates reflect representative hurdle rates applicable to that sector or kind of end-use. Table 3.2 lists the hurdle rates applied in scenario Market Drive.

Table 3.2 *Sector specific discount rates in the Market Drive scenario*

Sector	Discount rate
Power generation	8%
Industrial cogeneration	
Refineries	
Biomass conversion	
All processes in industry	10%
Space and water heating in residential sector, commercial sector and greenhouses	15%
Trucks, vans and buses	
Electric appliances	20%
Passenger cars	25%

Energy demand

Figures 3.1a (Rational Perspective) and 3.1b (Market Drive) present the development of the useful energy demand in the four main sectors.

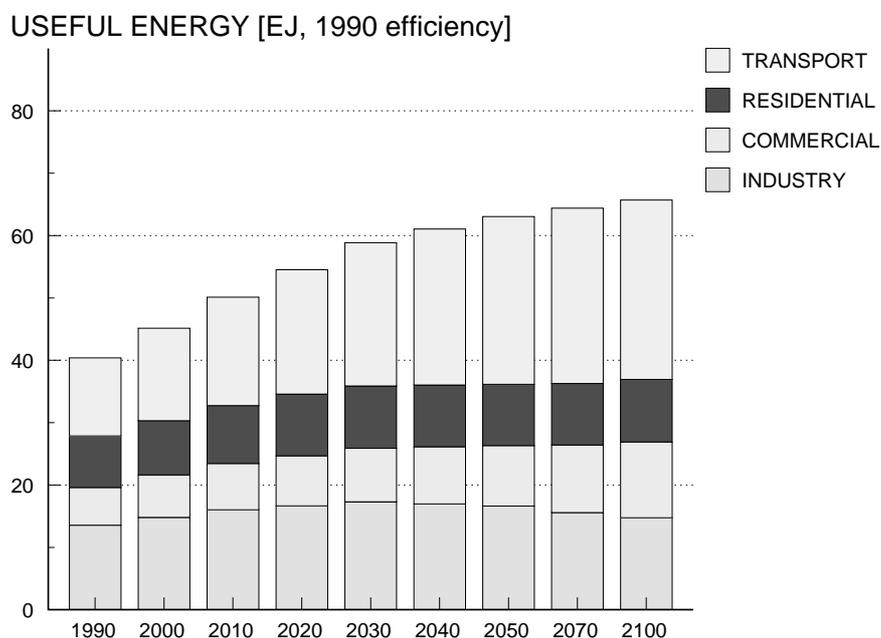
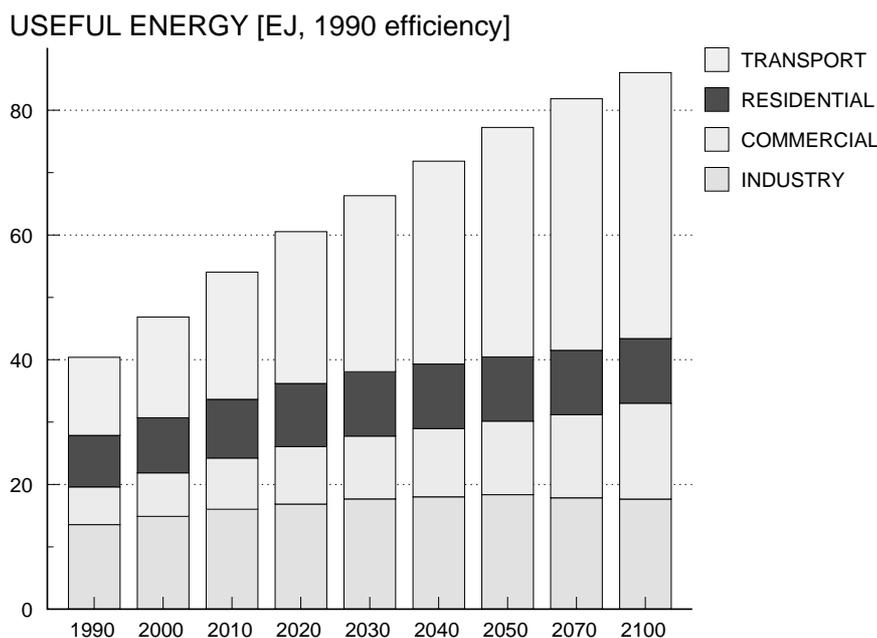


Figure 3.1a *Useful energy demand per sector in scenario Rational Perspective*



Figures 3.1b Useful energy demand per sector in scenario Market Drive

In scenario RP (Rational Perspective) the total of useful demand is projected to increase with 60% between 1990 and 2100. After 2050 the growth in demand is substantially less than before that date. In scenario MD (Market Drive) useful energy demand more than doubles between 1990 and 2100. For both scenarios the demand projection for the transport sector is much higher than in the other three sectors. The additional growth is projected to take place largely in air transport. The residential and industrial useful energy demands are almost identical in both scenarios.

3.2 Fossil fuel resources

The world's oil, gas and coal resources are a key factor for future energy supply. 'Ultimate resources' is an important notion in that respect. Ultimate resources are defined as the sum of identified reserves (proven and probable) and 'possible' or 'inferred' reserves. The latter may be found with a certain probability. If possible or inferred reserves are presented in certain amounts for different probabilities, modal values are used most commonly. Fossil fuel resources presented below generally refer to the end of year 1993. For reasons of consistency resource data have been converted to a single unit, EJ, and to year 1990 (MARKAL optimisations start in 1990) in Section 3.2.4.

3.2.1 Oil resources

Conventional oil resources

Almost all currently produced oil is conventional oil. Unconventional oil resources - heavy and extra-heavy oils, tar-sands, oil-shales - will be addressed in Section *Unconventional oil resources*. The US Geological Survey (USGS) is authoritative with respect to world's conventional oil and gas resources [17]. Data on world energy resource occurrence were developed in the framework of their World Energy Resources Program (1979-1995), on behalf of the US government. Table 3.3 shows their data.

Table 3.3 *World's conventional crude oil resources (billion barrels)*

	A Oil prod. 1997	B Cum. prod. 1993	C Identified Reserves 1- 1-93	D = B + C Original Reserves 1-1-93	E Undis- covered Oil	F = D + E Ultimate Resources
North America	5.2	199.0	112.0	311.0	90.3	401.4
Latin America	2.4	64.2	77.6	141.8	43.7	185.5
Western Europe	2.5	22.6	41.2	63.8	15.8	79.6
Eastern Europe/FSU	2.7	125.4	127.1	252.5	101.6	354.1
Africa	2.8	56.5	76.5	133.0	37.7	170.7
Middle East	7.9	184.6	597.2	781.8	117.4	899.2
Asia/Oceania	2.8	46.3	71.2	117.4	53.2	170.6
World	26.4	698.6	1,103.2	1,801.8	470.7	2,261.1

Source [17]

Identified Reserves include not only the Proved Reserves, but also any additional oil which may be discovered through extensions, new reservoirs, or improvements in recovery. The USGS defines ultimate oil resources as Identified Reserves plus the modal value of Undiscovered Resources. Some experts consider the USGS data to be too optimistic, e.g. geologist C.J. Campbell [18]. Most of the controversy pertains to the perceived high values the USGS attributes to identified reserves in the Middle East. The problem is the lack of public data, as most of the countries have state oil companies. The USGS admits the scarcity of data, but is satisfied that having had access, in the past, to convincing original data and, more recently, confirmation from reliable sources, permits them to stand with the reported values, which are comparable to those reported by OPEC. If the USGS data were too pessimistic, this would mean that an amount of oil comparable to the Middle East oil province would have to be discovered, which is highly unlikely.

Campbell's original assessment of world oil resources is considered to be pessimistic, e.g.:

- His original estimate for the UK was 15 billion barrel (bbl) [18]. His latest revision [19, 20] is 30 billion bbl, which is near to the USGS estimate of 36.3 billion bbl.
- Originally, Campbell estimated ultimate oil resources of Norway at 18 billion bbl [18]. Recently he revised this estimate to 27 billion bbl [19, 20, 21], which is only slightly lower than the USGS estimate of 29.6 billion bbl. However, the Norwegian Petroleum Directorate estimates Norway's total petroleum resources (oil and gas) at 80 billion bbl of oil. Half of that amount, 40 billion bbl, would be oil [22].

Much of the recent increase in Norway's ultimate oil resources is due to thorough reservoir management [23]. A study of 22 oil fields on the Norwegian continental shelf shows a rise in the average recovery factor from 34% in 1991 to 41% in 1996. Fields operated by Statoil currently average around 50% oil recovery. The current average planned recovery factor for all oil fields and discoveries in the Norwegian sector is 42%. Advances in oil exploration and production are a key factor in the development of oil resources of the North-west European Continental Shelf (NECS)[24]. Were the experience of the NECS to be replicated on a global basis, the reserves increment due to drilling advances could be as much as 350 billion bbl.

All in all the oil resource assessments of Campbell and the USGS differ a lot:

- His original estimate of world oil resources: 1,650 billion bbl (1991) [18].
- Campbell raised his original estimate to 1,800 billion bbl (1997) [19, 20], however, he still rejects 360 billion bbl of oil reserves attributed mainly to Middle East countries.
- The USGS estimate [17] of ultimate oil resources is 2,273 billion bbl (Table 3.3).

Considering possible downward revision of Middle East oil reserves and possible upward revision of oil resources due to advances in oil exploration and production, the USGS data are deemed realistic. After subtraction of cumulative oil production, recoverable conventional oil resources are 1,562 billion bbl, equivalent to 60 years of oil production.

Unconventional oil resources

Unconventional oil resources accrue from:

- about 570 billion bbl of recoverable heavy and extra-heavy oil resources,
- about 440 billion bbl of recoverable natural bitumen (tar sands),
- possibly 880 billion bbl of oil shale out of 13,900 billion bbl of oil shale in place.

Table 3.4 gives an overview of unconventional oil resources, based on [25, 26, 27].

Table 3.4 *World's unconventional crude oil resources (billion barrels)*

	Heavy oil	Tar sands	Oil shale ¹		Total
North America	44	309	355	(5,600)	708
Latin America	310	6	253	(4,000)	569
Western Europe	8		9	(150)	17
Eastern Europe/FSU	130	117	16	(250)	263
Africa	6		6	(100)	12
Middle East	61	5			66
Asia/Oceania	13		241	(3,800)	254
World	572	437	881	(13,900)	1890

¹ Figures refer to recoverable shale oil, between brackets oil shale in place.

Some 40% of recoverable heavy and extra-heavy oil resources, 240 billion bbl, are found in the Orinoco belt of Venezuela. Production started with so-called Orimulsion, an oil which is transported in heated tankers to coastal power stations. For Venezuela the challenge is not only to come up with a conventional development scheme, but also to push available technology world-wide to its practical limits. In 2000 production of extra-heavy crude in Venezuela will be boosted by 200,000 barrel per day (b/d) [28].

The province of Alberta in Canada is well endowed with natural bitumen or tar sands. According to the Canadian Association of Petroleum Producers the region would contain some 300 billion bbl of recoverable oil [29]. Current production of unconventional oil in Alberta is only 300,000 b/d. The goal for the region is 1.2 million b/d within 25 years. It has been estimated that Venezuela and Canada would hold 576 billion bbl of recoverable unconventional oil [26]. Countries like Russia, Kuwait, the US, and Columbia, could hold another 430 billion bbl of recoverable (extra) heavy oil and tar sands.

A number of (large) countries - China, the US, and Brazil - have enormous resources of oil shales. However, production of oil shale is generally not economic at current depressed oil prices. The recovery percentage is smaller for oil shale than for tar sands and extra-heavy oil, which have a recovery fraction from 10 to 25%. Some 120 billion tons of oil shale are deemed to be recoverable, equivalent to 880 billion barrels [26].

The total of recoverable unconventional oil resources, (extra) heavy oil, tar sands, oil shale, are estimated at 1,890 billion bbl, or 72 years of oil production. The reserve/ production ratio of conventional oil has been estimated at about 60 years. Therefore, total oil resources could be equivalent to 130 years of current oil production. A serious constraint could be the production capacity for unconventional oil. Development of unconventional oil requires massive investments and long lead times compared to conventional oil.

Around the turn of this century world-wide production of (extra) heavy oil and tar sands could be 1.5 million b/d. Under favourable conditions this level could be raised to 4 million b/d in 2010, 22 million b/d in 2030 and 40 million b/d in 2050 (55% of current oil production). Moreover, shale-oil production could be increased from a relatively low level in 2050 to a maximum of 20 million b/d in 2100. Total unconventional oil production could then approach the current level of oil production (72 million b/d).

3.2.2 Natural gas resources

As with oil, gas resources can also be split in conventional and unconventional resources. Conventional gas resources (excluding clathrates and other unconventional gas resources), as reported by the USGS [17], can be compared to estimates of conventional plus unconventional resources by Enron ('potential' resources) [30], as shown in Table 3.5.

The USGS data are almost equal to the proven, probable and possible gas resources reported by the Union Francaise des Industries Pétrolières (278 trillion cubic meter) [31]. The International Gas Union gives a figure of 404 trillion cubic meter [32]. Enron's estimate, which is the highest reported until now, includes unconventional gas resources.

Table 3.5 *Ultimate conventional and 'potential' natural gas resources according to the USGS and Enron respectively (trillion cubic meter)*

	A	B	C	D=B+C	E	F	G=D+E	H=D+F
	Gas	Cum.	Identif.	Original	Undisc.	Addit.	Ultim.	Ultim. acc.
	prod.	Prod.	Res. -	Reserve 1-	acc. to	acc. to	acc. to	to Enron
	1997	1993	1993	1-93	USGS	Enron	USGS	
North America	0.74	25.46	15.23	40.69	20.25	58.19	60.94	98.88
Latin America	0.09	1.12	6.60	7.72	6.03	11.61	13.74	18.10
West. Europe	0.28	4.53	8.21	12.74	5.83	5.36	18.57	18.10
East. Eur./FSU	0.62	13.97	44.71	58.69	51.37	92.32	110.06	151.01
Africa	0.09	0.88	11.37	12.26	8.89	7.28	21.14	19.54
Middle East	0.17	1.42	47.67	49.08	24.14	88.24	73.22	137.32
Asia/Oceania	0.24	2.19	11.64	13.83	12.68	19.12	26.51	32.95
World	2.22	49.56	145.40	195.00	129.19	282.12	324.19	477.10

Sources: [17, 30]

Unconventional gas resources comprise coal-bed methane, tight formation gas, and clathrates: methane hydrates found in Arctic areas and at distinct depths of the ocean floor. Information on clathrates is scattered. For instance, estimates of the amount of clathrates in ocean sediments range from 3,100 billion m³ to 7,600 trillion m³ [33]. Recently, a research and development programme on methane hydrates was initiated in the US [34].

Technology for recovering gas from clathrates is not available today. Recovery might cause methane releases to the atmosphere. Because recovery of clathrates is speculative, they have been largely omitted from the resource estimate. Conventional gas resources (USGS) have a reserve/production ratio of 125 years, whereas 'potential' gas resources (Enron) have a reserve/production ratio 190 years. The latter are used here as reference.

3.2.3 Coal reserves

The world coal reserves as reported in BP statistics [35], which are based on a WEC assessment, are shown - with a few minor changes [36] - in Table 3.6.

Table 3.6 *World coal reserves, end 1993 (billion tonnes of oil equivalent)*

	Coal product. 1997	Hard coal reserves 1993	Lignite reserves 1993	Total reserves 1993
North America	0.628	78.1	44.0	122.1
Latin America	0.031	4.6	1.5	6.1
Western Europe	0.122	19.4	20.2	39.6
Eastern Europe/FSU	0.350	90.8	59.8	150.5
Africa	0.120	40.5	0.4	41.0
Middle East	0.001	0.1		0.1
Asia/Oceania	1.070	115.7	48.3	164.0
World	2.321	349.3	174.2	523.5

Sources: [35, 36]

World coal reserves according to the international classification comprise:

- measured and indicated reserves,
- inferred reserves.

With ongoing geological research, resources evolve from ‘hypothetical’ into ‘proven’ [36]. The current reserve/production ratio for world coal reserves is approx. 220 years.

3.2.4 Fossil fuel resources available to Western Europe

World coal resources are deemed much larger than those of oil and gas. Coal reserves in Table 3.6 are defined more strictly than oil and gas resources. However, whatever the definition of coal reserves, they cannot be depleted in the 21st century. Conventional oil resources will probably be depleted in the course of the next century. Unconventional oil resources could stretch oil use beyond 2100. More or less the same holds for conventional and unconventional gas resources. CO₂ reduction policies could hamper high rates of production of coal, and at the same time enhance gas production.

Oil, gas and coal resources from the preceding sections are presented in EJ in Table 3.7.

Table 3.7 *Recoverable fossil fuel resources, year 1990 [EJ]*

	Conv. oil	Tar sands and (extra) heavy oils	Oil shale	Conv. gas ¹	Unconv. gas ²	Coal reserves	Total
North America	1,217	2,012	2,024	1,410	1,414	5,184	13,261
Latin America	741	1,767	1,446	487	208	259	4,908
West. Europe	353	46	54	552		1,682	2,687
East. Eur./FSU	1,361	1,408	90	3,710	1,526	6,357	14,452
Africa	692	34	36	773		1,728	3,263
Middle East	4,181	376		2,721	2,388	5	9,671
Asia/Oceania	749	74	1,374	938	240	6,975	10,350
World	9,294	5,717	5,024	10,591	5,776	22,190	58,592

¹ The USGS estimate is used as reference with respect to conventional gas resources.

² Enron data have been used to single out their unconventional resources (excluding clathrates).

How much fossil fuel could be used by Western Europe? From the distribution of fossil fuel consumption in long term energy scenario studies it has been deduced that Western Europe could use 10.5% of world’s fossil fuel resources (Table 3.8).

Table 3.8 *Reference fossil fuel availability for Western Europe, 1990-2100 [EJ]*

	Conv. oil	Tar sands and extra heavy oils	Oil shale	Conv. gas	Unconv. gas	Coal
Indigenous	353	46	54	552		1,682
Import	576	601	131	560	606	648
Total	929	647	185	1,112	606	2,330

In the ‘high-growth’ scenario and in the sensitivity analysis of the ‘low-growth’ scenario it is assumed that 15% of world’s fossil fuel resources could be available. Currently, Western Europe consumes approximately 15% of all fossil fuels in the world. In most long term scenario’s (IIASA-WEC, IPCC) the future share is deemed to be about 10.5%.

Production limits for unconventional oil should be accounted for, as some oil should be left for the 22nd century. Production of tar sands and (extra) heavy oil could be boosted to 40 million b/d in 2050. Total unconventional oil production could peak at 60 million b/d when shale oil production is shut in (Section 3.2.1). On top of these fossil oil resources a modest amount of ‘biocrude’ is

assumed to be available to Western Europe. However, this amount is relatively small and scenario-independent.

3.3 Fossil fuel prices

3.3.1 Long term prices for oil, gas and coal

Oil is a versatile fossil fuel with a large product range. As world-wide demand for oil is high and production is not evenly distributed over the globe, oil prices are rather volatile. The price of natural gas is generally tied to (a mix of) oil product prices. Natural gas is cheaper in North America and Europe than in Japan, which is due to:

- absence of indigenous resources in Japan,
- reliance on relatively costly import of Liquefied Natural Gas (LNG).

Price trends for heavy crude oil are determined for the two main scenarios (Fig. 3.2)⁸.

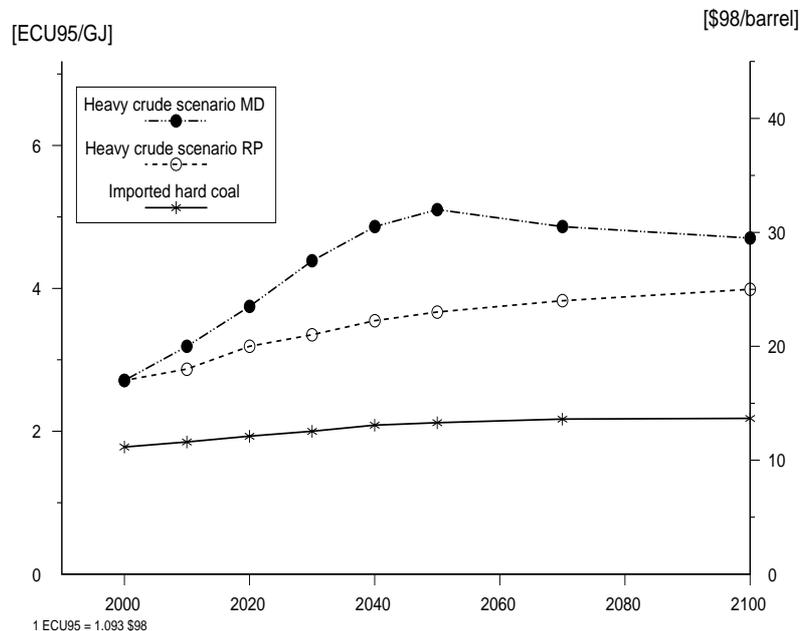


Figure 3.2 *Heavy crude oil prices and coal price for two scenarios*

Gas prices for power generation derived from these oil price trends will be shown in Section 3.3.2. The price of imported hard coal is equal for the two scenarios.

Imported hard coal is cheaper than indigenous coal in Western Europe. Therefore, hard coal production has been falling in Germany, Spain, and Great Britain. Indigenous coal production in Germany will probably be phased out in the beginning of the 21st century. The outlook for coal in the UK is better due to more favourable geological conditions. Production of lignite is important in Germany, and significant in Greece and Spain. Lignite production in Western Europe will probably remain stable during the first decades of the 21st century, after that, it will be phased out towards the end of the 21st century, as it will not be economic to produce all of the remaining lignite resources.

⁸ The currency used in this study is the ECU of year 1995.

Price trends for imported coal and heavy crude oil are based on a few considerations:

- The price of imported hard coal is assumed to increase with a sheer 0.35% per year until 2050. After that, the price is assumed to remain almost flat. This is on the low side of estimates of future coal prices [36, 37, 38]. Low coal prices will not materialise in case of an increasing demand for hard coal. *Therefore, the presumed low coal prices can only occur if coal demand is lower than today, e.g. due to CO₂ reduction policies.*
- Prices of heavy crude oil differ for the two main scenarios. The lower oil price level pertains to scenario *Rational Perspective* (RP), that has a rather low level of energy demand. In 2100 the price of heavy crude oil will have ended up at \$ 25/bbl (\$ 1998).
- Scenario *Market Drive* (MD), the high-demand scenario, requires higher oil prices. After a peak in 2050, the heavy crude oil price ends up at \$ 29.5/bbl in 2100.

Development of the crude oil price is crucial, as it probably also determines the price level of natural gas. The following notes give background for the assumed price levels:

- According to [36] the minimum required oil price ranges from less than \$ 10/bbl for most of the Middle East to about \$ 15/bbl for most of the North Sea and other offshore regions. These cost estimates have been made for a time horizon until 2020.
- The largest petroleum development in Canada, and the most costly offshore project in the world to date, is Hibernia field off Newfoundland (investment cost C\$ 7.5 billion). The total production cost is estimated at \$ 12/bbl, of which \$ 8.5/bbl for development.
- Production cost of synthetic crude from (extra) heavy oil and from tar sands could amount to \$ 15-20/bbl [25]. Shale oil production could be even more costly: \$ 20/bbl or more.

Thus, heavy crude prices would rise from their current depressed level to \$ 25/bbl or \$ 29.5/bbl in 2100, depending on the scenario. The oil price reflects a reimbursement for:

- development and production cost, rising from currently \$ 10-15/bbl for new offshore licences to \$ 20/bbl or more for the most expensive unconventional oils,
- an operating margin of \$ 3-5/bbl,
- a government take in the producing countries.

All in all, scenario RP is based on moderate price increases, leaving sufficient room for a modest operating margin and a small government take. Higher oil prices in scenario MD enable attractive operating margins and a more generous government take.

3.3.2 Fossil fuel prices for power generation

The price trends for heavy crude oil, presented in Section 3.3.1, have been translated into prices for natural gas for power generation. Three different options are considered:

- Base-load operation, e.g. in industrial CHP (Combined Heat and Power).
- Medium-load operation, e.g. combined cycle power plant for district heating.
- Total energy schemes with relatively high natural gas prices (gas engines).

Fuel prices for power generation in scenario RP, a scenario with a relatively low energy demand and with correspondingly low heavy crude oil prices, are shown in Figure 3.3.

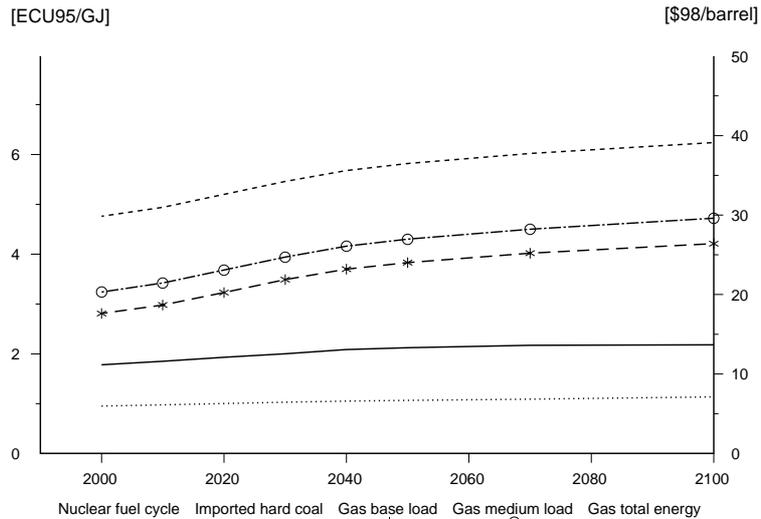


Figure 3.3 Fuel prices for power generation, scenario Rational Perspective (RP)

At the bottom of Figure 3.3 the development of nuclear fuel cycle costs is shown. The current type of fission reactor, LWR, uses lowly enriched uranium. World's uranium resources might be depleted if LWRs would remain the reference reactor type during the next century. However, this is not so much of a problem. Thorium could be used instead of uranium, thereby enlarging the total resource base. More serious is e.g. the issue of long living radioactive waste. If this issue would not be resolved in an acceptable way, it could seriously hamper growth of fission energy. Or, as some state with regard to this issue [39]: 'To be acceptable, one must be credible, to be credible, one must be transparent and responsible, and to be transparent and responsible, one must be independent. But being independent, transparent, responsible and credible is not enough to be acceptable'.

With this in mind it is deemed not probable that world-wide nuclear capacity will increase substantially. As a matter of fact, a world-wide stabilisation of nuclear capacity (based on fission energy) within a few decades is the reference assumption in the scenarios of the present study⁹. If such a development would materialise, uranium would not be depleted fast. Uranium is only a small fraction of total fuel cycle costs. Even assuming that the uranium price would rise with 2% per year in the first decades, and with 1.5%/year decreasing to 1%/year towards the end of the next century, nuclear fuel cycle costs would increase rather slowly (Figure 3.3).

The price of coal is assumed to increase slowly until 2050 and to remain almost flat after that, as has been noted before. For base-load gas-fired power, gas prices in scenario RP increase with 0.4% on average until 2100, which is a really moderate price increase.

In scenario MD, gas prices, which are based on oil product prices, increase relatively fast (1.3% per year) until 2050 and decrease slowly after that date (Figure 3.4). The development of LWR fuel cycle costs and the price of imported coal are the same in both scenarios.

⁹ It has been assumed that output from fission reactors remains almost flat or decreases slowly (installed capacity decreases in all scenarios, but this is partly offset by the increased load factor) until 2070. After that date installed capacity is assumed to decline further towards 2100.

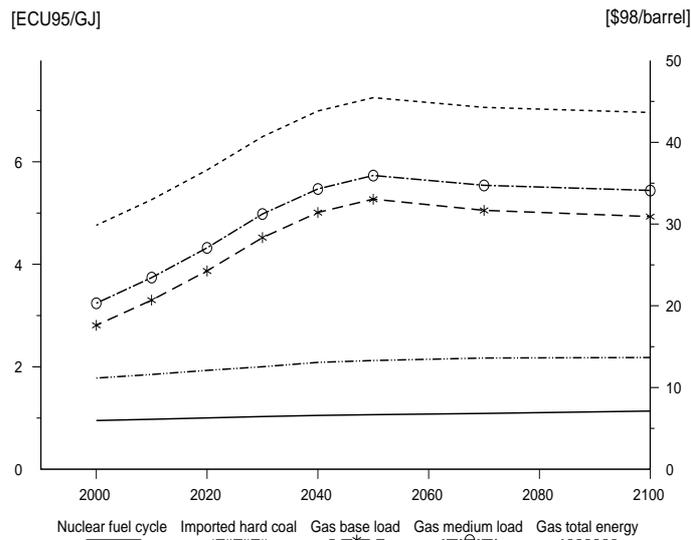


Figure 3.4 Fuel prices for power generation, scenario Market Drive (MD)

3.4 Power generation technologies

The MARKAL model for Western Europe contains 58 different technologies for power generation. The ECN contribution to the macro task ‘cost of fusion power’ contains data on 33 of them [40]. Power generation technologies which are expected to play a key role in the future energy system are described in Sections 3.4.1 - 3.4.5.

3.4.1 Fossil fuel based power generation

Coal is one of the main fuels for power generation. Until recently, coal-fired power plants in Europe were based on steam parameters up to 540°C and 250 bar, as set out in [41], with a corresponding net generating efficiency up to 43%. According to [41] supercritical live steam conditions of 620°C and 300 bar, single reheat with 600°C and 55 bar enable efficiencies beyond 45% (Figure 3.5).

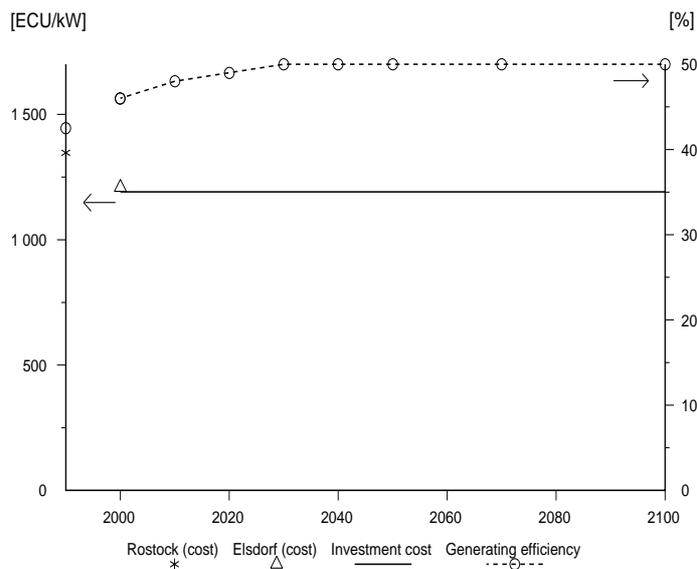


Figure 3.5 *Development of coal-fired power with supercritical steam parameters*

In Figure 3.5 investment costs of two German coal-fired power plants are shown on the left side. One is the 500 MW coal-fired power plant Rostock, with investment cost of ECU 1350/kWe [42]. The other one is a 500 MW coal-fired power plant at Elsdorf, with investment cost of ECU 1210/kW [43]. A similar level of investment cost is assumed here: ECU 1190/kW. Net efficiency is assumed to increase from 46% in 2000 to 50% in 2030.

Also Integrated Gasification Combined Cycle (IGCC) power plants are considered:

- Investment cost ECU 1450/kW in 2000, decreasing to ECU 1290/kW in 2040.
- Net generating efficiency increasing from 48% in 2000 to 52% in 2040.

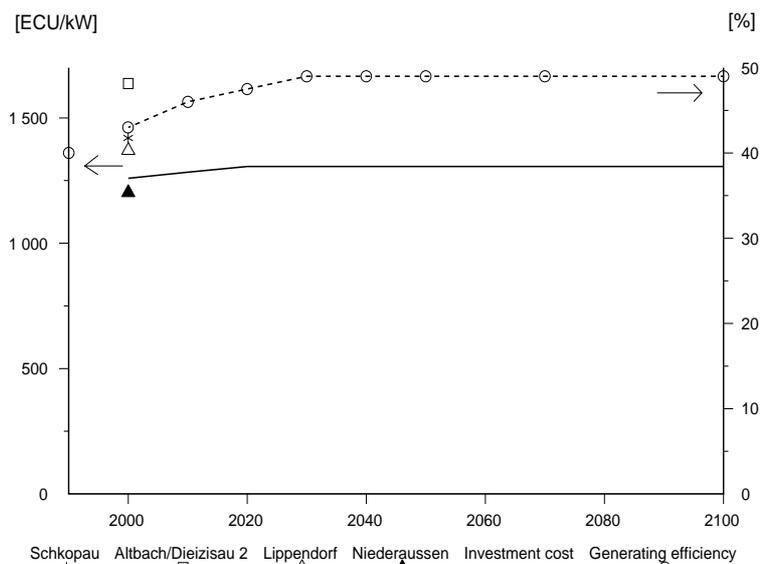
These assumptions are in agreement with [41], an FZ Jülich study for SERF.

Alternatively, IGCC with CO₂ capture and geological disposal could be applied:

- Investment cost ECU 1820/kW in 2010, decreasing to ECU 1710/kW in 2040.
- Net generating efficiency increasing from 43% in 2010 to 45.5% in 2040.

This technology has to be developed. Parameters have been derived from e.g. [44]. The option of CO₂ capture and geological sequestration is included in the models's database.¹⁰

Lignite-fired power plants are based on live steam parameters of 580°C and 260 bar [41], with net efficiency of about 43%. This optimised technology can be improved by integrated lignite drying in a fluidised bed with utilisation of the condensation heat of the water vapour [41]. Investment cost and net generating efficiency are shown in Figure 3.6.

Figure 3.6 *Development of lignite-fired power with use of latent heat of lignite*

Source: [41, 45, 46, 47, 48, 49]

This figure shows investment cost of lignite-fired power plants, built or to be constructed, on the left side. Investment costs range from ECU 1200/kW to ECU 1640/kW [45 - 49], depending on size and number of units. Lignite-fired power has the following characteristics [41]:

- Investment cost increasing from ECU 1260/kW in 2000 to ECU 1300/kW in 2020,
- Investment cost of desulphurisation and low-NO_x burners included,
- Net generating efficiency increasing from 43% in 2000 to 49% in 2030.

¹⁰ CO₂ sequestration in the Atlantic Ocean has not been taken into account due to lack of information and presumed lack of public acceptance.

Newly built gas-fired plants in Western Europe are mainly combined cycle plants. Other gas-fired options, like gas turbine power plants (Combined Heat and Power, CHP), and Total Energy (gas engines), are also included in the model. Characteristic parameters of a combined cycle power plant for district heating are shown in Figure 3.7. Investment costs are estimated at ECU 540/kW. Efficiency increases from 56% in 2000 to 60% in 2040.

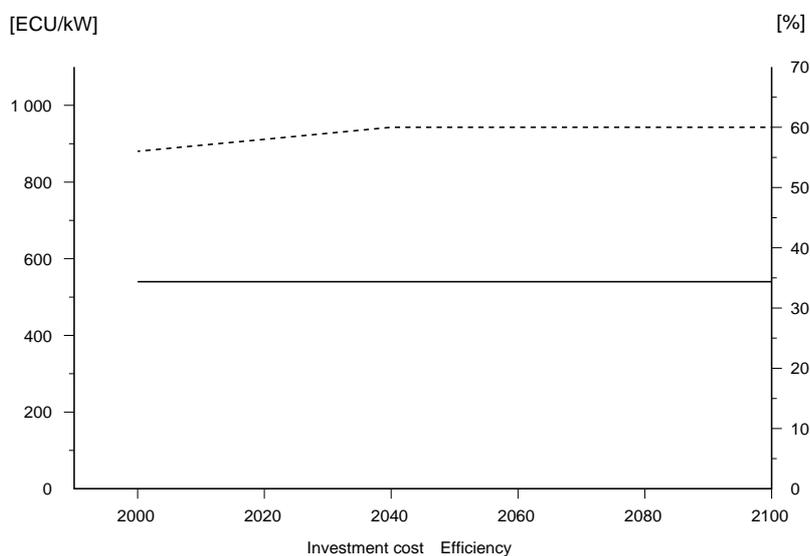


Figure 3.7 Development of gas-fired combined cycle for district heating

Alternatively, SOFC fuel cells integrated with a combined cycle power plant could be developed. It is assumed that this option will become available in 2010 (Figure 3.8).

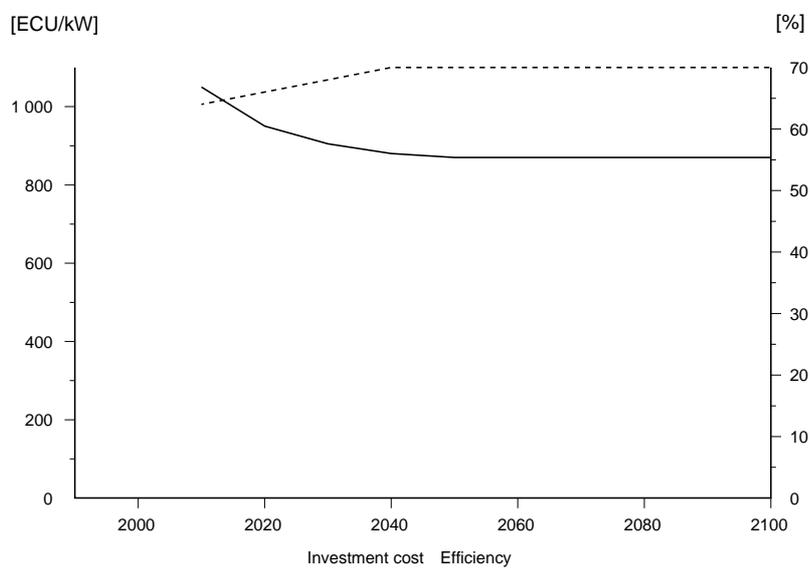


Figure 3.8 Development of SOFC integrated combined cycle for district heating

Parameters of SOFC fuel cells integrated with a combined cycle power plants are:

- Investment cost decreasing from ECU 1050/kW in 2010 to ECU 870/kW in 2050¹¹.

¹¹ In [41] Kolb gives a figure of DM 1400/kW (1997), which is roughly ECU 700/kW (1990).

- Net generating efficiency increasing from 64% in 2010 to 70% in 2040.

3.4.2 Fission power

Nearly all of installed nuclear power plant capacity in Western Europe is based on LWR technology. An alternative with attractive safety characteristics is the helium cooled High Temperature Reactor (HTR). Relatively small HTRs might become competitive to large LWRs. The HTR could use thorium instead of uranium. However, LWRs could probably use thorium too, if need would be. For modelling purposes it is not relevant if future fission reactors would be LWRs or HTRs. Other reactor types are not considered, either because they are questionable from the point of view of public acceptance (fast breeder reactors) or because information is hardly available (Energy Amplifier concept, see [41]). Investment cost estimates of LWRs are shown in Figure 3.9.

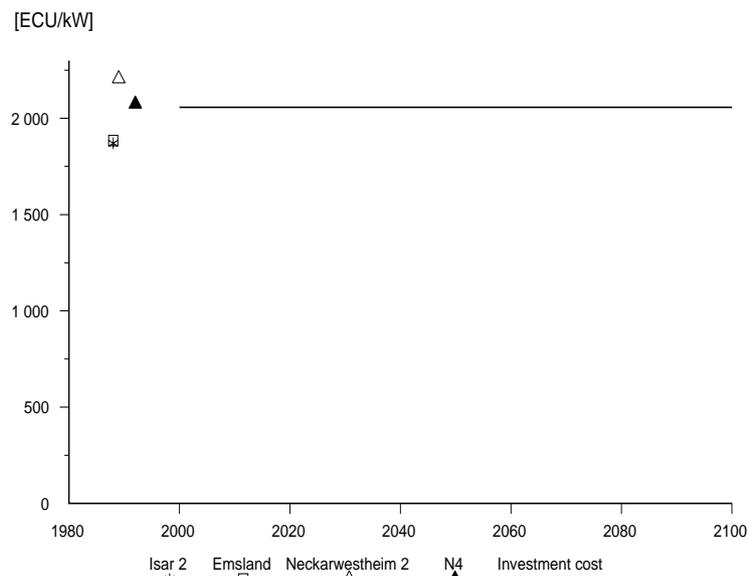


Figure 3.9 *Development of investment cost of LWR*

Investment costs of three German Konvoi plants, commissioned around 1988, as well as one N4 (planned but never been built in Belgium) are shown on the left side. Investment costs range from ECU 1870/kW to ECU 2200/kW [46, 47]. These figures include the first core and interest during construction (IDC), based on a discount rate of 5%. A representative investment cost figure is ECU 2060/kW, almost the same as investment cost of the EPR¹².

3.4.3 Fusion power

In [2] Gilli and Kurz give a detailed assessment of the economics of fusion power as a contribution to Macro task SE0 of SERF. As this study became available in an early stage of the SERF programme, the results are used as reference in the present study. However, other cost estimates are used in the sensitivity analysis. Investment costs of a single 1000 MW and a twin 1500 MW fusion power plant are shown in Figure 3.10.

¹² In [41] investment costs of the European Pressurised Water Reactor (EPR) are estimated at ECU 1600/kW in ECU's 1990, which is equal to ECU 1900/kW in ECU's 1995.

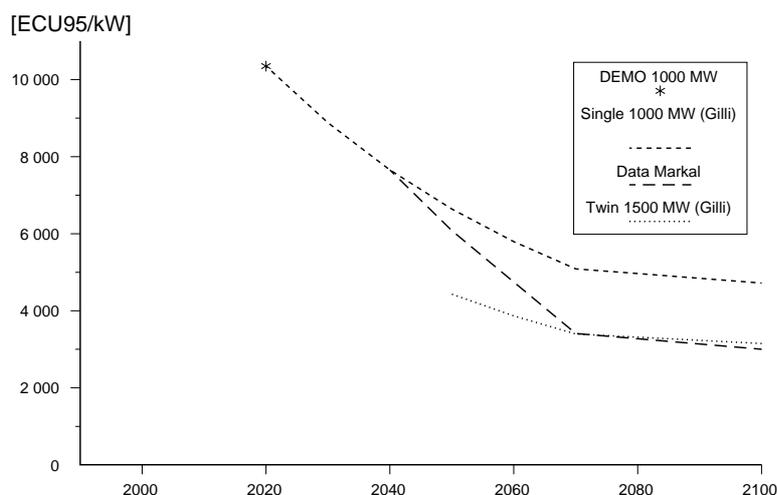


Figure 3.10 *Development of investment costs of fusion power plants*

Source: [2]

The study of Gilli and Kurz is based on analysis of the stage of development and demonstration on the one hand, and the stage of commercialisation on the other hand. In the first stage emphasis is on technical innovation and demonstration of the technical and economic feasibility. In that stage, investment costs come down rapidly.

The stage of commercialisation (after 2050) is characterised by technological learning due to technical innovations as well as production of a sizeable number of plants. In this stage costs come down more slowly. Two trends can be identified, based on [2]:

- Investment cost of a 1000 MW fusion power plant boils down to ECU 4440/kW.
- Investment cost of a twin 1500 MW fusion power plant or a single 2000 MW fusion power plant decreases from ECU 3210 in 2070 to ECU 2980/kW in 2100.

The investment cost of a twin 1500 MW fusion power plant is derived from the corresponding cost of a single 1000 MW fusion power plant, taking into account cost degression with unit size and cost degression with number of units at one site. Because of these two degression factors, the investment cost of a twin 1500 MW fusion power plant is 33% lower than that of a single 1000 MW plant, according to Gilli and Kurz [2].

Investment cost is assumed to decrease along the upper line, representing a single 1000 MW plant, until 2050. After that, investment costs approach the bottom line of a twin 1500 MW plant. Investment costs come down to ECU 3000/kW for a twin 1500 MW plant in 2100, consistent with the study of Gilli. This figure is based on a discount rate of 5% for inclusion of Interest During Construction (IDC). With higher discount rates (8 or 10%) the value of IDC is higher, and investment costs are correspondingly higher too.

3.4.4 Conventional and new renewables

Conventional renewables like hydro power have been addressed in [15], a study focusing on Western Europe until 2050. Data on investment cost, load factor, and minimum and maximum capacity of hydro power in Western Europe are still valid. For biomass fuelled power a range of options is available, which have been described in a recent analysis aimed at the quantification of the CO₂ reduction potential of biomass technologies for the Netherlands [48]. The availability of biomass in Western Europe has been analysed in [49].

Data on wind energy - onshore (inland and shore), near-shore, offshore - in Western Europe have been updated compared to [15]. Some salient data are shown in Figure 3.11.

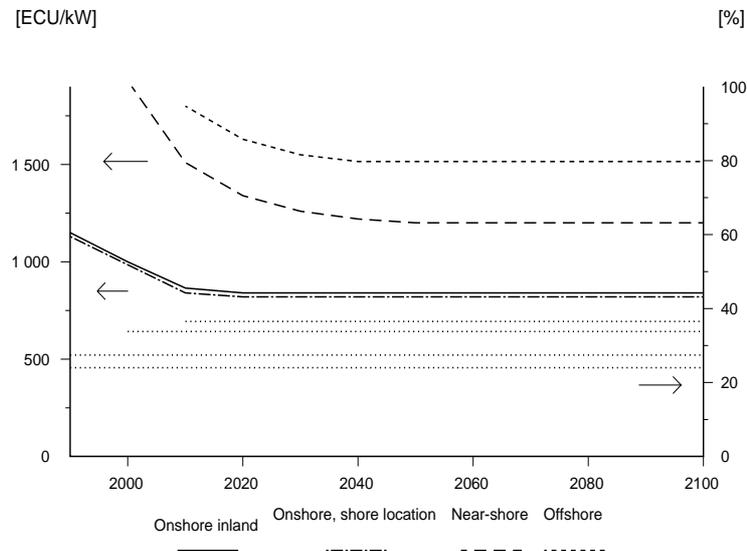


Figure 3.11 *Development of investment cost of wind turbines and average load factor for four different regions*

The two onshore regions considered are:

- Inland
- Shore location.

Ultimate investment costs are nearly the same, viz. ECU 840/kW and ECU 820/kW respectively in 2020. The average load factor is 24% and 27.4% respectively. The potential of inland locations is estimated at 33 GW, and that of shore locations at 42 GW.

Offshore is divided in two regions: near-shore (less than 10 km from the shore) and offshore. The investment costs of near-shore wind level off at ECU 1220/kW, and those of offshore wind farms at ECU 1550/kW in 2040. The average load factor is 33.8% and 36.5% respectively. The potential is estimated at 12.5 GW and 112.5 GW respectively.

The original MARKAL model for Western Europe until 2050 [15] included photovoltaic power (PV) for two Western European regions. The categories have been changed and reshuffled to four categories. Investment costs and load factors are shown in Figure 3.12.

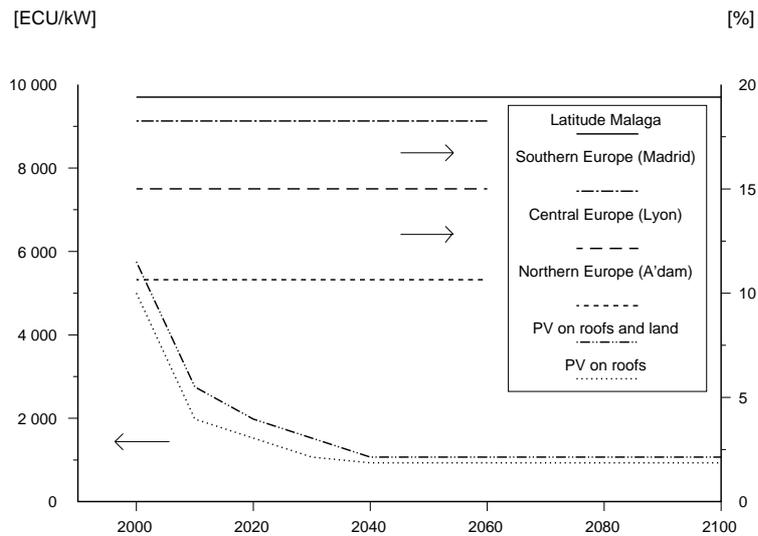


Figure 3.12 *Development of investment cost of solar PV and average load factor for four regions of Western Europe*

The two types of solar PV considered are:

- Average of roofs and land in Southern Europe with costs decreasing to ECU 1070/kW.
- Roofs in the three other regions, with costs decreasing to ECU 930/kW.

The average load factor ranges from 10.6% in Northern Europe to 19.4% on the latitude of Malaga. The potentials of the four regions in the year 2100 are estimated at:

- Northern Europe (central UK, IRL, NL, B, northern Germany, DK): 120 GW
- Central Europe (FR, Southern Germany, CH, AU): 180 GW
- Southern Europe (central Spain and Italy): 125 GW
- Latitude Malaga (most southern Spain, Italy, Greece): 50 GW

Besides, solar thermal power plants are available at the latitude of Malaga (investment cost decreasing to ECU 2200/kW, average load factor 25%, potential 5 GW) [50, 51]. The total potential of solar power (PV and solar thermal power) is estimated at 480 GW, whereas the potential of wind turbines is estimated at 200 GW (75 GW of which onshore).

A mature renewable option is tidal energy. A famous example is the tidal power station la Rance in France, which has been operating for 30 years. Other tidal power schemes are proposed for the UK (Severn estuary). Investment costs are estimated at ECU 1775/kW, the average load factor at 23%, and the Western European potential at 9.68 GW [52, 53].

Wave energy is a new renewable option. Countries with a relatively large wave energy potential are Portugal (2.4 GW) and Ireland (1.2 GW). A new device, called Archimedes Wave Swing with an installed capacity of 8 MW for each module, makes effective use of the energy in long waves on the Atlantic coast. Investment costs are estimated at ECU 1615/kW in 2040, the annual load factor is 50%, its potential is estimated at 4 GW [54].

3.4.5 Exotic renewables

Kolb gives an overview of 'exotic' renewables in the contribution of FZ Jülich to Macro task SE0 [41]. One of the 'exotics' is the so-called MegaPower Tower [55]. In a cable-rigged pipe, 5,000 m high and 50 m in diameter, the temperature difference between sea level and at great height is used: NH_3 is evaporated by sea water, ascends and condenses at the top in a voluminous condenser of 300,000 t. The vertical support is delivered by hydrogen in hydrogen-filled buoyancy compartments. The kinetic energy of NH_3 falling back to sea level is used to drive turbines, the total capacity of which amounts to 7 GW. An improvement upon this design is a two-cycle and two-media concept (NH_3 and hydrogen), based on a tower height of 7,500 m and a diameter of 2,500 m at sea level. NH_3 circulates between sea level and a condenser at 3,500 m, where it condenses due to the cooling effect of cold hydrogen circulating between 3,500 and a cooler at 7,500 m. Construction of such a MegaPower Tower could be feasible, but its costs are uncertain.

A rather futuristic option is space-based solar power. Sunlight is converted into electrical power via thin-film PV arrays in a geostationary orbit above the equator (about 36,000 km height). Electric power is converted into radio (micro) waves, beamed by wireless power transmission to ground-based receiving stations, reconvertng it to AC power to be provided to regular electric power grids. The system efficiency (from solar DC electricity to AC in the power grid) is around 54%, which could be increased to 70%. The sun shines 24 hours per day, except for 1% of the time when the orbit is in the earth's shadow. First rough cost estimates project a cost of 9 to 16 US\$/kWh in North Africa (the same latitude as part of the US).

Another 'exotic' option is the Solar Energy Tower of Zaslavsky of Techion (Israel) [56]. It is a project initiated more than a decade ago to utilise solar energy in desert areas for production of low cost electricity and desalinated water. The Solar Energy Tower uses the latent heat of evaporation and a natural, low efficiency, thermodynamic cycle:

- Sea water is transported by pipeline to a desert area.
- After filtration the water is pumped to the top of a tower of 1,200 m height and 400 m diameter (main shaft).
- Using the warm dry air at that height, the water is partly evaporated by spraying at the top of the tower, which causes a strong downdraft of cooled air.
- The air flows downward through the tall and large diameter shaft and drives air turbines and generators located radially around the base of the shaft.

A major improvement compared to the less efficient updraft open-cycle energy tower is the availability of hot air day and night. Power produced by such a Solar Energy Tower can be used for desalination of sea water in view of irrigation and drinking water needs. Zaslavsky projects electricity costs of a Solar Energy Tower at 3.7 €/kWh, assuming a 7.27% interest rate and a lifetime of 30 years (at 5% interest rate it would be 2.9 €/kWh).

It is certain that some exotic options will prove to be feasible. However, two of the above mentioned options are not very appropriate for the latitude of Western Europe: space based solar power and the Israeli Solar Energy Tower. The remaining third option, MegaPower Tower, could be applied in North Western Europe. The MegaPower Tower, however, poses a relatively large technical-economic risk in case of a first-of-a-kind plant.

Two other important notions in this respect are availability and geopolitical dimensions. The MegaPower Tower does not produce real base-load power, as the load factor is reduced by seasonal fluctuations of the temperature difference. The other two options would require power transmission from Northern Africa with its geopolitical dimensions. However, it should be noted that import of oil and gas also has geopolitical dimensions.

3.4.6 Production cost of different power generation technologies

Figure 3.13 shows the generation costs for the main power generating technologies for the year 2100, a discount rate of 5% and fossil fuel prices as assumed for the RP scenario in 2100. Fusion power is among the more expensive power generation technologies. Power generation from fission power is less expensive. Therefore, fission power would be favoured over fusion power in a situation without acceptance constraints for fission power.

It comes out that the gap between e.g. fusion power and renewable options like offshore wind and PV at central European latitude is rather small towards 2100. Taking into account the intermittent nature of wind and solar energy, it is allowed to generalise that fusion power and new renewables like offshore wind and PV at central European latitudes have generation costs which are of the same order of magnitude.

More information about the technologies considered and their comparative generation costs is presented in [40].

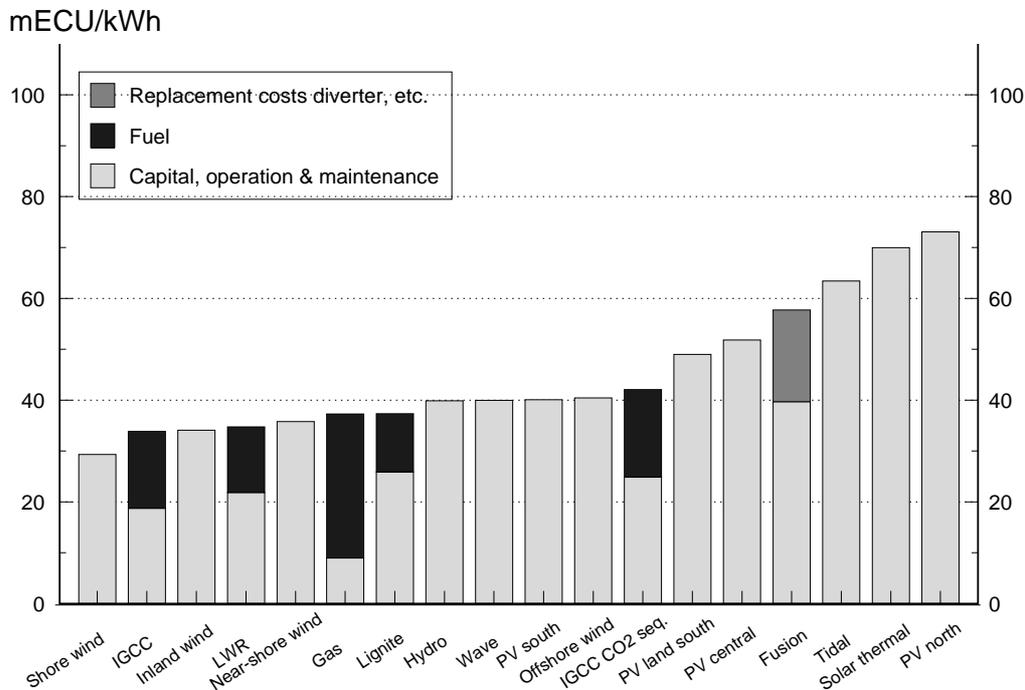


Figure 5.2 Comparison of generation cost of some representative power generation options of the 21st century, discount rate 5%, year 2100

3.5 Constraints to technologies

Some of the energy technologies incorporated in the MARKAL model are well known, e.g. proven coal and gas-fired power technologies. A lot of technologies are in the stage of development, demonstration, or (early) implementation, e.g. wind energy, biomass-fuelled power, PV, and other renewable options. Whether a long term option with a more speculative character like fusion power is included as an option in the model, depends on the time horizon used. The time horizon of the present study enables inclusion of fusion power.

Energy technologies that comply with a few requirements - availability of data on cost, performance and (long term) potential, sufficient public acceptance - have been included as options in the model. Inclusion in the model's data base implies that the technology can be made available to the extent of its competitiveness with other technologies in a certain period. A cumulative CO₂ constraint may have a large impact on the economic performance of energy options. One should consider possible technical-economic constraints to the wider application of technologies. For instance, wind energy and PV have been split in several categories, depending on wind regime and solar irradiation respectively. Each category has an upper bound in a specific period. Besides, the potential of a technology can be regulated by an upper bound on the investment per period of 10 years.

In this way optimisation with the model may provide plausible results. However, sometimes an additional constraint is needed. This is a growth constraint. If PV would not be cost effective in the first decades of the 21st century, MARKAL optimisations could show a negligible amount of PV until e.g. 2020, with a very fast growth after that, still within the bounds mentioned above. However, energy technologies have growth limits. So, for options like PV and fusion power an additional growth constraint has been added.

Public acceptance may have impacts on some technologies. Generally, the constraints assumed for a technology are not determined by public acceptance. The boundaries for wind power are more dependent on physical and geographical bounds than on subjective aspects like visual obtrusion. This could well lead to some overestimation of the practical potential of wind energy. However, it is certain that the physical constraints are so remote that a somewhat smaller on-shore wind energy potential could easily be compensated by a larger application of offshore wind farms. The only difference is then the total cost of a certain amount of wind capacity. It is an economic overestimation, not a physical one.

Public acceptance is not straightforward. However, it is difficult to imagine a Western European energy system largely based on fast breeder reactors. The fast breeder reactor has not been included in the model. Fission power based on LWRs (or HTRs) is considered as more or less accepted by the public. The capacity of fission power plants is assumed to decrease slowly to 70 or 80% (dependent on the scenario) of current capacity in 2070 with a further decline towards the end of the 21st century (see table 3.9). It is noted that one sensitivity analysis also included a substantial increase in the fission capacity. A partial substitution of coal or gas-fired power or even renewable energy for fission power in Western Europe is deemed possible. In a sensitivity analysis a gradual phase out of fission energy in the course of the next century has been assumed, in order to analyse its impact on the potential of competing technologies such as fusion power.

Table 3.9 *Default constraints assumed for energy technologies in Western Europe for the year 2100*

Hydro power	184 GW
Wind power onshore and offshore	200 GW
Photovoltaic power (PV)	475 GW
Fission power	40 GW
Fusion power	157 GW
CO ₂ sequestration	520 Mton CO ₂

Note: sensitivity analyses (see Chapter 6) include wider potentials for fission power and renewables.

3.6 Environmental policies to reduce CO₂ emission

Within the time horizon until 2100 a range of policy targets with respect to the reduction of greenhouse gases is possible. This section explains alternative emission targets for Western Europe and how these emission targets have been derived from the results of some key studies of the Intergovernmental Panel on Climate Change (IPCC).

The pre-industrial atmospheric CO₂ level was 280 ppm. Recently the CO₂ level surpassed the 360 ppm level. It is not possible to select one single reduction target for greenhouse gases. Our knowledge of the climate system, climate effects and effects on mankind is not sufficient to determine which atmospheric concentration levels are not dangerous. Therefore, IPCC has recently proposed a range of stabilisation levels in a Technical Paper [57].

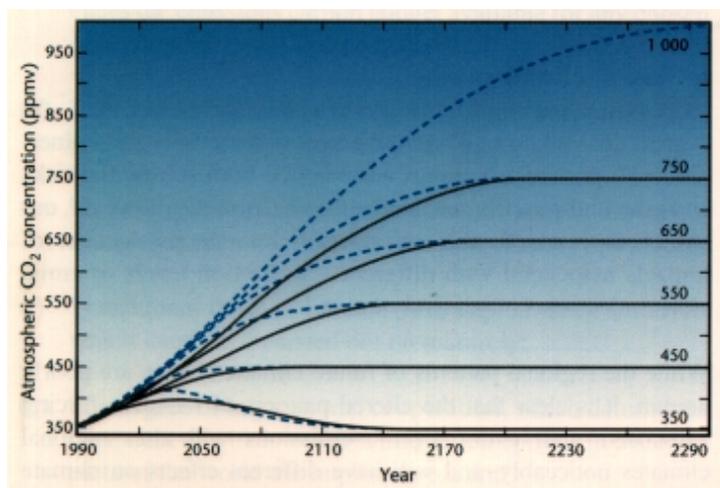


Figure 3.14 *Profiles of CO₂ leading to stabilisation at concentration from 350 to 1000 ppm [57]*

The CO₂ stabilisation scenarios which have been analysed by IPCC consider the period between 1990 and 2300. The stabilisation levels that have been explored range between 350 ppm and 1000 ppm (see Figure 3.14). The IPCC has also calculated the emission budgets between 1991 and 2100 that will lead to the various stabilisation levels. The emission budgets for this period range between slightly more than 300 Gt carbon and 1410 Gt carbon (see Table 3.10). These emissions correspond to stabilisation levels of 350 ppm and 1000 ppm respectively. It is noted that the global CO₂ emission from commercial fossil fuels in the year 1996 amounted to 6.3 Gt carbon (this figure is calculated from fossil fuel production data reported in BP statistics [58, 59]).

Table 3.10 *Global Cumulative CO₂ emissions 1990-2100 linked with various long term CO₂ stabilisation levels*

Global stabilisation level	[ppm]	350	450	550	650	750	1000
C	[Gt C]	308	630	878	1,068	1,213	1,410
CO ₂	[Gt CO ₂]	1,129	2,310	3,219	3,916	4,448	5,170

Note: The figures have been derived from [57].

It is noted (by IPCC) that somewhat different paths of concentration over time are also possible that will eventually lead to the same stabilisation level. Besides, mechanisms not included in simplified carbon cycle models could affect the result significantly. Biospheric exchange could modify the cumulative emission from fossil fuels during stabilisation by ± 100 GtC. In addition, there is uncertainty in climate feedbacks through e.g. ocean circulation and biogeochemistry. This could also noticeably modify the fossil fuel emissions consistent with stabilisation [57]. Finally, other greenhouse gases also change the radiation balance of the atmosphere. CO₂ has had, and is projected to have, the largest effect on radiative forcing. On the one hand the cumulative relative contribution of methane, nitrous oxides and halocarbons over the period 1990-2100 is projected to increase the radiative forcing of CO₂ with 27% to 39% depending on the IPCC92 emission scenario that is compared with. On the other hand the effect of sulphate aerosol could reduce the net radiative forcing from CO₂ with 13% to 21%.

Share of Western Europe in CO₂ emissions of the 21st century

To calculate emission budgets for Western Europe from global emission budgets requires allocation of emission budgets between world regions. Allocation rules for the differentiation of commitments between regions is an unresolved issue. Per capita CO₂ emissions differ substantially between world regions for a multitude of reasons. Further, emission projections without CO₂ policies indicate large autonomous growth in developing countries while the emission levels for the industrialised countries will grow more modestly. In 1990 and 1995 the share of Western Europe in the global CO₂ emissions was approximately 14.5% but this share will drop due to the larger growth in developing countries. Below, some possible allocations of emission budgets for Western Europe will be derived from the current emission distribution and from the results of existing global emission scenario studies.

The IPCC 1992 report [60] included 6 scenarios (IS92a - IS92f) with emission figures per world region. In the IS92a scenario, a scenario with substantial economic growth and no greenhouse gas reduction policy, the world's annual CO₂ emissions increase until 72 Gt CO₂ in 2100. The cumulative CO₂ emissions of IS92a between 1990 and 2100 amount to 5366 Gt CO₂ of which 590 Gt CO₂ occur in OECD Europe (11% of total). The IS92c assumes severe constraints for fossil fuel supplies, this results in much lower CO₂ emissions than in IS92a (see Table 3.11).

Table 3.11 *Cumulative CO₂ emissions 1990-2100 according to IPCC 1992 scenarios, calculated by linear interpolation of annual emission figures*

		IS92a	IS92b	IS92c	IS92d	IS92e	IS92f
Global cumulative CO ₂ emissions 1990-2100	[Gt C]	5,366	5,110	2,722	3,441	7,801	6,540
Western European cumulative CO ₂ emissions 1990-2100	[Gt C]	546	360	289	348	736	660
Western European share in global CO ₂ emissions	[%]	10.1	7.0	10.6	10.1	9.4	10.0

Note: The emissions for Western Europe have been calculated from the OECD Europe emission figures by correcting for the projected emissions of Turkey.

The share of the Western European CO₂ emissions ranges between 7% and 10.6% of global CO₂ emissions. Five out of the six scenarios have a share for Western European CO₂ emissions close to 10% of the global CO₂ emissions. Only one scenario differs with a 7% share, assuming that only the industrialised countries take measures to abate emissions while the rest of the world is not reducing its emissions. Here, the 10% share has been adopted to calculate emission budgets for Western Europe.

Calculation of emission budgets for Western Europe

The CO₂ emission budgets for Western Europe are based on the CO₂ budgets in Table 3.9 [57]. As the time period under consideration is slightly different (1990-2100 in the IPCC study versus 1985-2105 in the present study), the emission budgets have been adjusted with a factor 120/110. The emission share for Western Europe is calculated assuming a 10% share of the global share. Emission budgets have been calculated for long term stabilisation levels of 450, 500, 550, 650 and 750 ppm. Stabilisation at 350 ppm (this is below the current atmospheric concentration) or at 1000 ppm has not been considered. The resulting emission budgets are presented in Table 3.12.

Table 3.12 *CO₂ emission budgets for Western Europe for the period 1985-2105 for different stabilisation scenarios*

Global stabilisation level	[ppm]	450	500	550	650	750
Cumulative CO ₂ emissions 1985-2105	[Gt CO ₂]	252	305	351	427	485

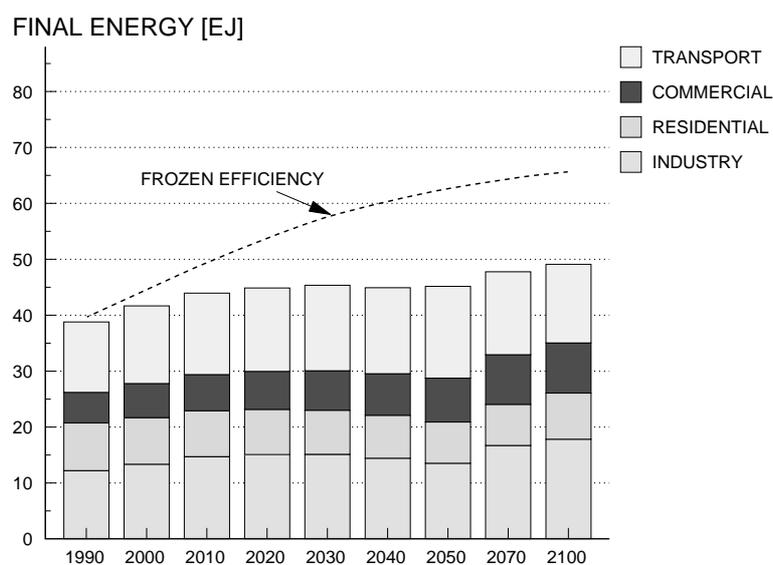
Note: Budgets for Western Europe have been calculated assuming a 10% share of global emissions.

4. TWO SCENARIOS WITHOUT CO₂ CONSTRAINTS

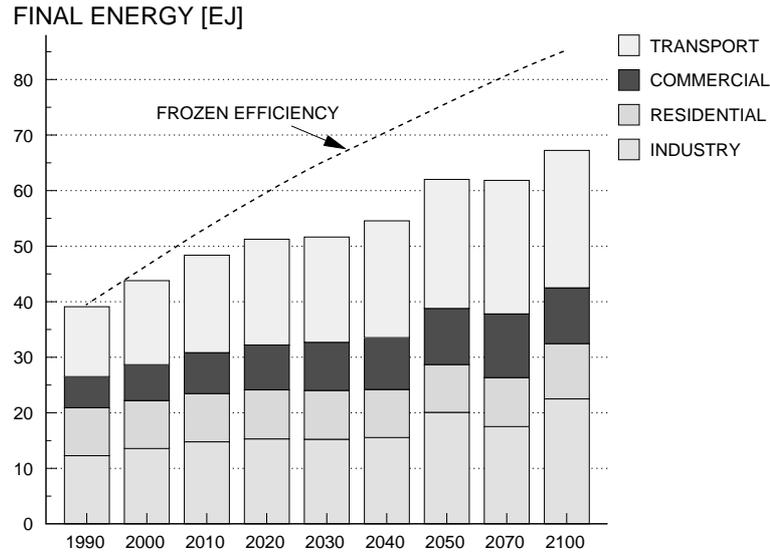
This chapter presents the two scenarios that have been developed. The assumptions behind the scenarios have been described in Chapter 3. The discussion of results pays some attention to the results for end-use sectors (Section 4.1). However, emphasis is on the power generation sector as this study focuses on the future prospects of fusion power.

4.1 Sectoral results

The final energy demand projection in Figure 4.1 is considerably lower than the final demand projection in case of frozen efficiency. This is due to substantial increases in the efficiency of end-use technologies. The larger part of the efficiency improvements involves explicit technology changes within the MARKAL model. In some cases, however, it also involves autonomous efficiency improvements, e.g. as a result of larger sized aircraft and increased seat occupancies in air transport. In scenario RP more efficient technologies are introduced than in scenario MD, due to the lower discount rate in scenario RP.



Figures 4.1a Final energy demand per sector in the base case of Rational Perspective, dashed lines represent final energy demand



Figures 4.1b *Final energy demand per sector in the base case of Market Drive, dashed lines represent final energy demand*

The range in developments in electricity demand in Rational Perspective and Market Drive including the results with scenario variants of CO₂ reduction policy is shown in Figure 4.2.

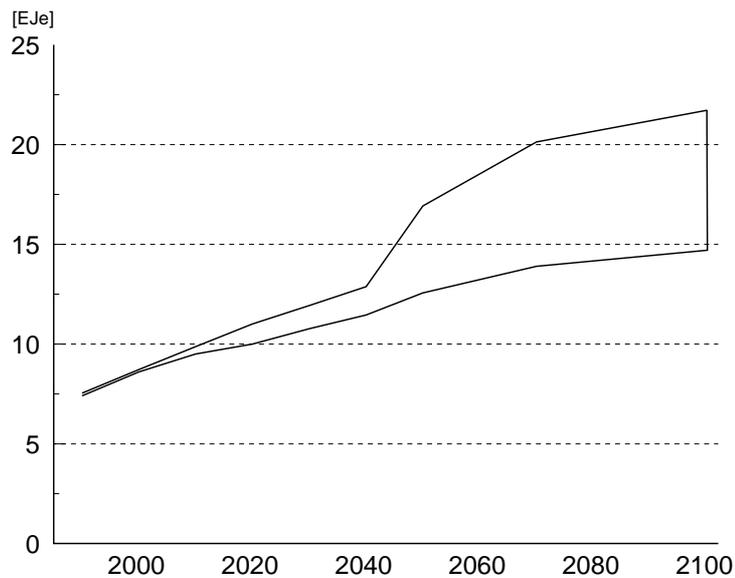
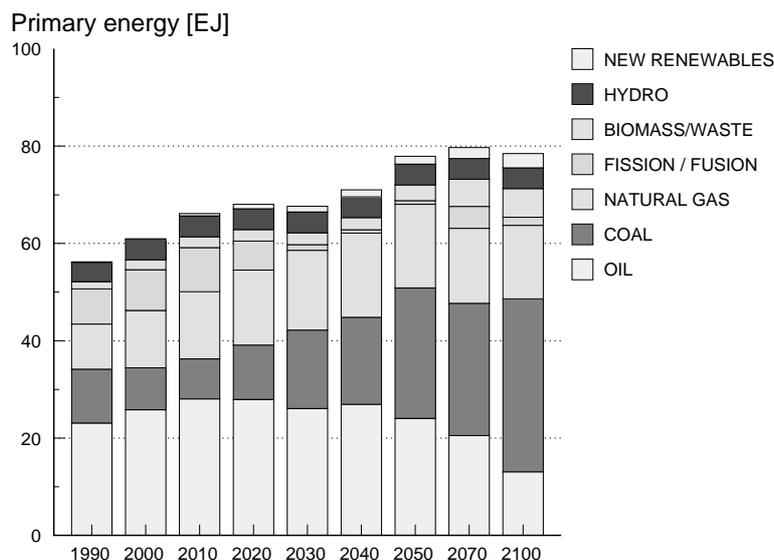
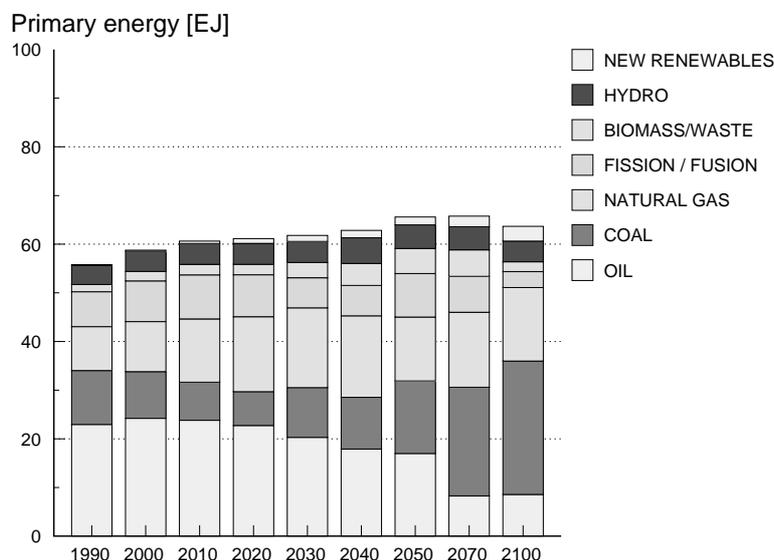


Figure 4.2 *Range of electricity demand in the scenarios and variants*

The increase in electricity demand ranges until 2050 between 70% and 130% compared to the 1990 electricity demand. In some of the scenario variants electric heat pumps and electric passenger vehicles gain a large market share, which results in a considerable jump in power consumption after 2040. It is noted that electricity demand grows faster in the scenarios with CO₂ constraints due to substitution of fossil fuels by electricity e.g. for space and water heating and for passenger transport.

4.2 Primary energy mix

The total level of primary energy demand (Figure 4.3) is in line with the development of total final energy demand (see Figure 4.2), with an almost constant energy requirement for scenario RP, and a slightly increasing energy requirement for scenario MD.



Figures 4.3a and 4.3.b Total primary energy mix for the base cases of the scenarios Rational Perspective (top) and Market Drive (bottom)

Several changes in the fuel mix occur over time. Changes until the year 2030 are largely in line with the earlier MARKAL study until 2050 [14, 15]. Oil consumption remains rather flat, gas consumption increases until 2020, and coal consumption decreases first (until 2010) and rises again after that. Trends for oil, gas, and coal are more or less the same for both scenarios. New renewables (wind, biomass) gain a small share of about 7% in 2050.

After 2030 appreciable changes occur. Coal becomes the dominant energy source with a share in TPER (Total Primary Energy Requirement) of about 50% in 2100. The contribution from oil decreases considerably, mainly due to the cumulative resource constraint imposed. New renewables - wind, biomass, PV - are more important in 2100 than in 2050.

The development of fission energy is different for the two scenarios. In case of scenario RP fission energy shows some decline until 2040, and a revival after that. The higher discount rate governing investment decisions for power generation in scenario MD causes a virtual phase-out until 2070, when fission energy shows some recovery.

The energy prices for fossil fuels are largely determined endogenously in the model. To understand the changes occurring in the fuel mix, it is important to know the development of the shadow prices. Figure 4.4 gives the shadow prices for four energy carriers in the RP scenario.

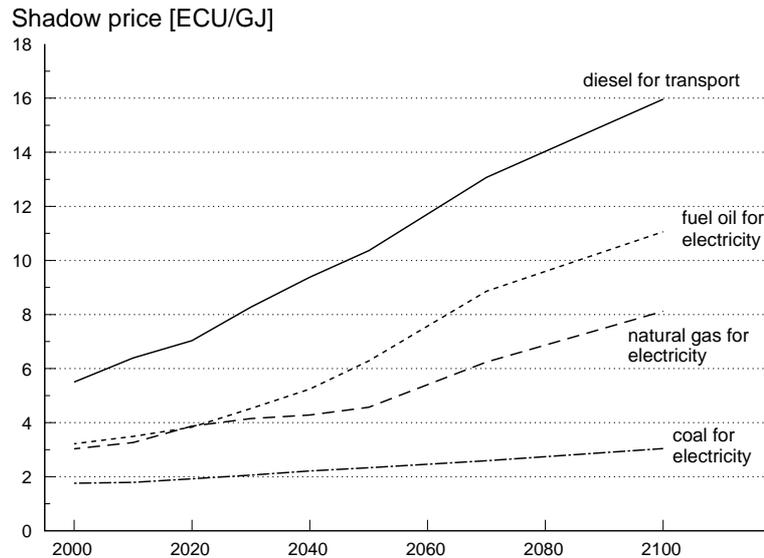


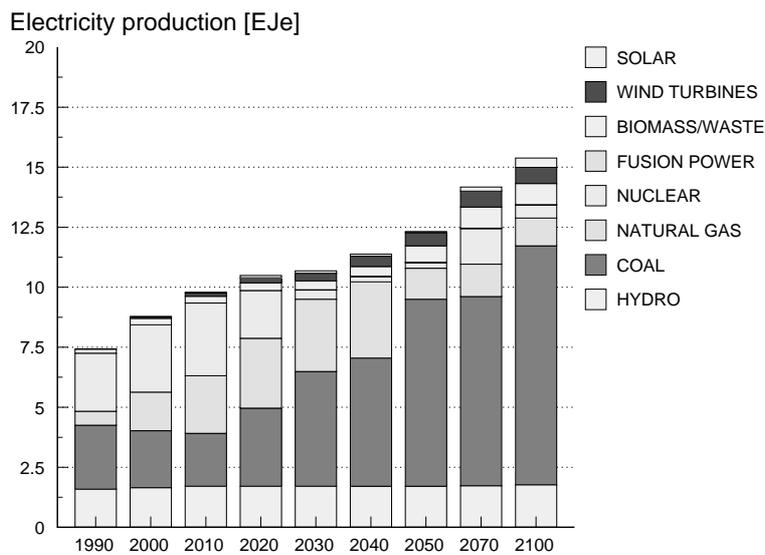
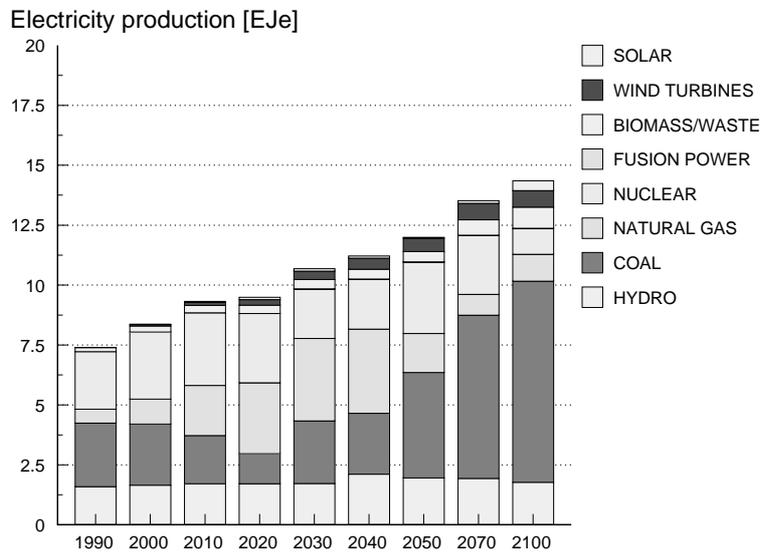
Figure 4.4 *Shadow prices of diesel, fuel oil, natural gas and hard coal in the base case of the RP scenario*

In the unconstrained RP scenario (base case) the shadow prices for oil products and natural gas show a significant increase over time due to scarcity. By the year 2100 the shadow price of heavy fuel oil amounts to ECU 11/GJ. In 2100 the shadow price of natural gas is ECU 8/GJ. The shadow price of hard coal shows a much more moderate increase. It is noted that the shadow prices in the MD scenario show a similar pattern.

The limited availability of oil and natural gas and the resulting increasing shadow prices lead to efficiency improvements and substitution effects. This is the clearest in the case of oil. Oil products are used in an efficient way e.g. via a wide penetration of more efficient vehicles, oil products have a continuous smaller role for space heating purposes and fuels not based on oil are increasingly used in the transport sector.

4.3 Power generation and the role of fusion energy

The trends for power generation are more pronounced (Figure 4.5) than those of primary energy demand (Figure 4.3).



Figures 4.5a and 4.5b *Power generation by source for the base cases of Rational Perspective (top) and Market Drive (bottom)*

In case of scenario RP coal shows a rather steep decline until 2020. After that, coal regains its current level in 2030 and 2040, and becomes the dominant fuel for power generation in 2050. Natural gas shows a steady increase until 2040. After that, it loses much of its market share to coal. Fission power declines slightly until 2040, but shows a recovery from 2050 onwards. These trends can be explained as follows:

- Coal loses market share to natural gas in the first decades, when the gap between coal and gas prices is still narrow.
- Coal quickly regains its market share from 2030 onwards due to the increasing competitive edge for coal-fired power.
- Fission power declines until 2040, when gas and coal-fired power are cheaper, from 2050 onwards fission power is competitive compared to gas and coal-fired power.

In scenario MD coal shows a small decline until 2010. After that, coal becomes the dominant fuel for power generation. Gas-fired power increases until 2040, but decreases fast after that date. Fission power declines fast after 2020, and shows some revival around 2070. Coal becomes even more important in scenario MD than in scenario RP because of the relatively high price level of natural gas in scenario MD. The more marginal role of fission power is due to the higher discount rate for power generation (8% instead of 5%).

As fusion power is rather costly (e.g. compared to fission power), it cannot compete with alternative base-load power options in the base cases of both scenarios. So, irrespective of the discount rate used, fusion power needs some incentive, such as a cumulative CO₂ constraint, in order to become competitive to coal-fired power. New renewables - wind, biomass, PV - show a modest market share under the same circumstances.

1.3 CO₂ emissions

It is interesting to see what the CO₂ emissions in both of the scenarios are. Total CO₂ emissions are shown in Figure 4.6.

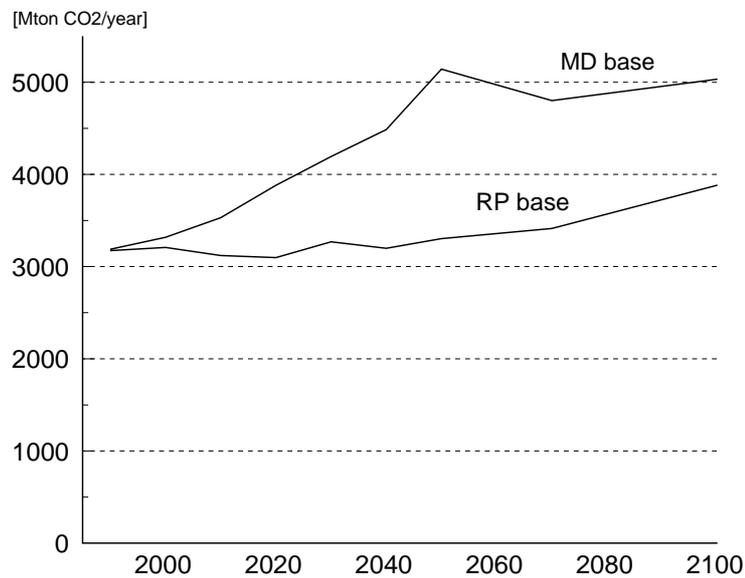


Figure 4.6 *Western European CO₂ emissions, base case scenarios Market Drive and Rational Perspective*

CO₂ emissions are closely related to fossil fuel consumption. In scenario RP primary fossil fuel consumption is stable and changes in the fossil fuel mix are small until 2050 (Figure 4.3). Therefore, CO₂ emissions remain stable until 2050 (Figure 4.6). After that, coal consumption increases at the expense of oil. Moreover, fission power is more and more constrained. CO₂ emissions increase too, ending up 20% higher in 2100 than in 1990.

In scenario MD fossil fuel consumption rises until 2050. After that date, fossil fuel consumption declines (Figure 4.3), whereas the contribution from fission power and new renewables increases. Coal consumption shows a surge from 2020. Particularly in the period 2070-2100 fission power is constrained. CO₂ emissions increase until 2050, and remain rather stable after that date. In 2100 CO₂ emission is 60% higher than in 1990. Figure 4.7 shows the increase of CO₂ emissions from power generation in both scenarios.

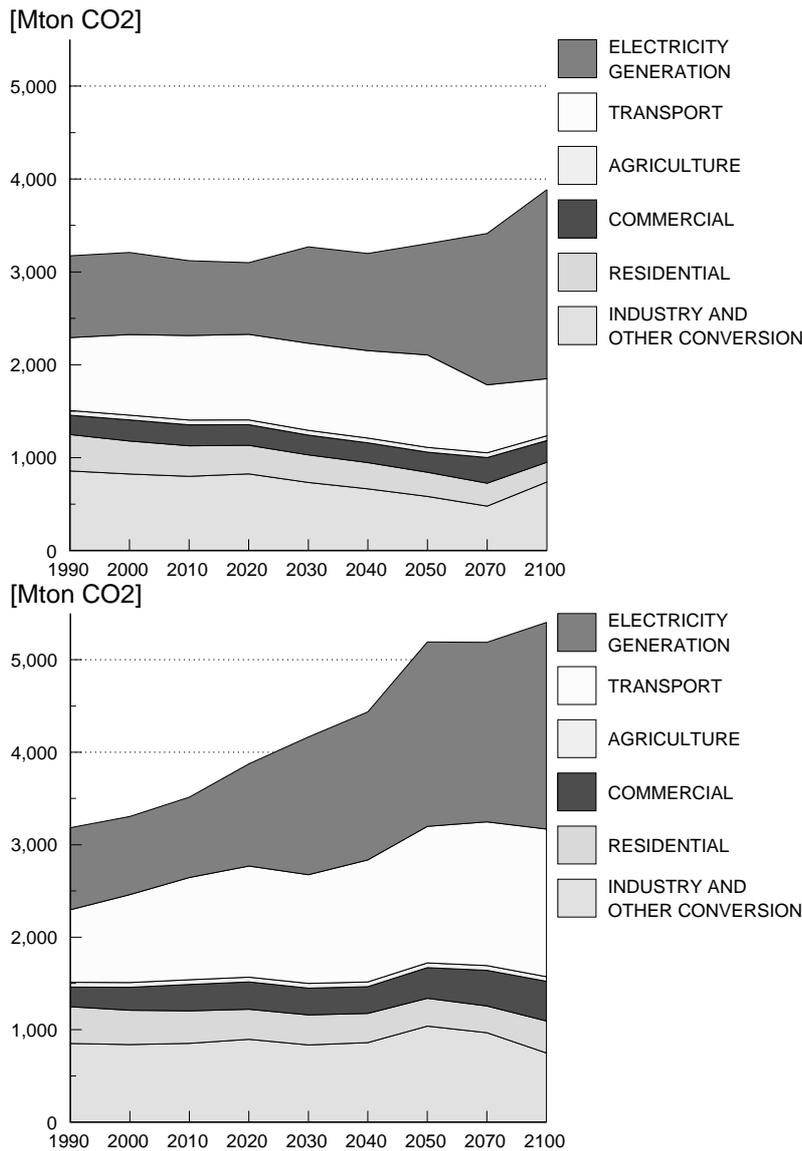


Figure 4.7 CO₂ emissions per sector in scenarios Rational Perspective (top) and Market Drive (bottom)

Some trends seem to be particularly pervasive:

- The power generation sector has the largest share of CO₂ emissions. Some of the CO₂ emissions, particularly in the last half of the next century, are due to increasing substitution of electricity for direct use of fossil fuels in transport. CO₂ emissions from the residential, commercial and agricultural sectors decline steadily in scenario RP. In scenario MD, however, CO₂ emission from the commercial sector increases.
- In both of the two scenarios electric vehicles become economically attractive towards the end of the next century. This is most clearly demonstrated by the decline in CO₂ emissions from 'Transport' in case of scenario RP during the period 2050-2100.
- Moreover, in scenario RP the resource crunch with respect to oil is such that natural gas is used for production of substitutes for oil products (gas-oil, kerosene), which is exhibited by the rebound in the sector 'Industry and other conversion' from 2070 to 2100. This is because natural gas is no longer used to a large extent for power generation nearing the 21st century, thereby leaving room for substitution of natural gas for oil.

2. SCENARIO VARIANTS WITH CO₂ POLICY AND VARIOUS DISCOUNT RATES

2.1 Scenario variants with CO₂ policy

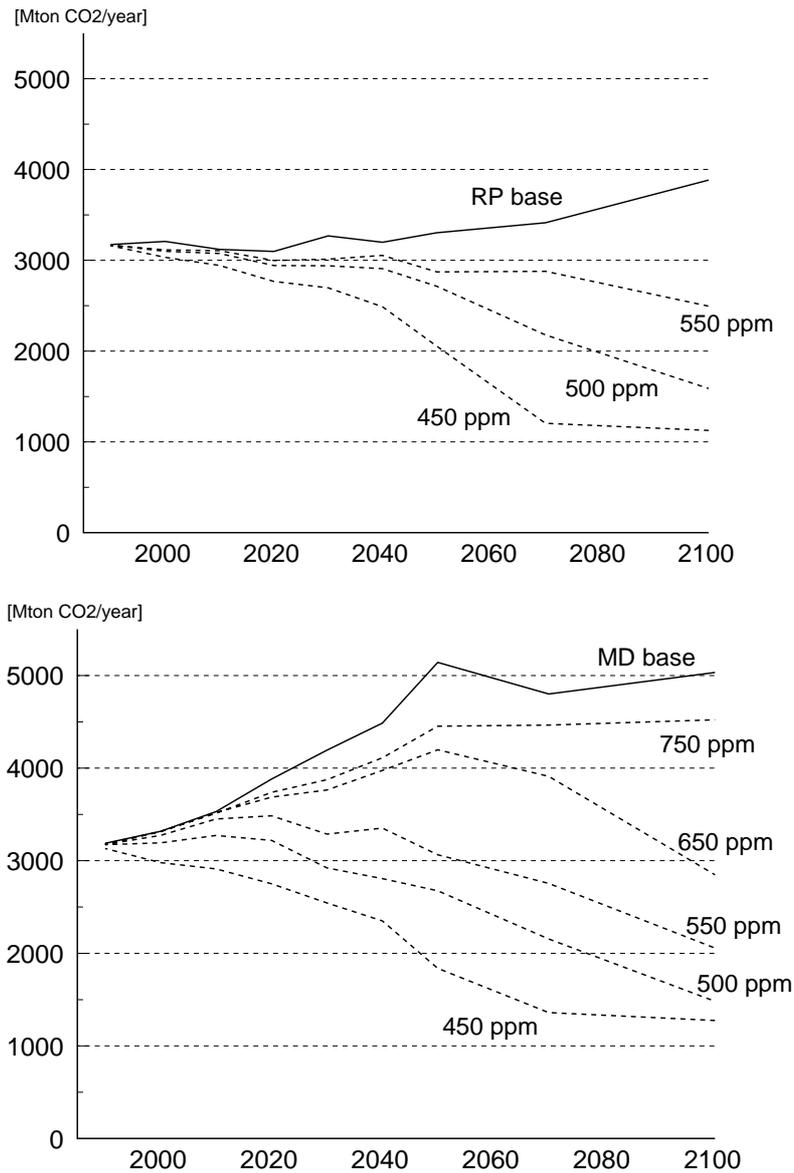
In the base case scenarios (Chapter 4) no CO₂ reduction policy was assumed. Within the time horizon until 2100 several policy targets with respect to reduction of greenhouse gas emissions could be implemented. If CO₂ emissions are constrained, this will affect technology choices within the energy system, eventually triggering fusion power.

2.1.1 Changes in assumptions

CO₂ reduction policy can be instrumented with many kinds of policies. Specific policy instruments have not been considered here. CO₂ reduction policy is simply simulated by putting a constraint on the cumulative CO₂ emission. Several CO₂ budgets are used for the cumulative release of CO₂ from the Western European energy system during the period 1990-2100. Emission budgets are derived from the range of stabilisation targets considered by IPCC [57]. Emission budgets have been calculated for global CO₂ stabilisation levels of 450, 500, 550, 650 en 750 ppm, as set out in Section 3.6. The emission budget for Western Europe is based on a 10% share of the global CO₂ emission.

2.1.2 Results

Figure 5.1 shows the emission patterns, which are optimised over time, of the scenarios Rational Perspective and Market Drive. Emission budgets linked with stabilisation levels of 750 ppm and 650 ppm are not constraining for the Rational Perspective scenario. Thus, these cases are not presented in Figure 5.1a. The unconstrained CO₂ emission of scenario MD corresponds to a higher CO₂ level than any of the CO₂ emission levels contemplated. The most stringent CO₂ reduction case of scenario MD - stabilisation at 450 ppm - leads to an emission of 2550 Mton CO₂ in 2030 (20% below the 1990 level) and of 1350 Mton CO₂ after 2070 (more than 55% below the 1990 level). Similar stringent CO₂ reductions are observed in the 450 ppm stabilisation case of scenario RP.



Figures 5.1a and 5.1b CO₂ emission patterns in the CO₂ variants of scenarios Rational Perspective (top) and Market Drive (bottom)

Figure 5.2 shows the CO₂ emissions from power generation for scenario MD and its variants. The CO₂ emission from power generation in the unconstrained MD scenario increases with more than 150% in 2100 compared to 1990. This is because electricity demand rises and coal becomes the dominant fuel for power generation (fission power becomes more and more constrained towards 2100). In the 650 ppm CO₂ reduction case the CO₂ emission in 2100 is below the 1990 level. In the more stringent CO₂ reduction cases it ends up at a level of about 300 Mton CO₂, which is 65% below the 1990 level.

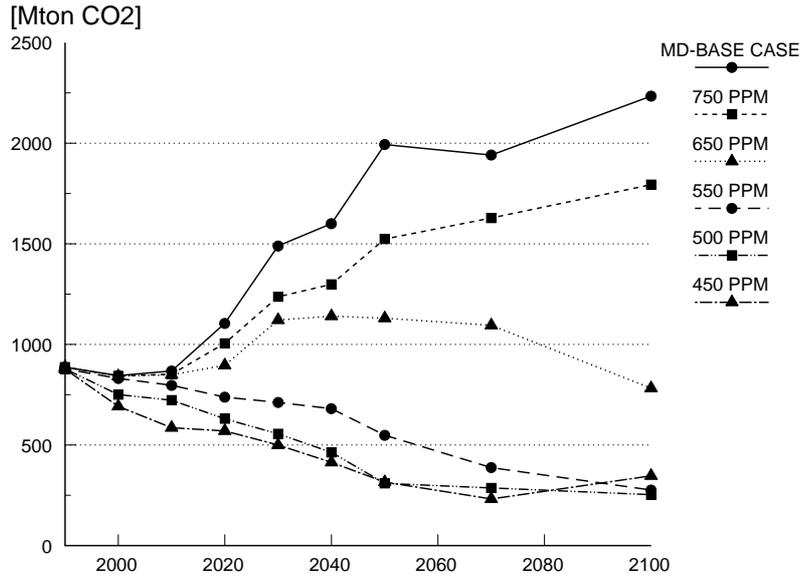


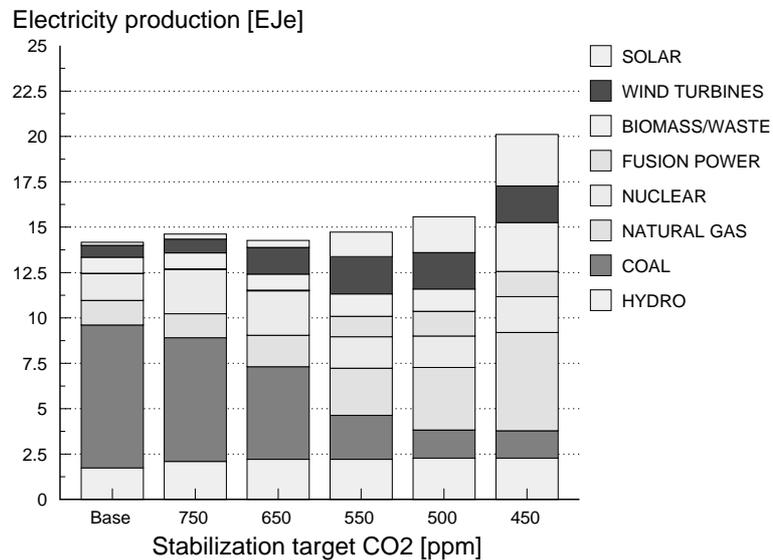
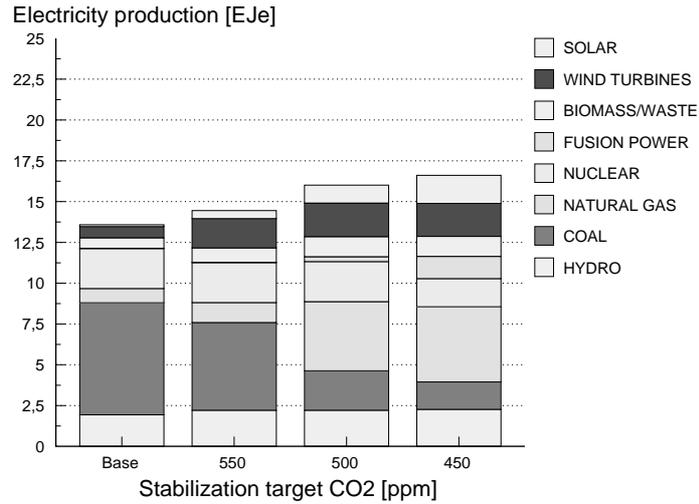
Figure 5.2 *Development of CO₂ emissions from power generation as a function of time and as a function of CO₂ stabilisation levels, scenario MD*

Generally, more power is generated at more ambitious CO₂ stabilisation levels. This is the net result of two opposite trends, viz. electricity conservation and substitution of fuels by electricity, for instance in the residential market (heat pumps) or in transport (electric vehicles). Only in the MD variant with stabilisation at 650 ppm, power generation decreases compared to the 750 ppm case, as electricity conservation exceeds substitution towards electricity (scenario MD has a relatively high discount rate for end-use decisions on electric appliances). In the CO₂ reduction cases of RP, electricity conservation and substitution of electricity for fossil fuels start at relatively mild CO₂ reduction targets.

In case of CO₂ variants, the emission of CO₂ is reduced by changes in the technology mix of the energy system. The power generation sector changes considerably with more stringent CO₂ targets. Figures 5.3 and 5.4 show the consequences of increasing CO₂ constraints for the power generation mix in the years 2070 and 2100 respectively.

Figure 5.3 shows that fusion power is competitive in scenario MD at a CO₂ stabilisation level of 550 ppm in 2070. In case of scenario RP stabilisation at 500 ppm is the critical level in 2070. As scenario MD is more demanding from the point of view of CO₂ reduction, fusion power is competitive at a higher CO₂ level than in scenario RP. Fusion power becomes attractive at a shadow price of approximately ECU 30/tCO₂. At stringent CO₂ targets fusion power is constrained by upper bounds assumed. Fusion power is maximised in case of scenario RP at 450 ppm, and in case of scenario MD at 500 ppm.

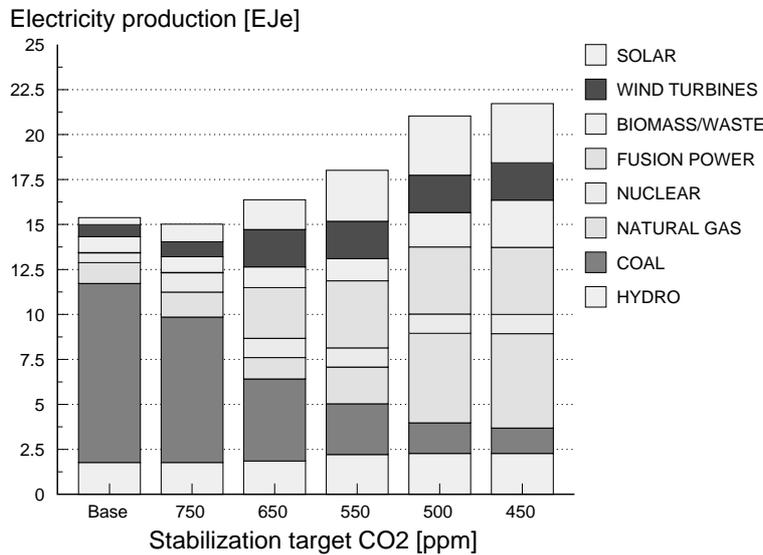
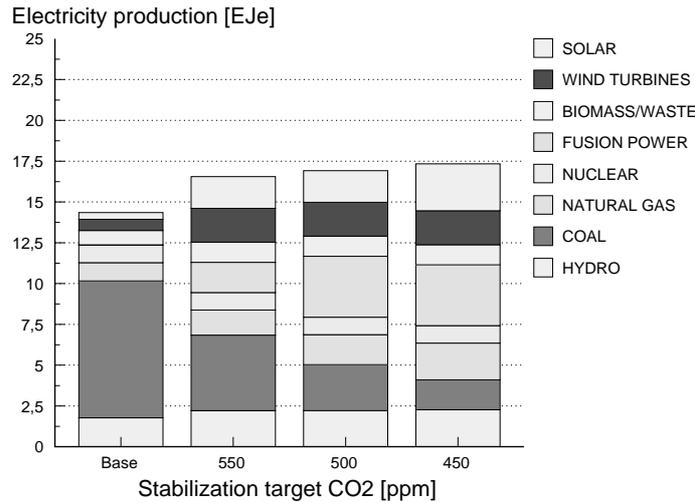
Coal-fired power shows the tendency to dwindle with increasing CO₂ constraints. The remaining coal-fired power in case of stringent CO₂ reduction targets proves to be equipped with CO₂ separation and geological sequestration. Natural gas gains importance in case of CO₂ constraints. As the total amount of natural gas is limited, gas from other sectors (industry, residential and commercial heating) is shifted to power generation.



Figures 5.3a and 5.3b Power generation by source, year 2070, scenarios Rational Perspective (top) and Market Drive (bottom) with increasing CO₂ constraints

Power production from hydro and fission power remains more or less constant. They are limited by physical occurrence (hydro) and presumed acceptance (fission) respectively.

With more stringent CO₂ reduction targets, new renewables like wind turbines, photovoltaic power (PV) and biomass fuelled power achieve substantial shares in power generation. First, (onshore) wind power and biomass fuelled power are introduced. More drastic CO₂ stabilisation levels are needed for a large contribution from PV.



Figures 5.4a and 5.4b *Power generation by source, year 2100, scenarios Rational Perspective (top) and Market Drive (bottom) with increasing CO₂ constraints.*

Figure 5.4 shows a similar pattern for the power generation mix in 2100 under increasing CO₂ constraints. Total power generation increases, the share of coal-fired power drops and the share of renewables increases. The main difference compared to 2070 is the smaller role of natural gas and the larger role of fusion power and renewables. The figure also shows that fusion power is competitive in 2100 in scenario RP, if global CO₂ emission stabilises at 550 ppm. Scenario MD requires a stabilisation level of 650 ppm. In scenario RP fusion power is the main power source, if CO₂ levels off at 550 ppm. In scenario MD gas-fired power and fusion power are the main power sources at 500 ppm.

Marginal cost of CO₂ reduction for RP variants is less than ECU 200/tCO₂ (Figure 5.5). Fusion power start to become cost-effective at ECU 32/tCO₂.

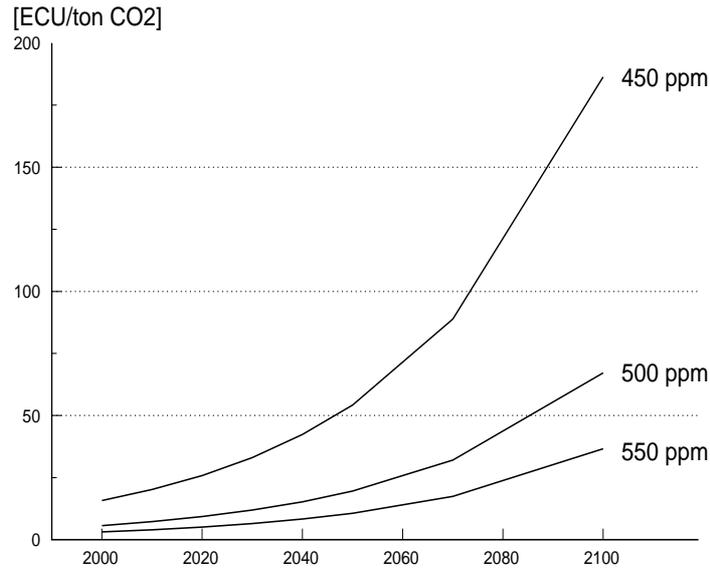


Figure 5.5 Marginal cost of CO₂ reduction in scenario Rational Perspective

Figure 5.6 shows the marginal cost of CO₂ reduction for MD variants. CO₂ reduction costs are higher in scenario MD than for similar cases of scenario RP. Yet, the 500 ppm case, corresponding to CO₂ reduction costs of ECU 300/ton in 2100, seems sensible. However, the marginal costs at the 450 ppm level are so high, that the optimisation results do not look valid: accounting for carbon taxes, a manifold increase of energy prices would be required. In reality this would result in serious demand reductions.

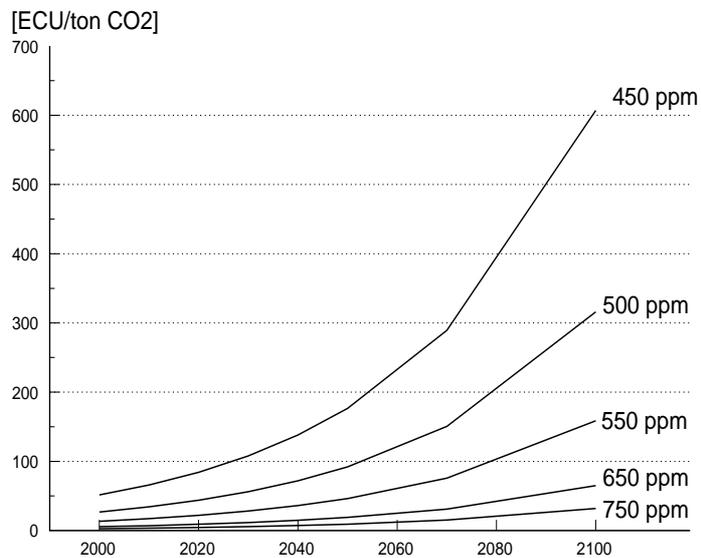


Figure 5.6 Marginal cost of CO₂ reduction in scenario Market Drive

Figure 5.7 shows the cost of CO₂ reduction as a percentage of GDP for the various CO₂ stabilisation levels considered. In case of scenario RP the CO₂ reduction costs are rather modest, because of the generic discount rate of 5%. In case of scenario MD CO₂ reduction is much more costly, because the energy demand is higher and the discount rate ranges from 8% for power generation to 10% and more for other sectors of the economy.

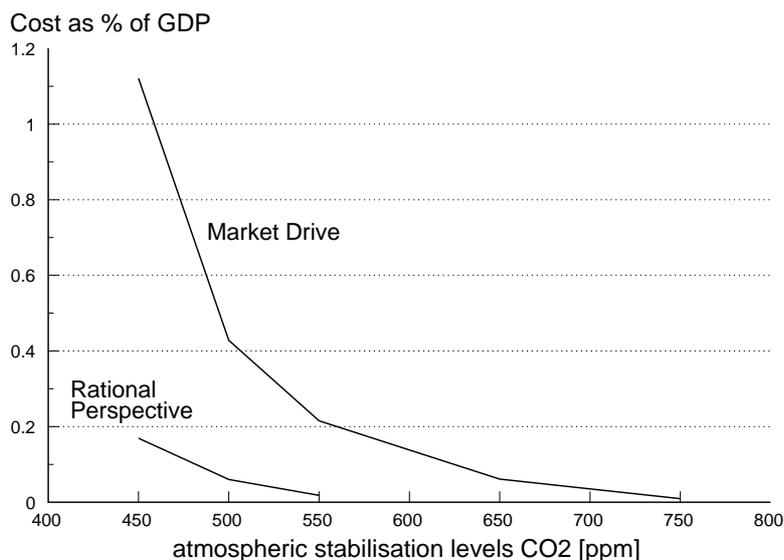


Figure 5.7 Cost of CO₂ reduction over the time period 1990-2100 (expressed as discounted cost of CO₂ reduction per discounted GDP), scenarios RP and MD

2.2 Scenario variants with different discount rates

Fusion power is a technology with both relatively high initial cost and annual variable cost. As other technologies have a different ratio of investment cost and annual cost, the comparative cost-effectiveness of fusion power depends on the interest rate that is applied. In the scenario variants presented here, the discount rate has been varied compared to the base case and CO₂ stabilisation cases, in order to analyse the sensitivity of the results to the discount rate assumed.

2.2.1 Changes in assumptions

Scenario RP has a uniform discount rate of 5%, whereas scenario MD has sector specific discount rates or hurdle rates. Scenario RP is altered by substitution of the set of discount rates of scenario MD for the generic 5% discount rate. In the same way a uniform discount rate of 5% is substituted for the various discount/hurdle rates of scenario MD.

2.2.2 Results

In Figure 5.8 the results are shown of CO₂ reduction cases of scenario RP, using the set of discount/hurdle rates of scenario MD. In comparison with the case with a uniform 5% discount rate (Figure 5.4a), renewable options like wind energy and solar energy lose some of their market share. Wind energy and solar power are more capital intensive than fusion power, because a relatively large part of the power generation costs of fusion power is related to regular replacement of diverter, blanket, and first wall.

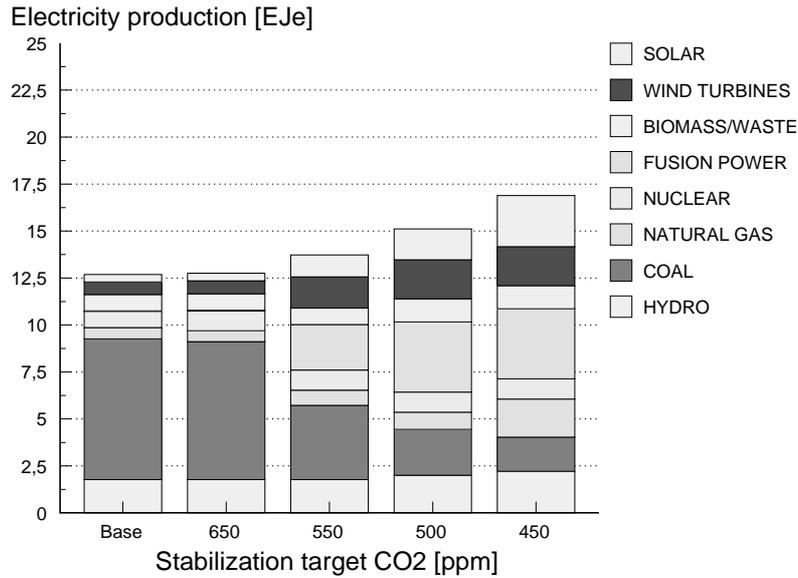


Figure 5.8 Power generation by source, year 2100, scenario RP, discount rate 8%

In addition, Figure 5.9 shows CO₂ reduction cases of scenario MD with a uniform 5% discount rate (usual in scenario RP). In comparison with the ‘ordinary’ MD scenario (Figure 5.4b) fusion power has a smaller market share in case of CO₂ stabilisation at 650 ppm. Here the change in discount rate works in the opposite direction: a lower discount rate gives capital intensive options like wind and solar energy a small competitive edge.

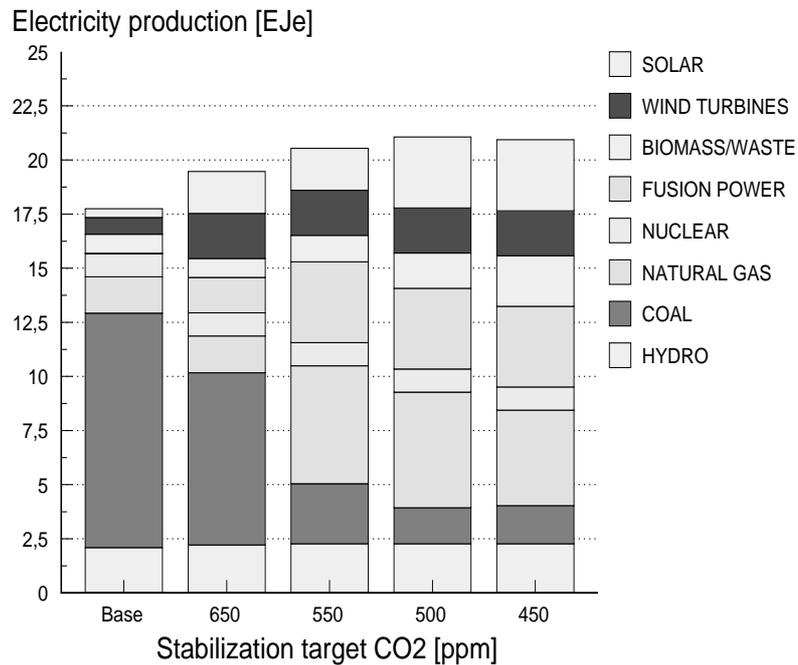


Figure 5.9 Power generation by source, year 2100, scenario MD, discount rate 5%

3. ADDITIONAL SENSITIVITY ANALYSIS

3.1 Sensitivity analysis with different assumptions on fission power

3.1.1 Changes in assumptions

In scenario RP and scenario MD fission power is assumed to decline gradually until year 2070, when fission power has an upper limit corresponding to 70% and 80% respectively of the current installed nuclear capacity in 2070¹³. After that, fission power is assumed to decline further. In addition to the ‘smooth’ phase-out of fission power in the scenarios RP and MD (to be completed in 2130), two contrasting sensitivity cases are analysed:

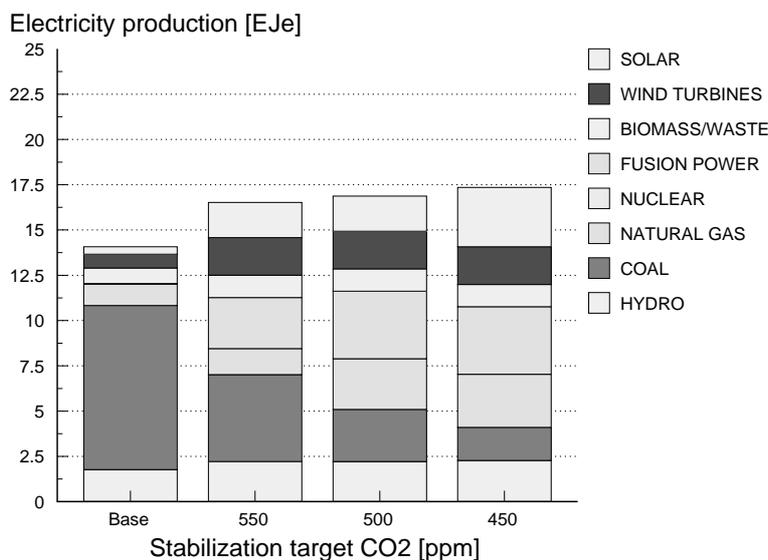
1. A variant of scenario RP with a complete phase-out of fission energy in 2080. In this case it is assumed that investment in fission power is not allowed anymore from 2050 onwards, which means that fission power is phased out completely in 2080.
2. An MD scenario variant with an upper limit for fission power permitting an increase of almost 60% compared to the current installed capacity (upper limit: 200 GW). This assumption is in agreement with one for Western Europe in the recently published WEC/IIASA scenario study [61].

3.1.2 Results

RP scenario variant with phase-out of fission power in 2080

If we compare the consequences of a complete phase-out of fission power in 2080 (Figure 6.1) with those of the ‘ordinary’ RP scenario (Figure 5.4a), the share of fission power is largely taken over by fusion power in the 550 ppm case.

In the 500 and 450 ppm case, when fusion power is already maximised, natural gas and PV get larger shares.



¹³ The decline in maximum installed fission capacity until 2070 is partially offset by the assumed increase of the load factor from 75% in 2000 to 87.5% in 2050.

Figure 6.1 *Power generation by source, year 2100, RP scenario variant with phase out of fission power in 2080*

RP scenario variant with large potential for fission power

Figure 6.2 shows the consequences of an MD scenario variant with a large potential for fission power (up to 200 GW).

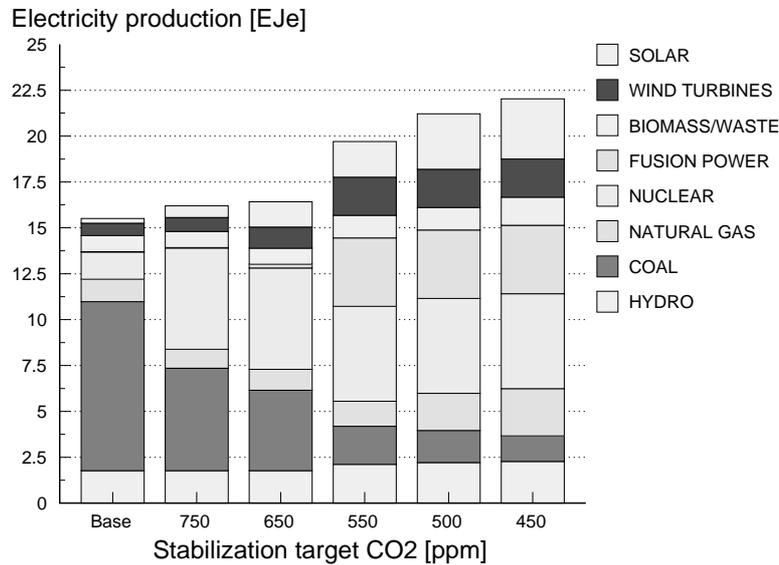


Figure 6.2 *Power generation by source, year 2100, MD scenario variant with large potential for fission power (up to 200 GW)*

In this case, which is highly optimistic with respect to fission power, fusion power remains economically viable in case of CO₂ reduction, although the market share of fusion power is really small in the 650 ppm case. As a matter of fact, in this particular case the marginal CO₂ reduction cost is ECU 67/tCO₂, which is about twice the 'normal' level of some ECU 30/tCO₂. The higher marginal CO₂ reduction cost, corresponding to the introduction of fusion power in this 650 ppm CO₂ reduction case, is due to the fact that natural gas remains available for power generation in the last decades of the 21st century.

3.2 Sensitivity analysis for fossil fuel availability

3.2.1 Changes in assumptions

In scenario MD fossil fuel availability is high: 15% of global resources are assumed to be available to Western Europe. In scenario RP the corresponding figure is 10.5%. Essentially, this means that in scenario MD developing countries are not able to increase their share of fossil fuel consumption, whereas scenario RP gives some room for increased fossil fuel consumption in developing countries. It seems sensible to add a sensitivity case of scenario RP with the high fossil fuel availability of scenario MD.

3.2.2 Results

Figure 6.3 shows the results of variants of scenario RP with high fossil fuel availability. The main differences compared to the 'ordinary' RP scenario (Figure 5.4a) pertain to the larger share of gas-fired power, the smaller share of coal-fired power in the 550 and 500 ppm cases, and the smaller shares of fusion and solar power in the 550 ppm case.

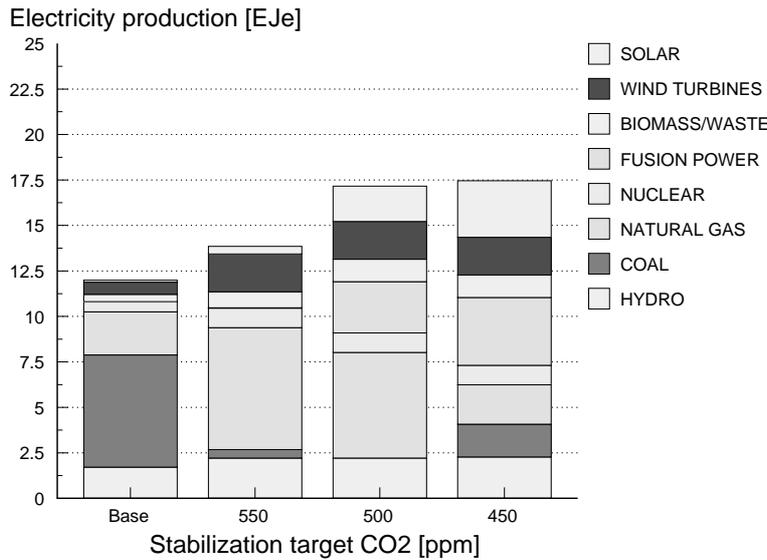


Figure 6.3 Power generation by source, year 2100, scenario RP, high fossil fuel availability

From the comparison of the base cases (without CO₂ constraints) it can be concluded that natural gas is indeed constrained in the ‘ordinary’ RP scenario. If a larger amount of fossil fuels is assumed to be available, the power generation mix shows a shift from coal to gas, even if there is no CO₂ constraint. That is why fusion power is not competitive in the case of CO₂ stabilisation at 550 ppm. Note that a larger availability of natural gas also reduces the market share of solar power at the 550 ppm level. At lower atmospheric CO₂ levels fusion power and solar power show their original market shares, whereas gas-fired power holds a competitive edge over coal-fired power. Figure 6.4 shows shadow prices of fossil fuel based energy carriers in this specific case.

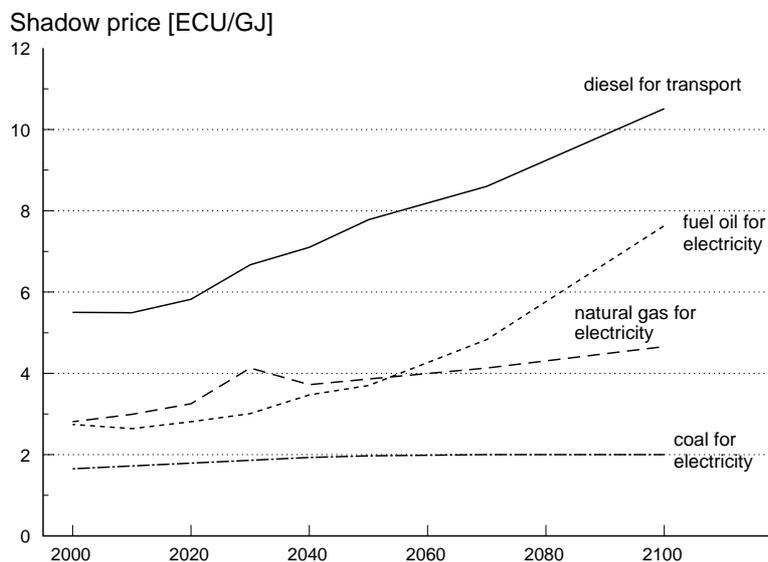


Figure 6.4 Shadow prices of diesel, fuel oil, natural gas and hard coal in the base case of the RP scenario with high fossil fuel availability

The differences in the power generation mix, if CO₂ reduction is absent, result from the lower shadow prices for fossil fuels: the shadow prices are substantially lower in the base case of this sensitivity analysis than in the ‘ordinary’ base case of scenario RP (compare Figure 6.4 with Figure 4.4).

3.3 Sensitivity analysis for availability of renewables

3.3.1 Changes in assumptions

In the ‘ordinary’ RP and MD scenarios wind and solar power are allowed to expand to relatively high levels, viz. 200 GW (200,000 MW) and 480 GW respectively. However, some novel renewable options could become available in the next century. Eventually, the maximum capacities for wind and solar energy could exceed the above mentioned levels. It is very difficult to make sensible assumptions for ‘exotic’ renewables, because little is known of them. Therefore, a sensitivity analysis has been done with a 2.5 times higher maximum capacity for wind and solar energy as well as lower investment cost for PV (a drop until 600 ECU/kW).

3.3.2 Results

Figure 6.5 presents results of a sensitivity case of scenario MD with a higher than ‘normal’ potential of wind and solar energy as well as lower investment cost of PV. Comparison of Figure 6.5 with Figure 5.4b (the ‘ordinary’ MD scenario), shows that fusion power is no longer competitive at the 650 ppm level. Fusion power loses market share at 550 and 500 ppm. However, a more ample availability of wind and solar energy is more threatening to gas and coal-fired power than to fusion power.

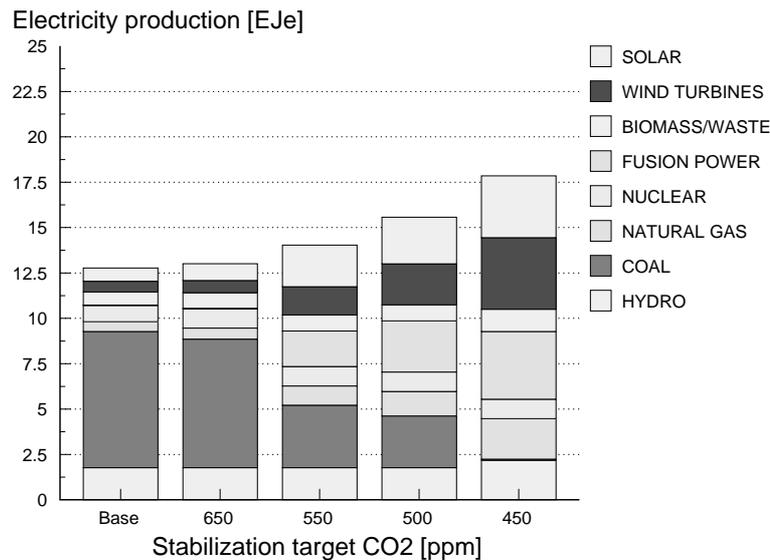


Figure 6.5 Power generation by source, year 2100, scenario MD, high potential for renewables

Figure 6.6 shows in detail the change in power generation based on PV for the 500 ppm case of the MD scenario variant with a higher potential of renewables.

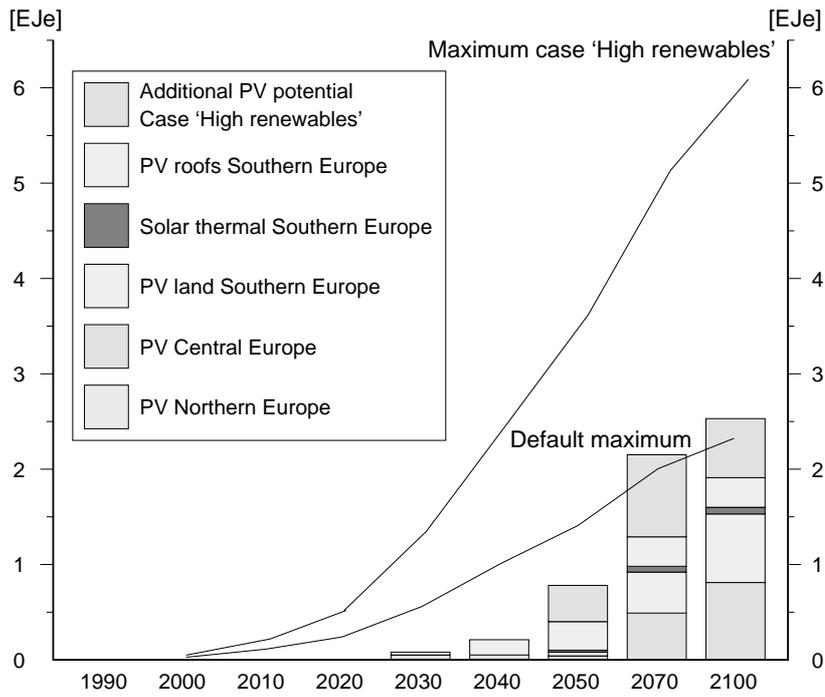


Figure 6.6 Power generation from PV (and solar thermal power plants) for scenario MD with additional renewables potential (500 ppm CO₂ reduction case)

One can observe that PV gets a larger market share in 2050, 2070, and 2100. However, the level of deployment of PV is only slightly higher than the ‘default’ maximum for PV. Apparently, the maximum contribution from intermittent power generation options like wind turbines and photovoltaic power is limited by energy system aspects. Such limitations are also confirmed by other analyses such as [62].

3.4 Sensitivity analysis for the cost of fusion power

3.4.1 Changes in assumptions

Cost data of fusion power plants in all scenarios and variants presented before have been derived from the study of Gilli and Kurz [2]. Their figures - e.g. ECU 3000/kW in 2100 for a twin 1500 MW fusion power plant - are used as reference. However, fusion power could prove to be more expensive. Therefore, in a sensitivity case of scenario MD the investment costs of an advanced 1000 MW fusion reactor according to Knight and Cook (Macro task E1) [63] have been substituted for the figures from the study of Gilli and Kurz. It turns out that these investment costs are 20% higher than the figures of Gilli and Kurz.

3.4.2 Results

Figure 6.7 presents results of a sensitivity case of scenario MD with 20% higher investment costs for fusion power plants. If we compare the results in Figure 6.7 with those of Figure 5.4b, fusion power is only slightly less competitive in the case of stabilisation of atmospheric CO₂ at 650 ppm. However, the differences are less pronounced than in the RP scenario variant with high fossil fuel availability (Figure 6.3) or the MD scenario variant with high potential of renewables (Figure 6.5).

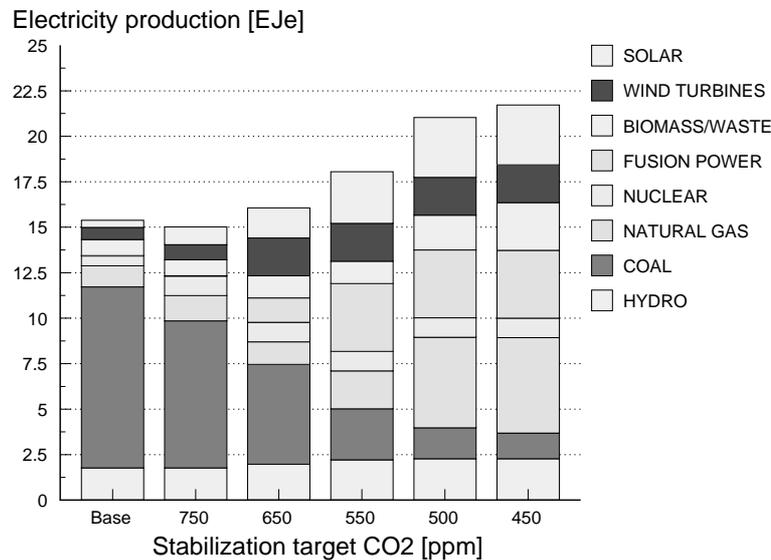


Figure 6.7 *Power generation by source, year 2100, scenario MD, high investment cost of fusion power*

3.5 Sensitivity analysis with fusion power not available

It is uncertain whether fusion power will become available as a commercial technology. If fusion power would not be available, other technologies have to take over the CO₂ reduction from fusion

power. This sensitivity analysis aims to give insight in how the energy system would be without fusion power and how costs would be in that case.

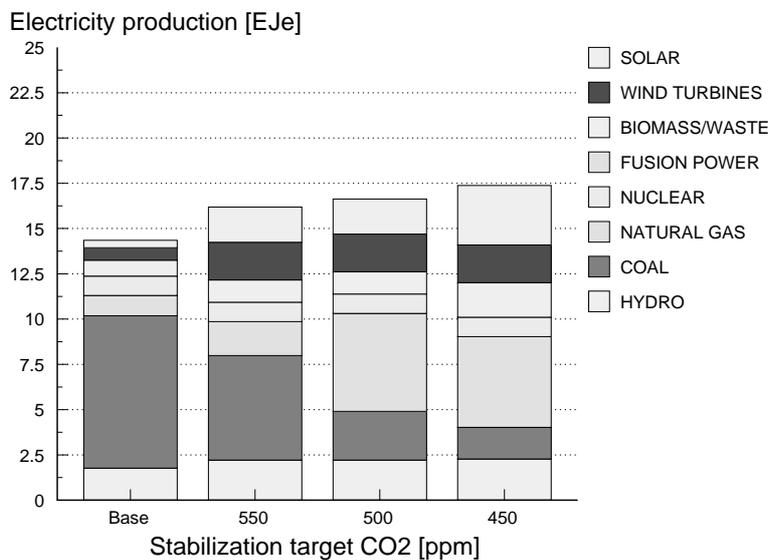
3.5.1 Changes in assumptions

In this sensitivity analysis fusion power is not considered available, both for the Rational Perspective and Market Drive scenarios and their respective CO₂ emissions variants.

3.5.2 Results

Figure 6.8 shows the consequences of the absence of fusion power as an option, in case of both scenario RP and scenario MD. In scenario RP the main difference is that coal-fired power becomes slightly more important at the 550 ppm stabilisation level. This means that more CO₂ reduction is required in other sectors of the energy system. However, coal-fired power does not offer any solution for more stringent CO₂ reduction cases. The potential of coal-fired power with CO₂ separation and sequestration is already used if fusion power is available. Therefore, gas-fired power is used to cope with the absence of fusion power as an option. This means that natural gas has to be conserved in other sectors (presidential and commercial sector, industry), as scenario RP has limited cumulative supplies of natural gas.

In scenario MD the absence of fusion power results in a slightly larger share of coal-fired power at the modest 650 ppm level. Again, this means that CO₂ emission is reduced in other sectors of the energy system. However, at more stringent CO₂ stabilisation levels the answer to the absence of fusion power is a larger share of gas-fired power (just like in the corresponding RP variants) and a larger share of biomass fuelled power.



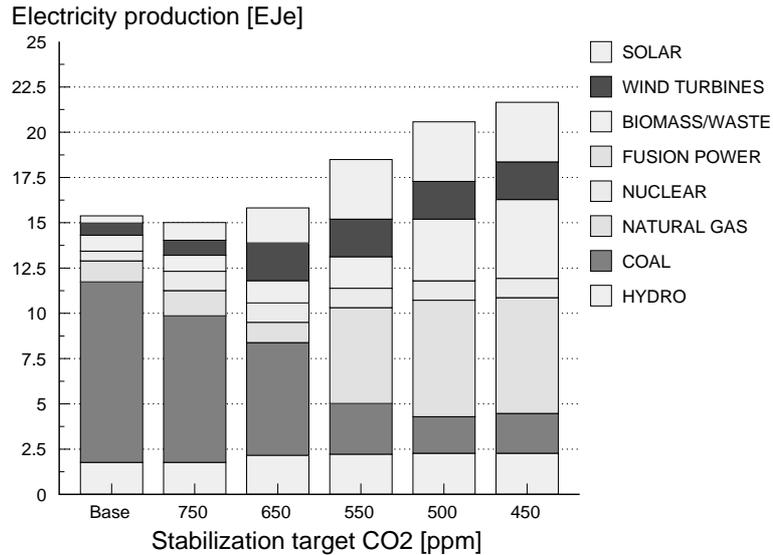


Figure 6.8 Power generation by source, year 2100, scenarios with fusion power assumed not available, Rational Perspective (top) and Market Drive (bottom)

Scenarios without fusion power are feasible, even at stringent CO₂ stabilisation levels. This is because fusion power can only attain substantial shares in power generation towards the end of the next century, if global CO₂ stabilisation at e.g. 550 ppm is needed. Substitution of gas-fired power and eventually biomass fuelled power for fusion power and the other changes in the energy system needed in order to make gas available for power generation, would have more or less significant effects on the marginal cost of CO₂ reduction, as exhibited in Figure 6.9 (scenario RP) and Figure 6.10 (scenario MD).

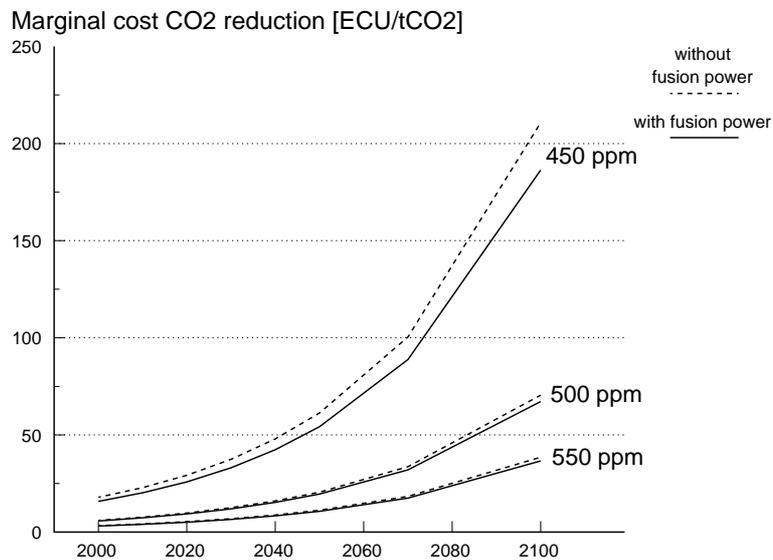


Figure 6.9 Marginal cost of CO₂ reduction in scenario RP, with and without fusion power

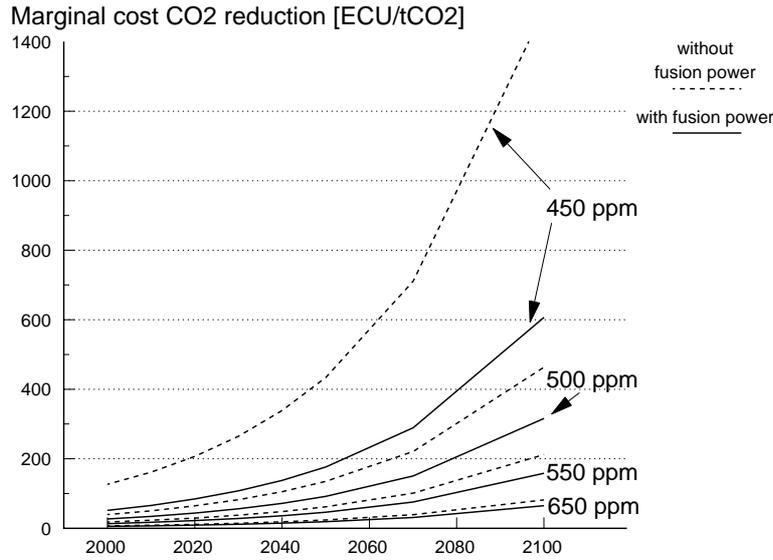


Figure 6.10 Marginal cost of CO₂ reduction in scenario MD, with and without fusion power

These figures demonstrate that fusion power has the effect of lower CO₂ reduction costs, presumed it is available. This effect is most pronounced, if fusion power is deployed to its maximum extent, notably in the 500 or 450 ppm stabilisation cases of the scenarios. Therefore, fusion power is of great importance in case of stringent CO₂ reduction.

Finally, the effect of fusion power on the CO₂ reduction cost as percentage of the GDP is shown in Figure 6.11. From this figure one can conclude that the effect of fusion power becomes more important at more stringent CO₂ stabilisation levels: it is much more difficult to substitute fusion power in such cases than in case of moderate CO₂ reduction.

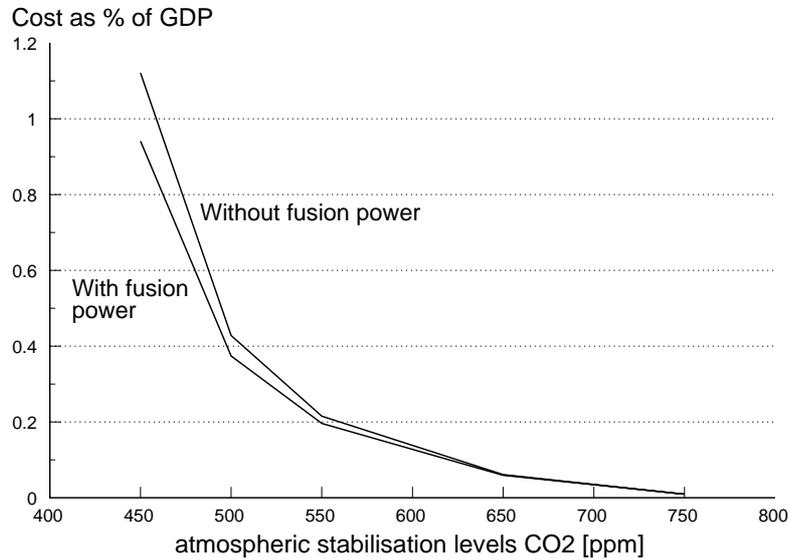


Figure 6.11 Cost of CO₂ reduction over the time period 1990-2100 (expressed as discounted cost of CO₂ reduction per discounted GDP), scenario MD

4. DISCUSSION

4.1 Limitations of the scenario approach

An analysis of the competitiveness of fusion power in Western Europe, like the present study, needs a time horizon of some hundred years from now. It is not the purpose of this study to determine the optimal strategy towards commercial fusion power. Nor is its intent to assess the probability of availability of fusion power. This study considers various scenarios, CO₂ reduction variants, and other cases, with and without fusion power.

The development of fusion power is unpredictable for a number of reasons. Nobody can foresee the outcome of the quest for fusion power. Therefore, we have to rely on some crude assumptions with respect to the timing and cost of a commercial fusion reactor. Energy scenarios can be structured in such a way that they enable an analysis of various developments of the energy system and an evaluation of the potential of fusion power.

The main limitations of the scenario approach are connected with uncertainties in variables like energy demand for end-user purposes. Long time horizon issues such as technological change, discount rate, and (political attitudes towards) climate change also need attention. On a global level we could add the uncertainty with respect to population growth. In Western Europe, however, population growth will probably be negligible. Developing scenarios for Western Europe with a time horizon until 2100 is challenging. It has been done by reputed institutes like IIASA and IPCC. Such scenarios should account for the poor predictability of energy demand, particularly with respect to demand for transport. So the scope of the scenarios has to be so large that they can cope with the wide range of energy demand projections.

No one can foresee technological change with accuracy. The eventual availability of fusion power is certainly not the only question mark. Today we are witness of innovations in energy demand technologies, e.g. with respect to lighting (LEDs) and heating (minimum energy buildings and houses). Simultaneously, the power generation market is changing continuously (introduction of wind turbines, biomass fuelled power). If development of photovoltaic power (PV) would be successful, this could change the long term energy outlook profoundly. It is certain that our current view on the development of prospective technologies like PV or fusion power will prove to be at least partially wrong. However, the best way to account for these uncertainties is to include as many efficiency improvements and energy supply technologies as possible in the model of Western Europe. Moreover, sensitivity analysis is performed for e.g. the cost of fusion power and the availability or potential of technologies competing to fusion power.

When we approach the year 2100, issues like climate change and depletion of fossil fuel resources will have gained importance. Such intergenerational issues should be taken into account consistently. Therefore, a relatively low discount rate of 2.5% has been applied to depletion of fossil fuel resources as well as emission of CO₂ over time (the latter in case a cumulative CO₂ constraint is imposed). Simultaneously, capital investment alternatives can be weighed with a discount rate of 5, 8 or 10% (depending on the scenario).

It is self-evident that long-term issues like climate change and depletion of fossil fuel resources deserve a global outlook. Therefore, world wide fossil fuel resources have been estimated, and they have been distributed to Western Europe in some way (depending on the scenario). In the same way several global CO₂ stabilisation levels have been attributed to Western Europe by means of corresponding cumulative CO₂ budgets.

The way in which the model and the scenarios have been structured ensures that the outcome of the study is representative of Western Europe. It is admitted that some assumptions are normative. For instance, we assume that fission power will decline gradually until 2070 and even relatively fast after that. This seems to be at odds with the view on fission power in most of the IASA-WEC scenarios (1995). However, it could be argued that most of these scenarios and even more the most recent IASA-WEC scenarios (1998) are overoptimistic with respect to fission power (in any case for Western Europe).

4.2 Expected benefits of fusion power

The main benefit of fusion power is its potential to contribute to CO₂ reduction in a cost-effective way. CO₂ reduction is the main determinant to the potential of fusion power. If climate change is an issue, fusion power may have an impact, just like other CO₂ free options. Besides CO₂ policy, several variables have been taken into account, such as:

- the development of energy demand for end-use purpose,
- the discount rate used,
- the amount of fossil fuels available to Western Europe,
- the extent to which renewable energy would be available,
- the extent to which fission power is assumed to be available,
- the level of investment cost of fusion power.

It does not make sense to focus on extreme levels of variables at which fusion power would become economically marginal. There is a variant with a large potential for renewable energy. There is also a variant of the ecologically driven scenario with ample fossil fuel availability. In nearly all of these cases the introduction of fusion power shifts to somewhat more stringent CO₂ stabilisation levels. However, CO₂ reduction policy remains the main single determinant to the potential of fusion power.

Although CO₂ reduction is achievable without fusion power, albeit at a higher cost, stringent CO₂ targets may be difficult to achieve in that case. However, this is not the whole story. Even if CO₂ reduction until 2100 does not require fusion power, we should wonder whether real alternatives are available. We have to take a step backwards and look at the origin of the climate change issue, viz. world-wide combustion of fossil fuels. Heavy reliance on CO₂ sequestration would not be practicable due to depletion of fossil fuels. Increased use of fission power could prove to be unacceptable, presumed that it would be sustainable. For renewables like wind and solar energy the issue is not their potential to make inroads in the power generation market, but their intermittent nature, precluding substitution of base-load power generation options such as fusion power. Therefore, we should be careful in claiming that some scenario without fusion power is feasible.

We did not investigate other CO₂ free options like the Energy Amplifier - a particle accelerator as neutron source for a breeder reactor using Thorium as fuel - or so-called 'exotic' renewables. These are addressed by FZ Jülich in their study for the SERF programme [41]. Such options could have their own drawbacks, presumed they would be feasible. All in all, fusion power is one of the few CO₂ free and virtually inexhaustible power generation options to become available in the course of the next century.

5. CONCLUSIONS AND RECOMMENDATIONS

The large investments needed for fusion R&D on one hand, and the possibly large benefits to the (Western European) energy system in the long term (beyond 2050) on the other hand, deserve a closer examination of the potential benefits of fusion power. This is the rationale of the programme of Socio-Economic Research on Fusion Energy (SERF) initiated by the European Commission (DG XII) in 1997. As part of this research programme a scenario analysis has been performed to explore alternative long term development paths of the energy system of Western Europe and to analyse the cost-effectiveness of fusion power in these scenarios/variants. This is part of the macro task 'long term scenarios'.

The MARKAL model used for this analysis includes a large number of energy technologies, which are able to compete for a role in the energy system. The optimisation model is based on cost minimisation. Not only a large number of energy demand and supply technologies and their load characteristics have been considered, but also (cumulative) availability and cost of fossil fuels. Investment costs of the technologies are based on estimates with an equal degree of optimism. In addition, practical upper limits, investment bounds, and growth constraints are added in order to avoid a 'land-slide' for a particular option.

This scenario analysis has been done with two contrasting (energy demand) scenarios. In addition, some 60 scenario variants have been defined. This large number of cases was needed, because there are *prima facie* many possible key variables which could be varied across the variants. The key model inputs include the level of energy demand for end-user purpose, CO₂ reduction targets (cumulative CO₂ constraints), fossil fuel prices, availability of fossil fuel resources, discount rate, and practical potential as well as acceptance of technologies competing with fusion power.

From the present scenario analysis conclusions can be drawn with respect to:

1. The future cost-effectiveness and role of fusion power.
2. Development of the energy system of Western Europe in the absence of CO₂ policies.
3. Development of the energy system of Western Europe if substantial CO₂ reductions are required.

Conclusions with respect to cost-effectiveness and role of fusion power

- Fusion power cannot compete with alternative base-load power options in the absence of CO₂ reduction policies. This is because fusion power is rather costly compared to coal-fired power and fission power. Irrespective of the discount rate used, fusion power needs some incentive, such as a cumulative CO₂ constraint.
- In case of CO₂ constraints, fusion power starts to become competitive at shadow prices ranging from about 30 to about 70 ECU/tCO₂. In case of a scenario with relatively low energy demand fusion power obtains a share in power generation which is somewhat higher than that of fission power (which is at its upper bound), if global stabilisation of CO₂ at 550 ppm would be needed (slightly decreasing CO₂ emission in Western Europe). In case of a 'high demand' scenario, fusion becomes already competitive in 2070 if stabilisation of atmospheric CO₂ at 650 ppm is aimed for.
- With more stringent CO₂ constraints fusion power becomes more important, particularly towards 2100. In the most stringent CO₂ reduction cases aiming at stabilisation of CO₂ at 450 ppm, the installed capacity of fusion power is guided by the maximum introduction pattern. The maximum capacity in 2100 is about 160 GW.

- The possible role of fusion power as described above appears to be fairly robust. In the sensitivity analysis key variables have been varied:
 - The role of fusion power in CO₂ constrained cases is not very sensitive to the discount rate assumed. Renewable options like photovoltaic power - at unfavourable latitudes - proved to be more sensitive to high discount rates than fusion power. This is because the generation cost of fusion power to a large extent depends on recurring costs of operation and maintenance and replacement of diverter, blanket, and first wall.
 - If a complete phase-out of fission power in 2080 is assumed, fusion power can profit somewhat in the case of a moderate CO₂ reduction target.
 - If fission power is allowed to grow (from 125 GW up to 200 GW), fusion power is less prominent. In the moderate 650 ppm CO₂ reduction case of the 'high demand' scenario, fusion power is introduced at a cost of 67 ECU/tCO₂.
 - If ample availability of fossil fuels (natural gas) is assumed in combination with the ecologically driven scenario, fusion power needs a more stringent CO₂ reduction level in order to be introduced than under 'normal' conditions.
 - If higher potentials (and in some cases lower cost) are assumed for wind and solar power, fusion power can only compete under more demanding CO₂ reduction constraints. Fusion power would no longer be competitive in the 'high demand' scenario with 650 ppm stabilisation target. If the CO₂ reduction target is more stringent, fusion power remains competitive.
 - If the investment cost of fusion power is assumed to be 20% higher than normally assumed - the reference investment cost being ECU 3000/kW (ECU of the year 1995) in 2100 - fusion power is introduced at a slower pace in case of a moderate CO₂ reduction target.
- Within the time horizon of 2100, equal CO₂ stabilisation levels can be attained, albeit at a higher cost, if fusion power is assumed not to be available. The benefits of fusion power depend on the level of CO₂ stabilisation aimed for, just like the economic potential of fusion power, and on the level of energy demand of a scenario. Therefore, particularly in case of a scenario with low energy demand and moderate CO₂ reduction levels the benefits of fusion power are relatively small.
- Renewables - hydro, wind, biomass fuelled power, photovoltaic power - are able to make substantial inroads in the power generation market. However, wind and solar energy are intermittent energy sources, which cannot substitute base-load power like fusion power. In addition to renewables, fusion power is one of the few CO₂ free and virtually inexhaustible energy options which could become available.

Conclusions with respect to the energy system of Western Europe in the absence of CO₂ policies

- CO₂ emissions from the energy system will not decrease autonomously, despite availability of wind and solar power (PV).
- Oil becomes scarce in both base case scenarios. Thus, oil products are used more efficiently or substituted by natural gas, electricity (electric vehicles) or a modest amount of biocrude (imported from South America).
- Natural gas also becomes scarce, except for the variant with ample availability of natural gas in combination with the ecologically driven scenario.
- The cost-effectiveness of fission power depends on the availability and cost of fossil fuels over time, and on the discount rate used. Fission power is competitive from 2020 to 2070, depending on the discount rate used (5% and 8% respectively). In case of a CO₂ constraint fission power is competitive anyhow.
- The contribution from renewables like onshore wind, photovoltaic power, and biomass to the primary energy demand, will grow steadily to almost 20% in 2100.
- The demand for electricity and for transport will grow faster than other demands.
- The demand projection for transport shows the largest gap between the two scenarios, which is mainly due to the large differences in the projections for air transport.
- Efficiency improvements in demand side technologies will continue. They will account for annual reductions in final energy demand in the order of 0.7 % per year in average for Western

Europe. It should be noted that this effect is only a part of net energy intensity improvements; structural changes are the other important element of overall efficiency improvements.

Conclusions with respect to the energy system of Western Europe if substantial CO₂ reductions are required

- To reach certain CO₂ stabilisation targets, the more substantial part of emission reduction is projected to occur after the year 2040. Some of the inflexibility in the first decades is caused by existing capacities with a long lifetime. Another part is caused by the maximum introduction pattern of some new technologies.
- Technical innovation and availability of new technologies is not sufficient in order to get substantial CO₂ emission reductions. Decisions on investments in technologies need to be influenced as well, e.g. by imposing carbon taxes on fossil fuels.
- Reaching stabilisation at 450 ppm is generally difficult and involves high cost, particularly in the 'high demand' scenario.
- Additional efficiency improvements on top of the efficiency improvements in the baseline contribute most substantially to emission reduction.
- Decarbonisation of fuels - fuel switch to natural gas, CO₂ separation and sequestration, biomass-fuelled power - will provide the second largest contribution to CO₂ emission reduction.
- The energy system changes profoundly if CO₂ constraints are imposed. Then, both in high-demand driven and ecologically driven scenarios, coal-fired power loses market share and fusion power becomes economically attractive. In addition, gas-fired power is substituted for coal-fired power.
- Intermittent renewables - wind, PV - will encounter limits to their market share. These bounds are not only related to available sites (onshore wind) and maximum growth rates. In the long term, energy system constraints are limiting the role of intermittent renewables (electricity storage, load management).
- If accepted by the public fission power would be a cost-effective option for reducing CO₂ emissions.
- Substitution of electricity for fuels - electric vehicles, electric heat pumps - is a robust option for CO₂ reduction and efficiency improvement (with the benefit of oil conservation), which is exhibited by occurrence in scenarios without CO₂ constraints.
- The prospects of large scale use of hydrogen do not look good. Hydrogen produced from renewables is too expensive. If CO₂ sequestration capacity is available, CO₂ separation and sequestration from industrial processes (refineries) and fossil-fuelled power generation has a competitive edge over CO₂ from fossil-based hydrogen production.

REFERENCES

- [1] P. Lako, J.R. Ybema, A.J. Seebregts: *The role of fusion power in energy scenarios. Proposed method and review of existing scenarios*. ECN-C--98-009, Petten, 1998.
- [2] P.V. Gilli, R. Kurz: *Fusion power as an additional vector in the IIASA-WEC world scenarios*. Arge Wärmetechnik, Graz (Austria), October 1998.
- [3] T. Kenneth Fowler: *The fusion quest*. John Hopkins Univ. Press, Baltimore, 1997.
- [4] IIASA-WEC: *Global energy perspectives to 2050 and beyond*. IIASA, 1995.
- [5] Intergovernmental Panel on Climate Change: *Climate Change 1995 - economic and social dimensions of climate change*. Cambridge University Press, 1995.
- [6] *Testimony before the Committee on Energy and Natural Resources* by V.S. Rezendes, Director of 'Energy, Resources and Science Issues', on Administration's Proposal in Support of the Kyoto Protocol. GAO/T-RCED-98-219.
- [7] *The evolution of the world's energy system 1860-1960*. Shell venster, 3/4 1995.
- [8] N. Mattson and C.-O. Wene: *Assessing new energy technologies using an energy system model with endogenized experience curves*. Int. J. of Energy Res., Vol 21, 385-393, 1997.
- [9] European Commission DG XII, Poles 2.2, EUR 17358 EN, 1996.
- [10] L. Neij: *Use of experience curves to analyse the prospects of diffusion and adoption of renewable energy technology*. Energy Policy, Vol. 23, No. 13, 1099-1107, 1997.
- [11] J.R. Ybema et al: *Prospects of energy technologies in the Netherlands, Volume 1 and 2*. ECN-C--95-002 and ECN-C--95-039, Petten, 1995.
- [12] ETSU: *An appraisal of UK Energy Research, Development & Dissemination, R83*. ISBN 011515497, 1994.
- [13] IKARUS: *Instrumente für KlimagAs RedUktions Strategien*. Zusammenfassender Zwischenbericht für die Projektphase 3. Stand Ende 1993, FZ Jülich, 1994.
- [14] J.R. Ybema et al: *Scenarios for Western Europe on long term abatement of CO₂ emissions*. ECN-C--97-051, Petten, 1997.
- [15] P. Lako et al: *CO₂ abatement in Western European power generation*. ECN-C--97-053, Petten, 1997.
- [16] IEA-ETSAP: *New directions in energy modelling - summary of Annex V (1993-1995)*. ETSAP-97--1, Petten, 1997.
- [17] C.D. Masters et al.: *World resource statistics geared for electronic access*. Oil&Gas Journal, 13 October 1997, 98-104.
- [18] C.J. Campbell: *The golden century of oil 1950-2050*. Kluwer Academic Publishers, 1991.
- [19] C.J. Campbell: *Better understanding urged for rapidly depleting reserves*. Oil&Gas Journal, 7 April 1997, 51-54.
- [20] C.J. Campbell: *Depletion patterns show change due for production of conventional oil*. Oil&Gas Journal, 29 December 1997, 33-37.
- [21] C.J. Campbell: *Major exporter nearing peak*. Petroleum Economist, April 1998, 7-8.
- [22] E. Kvadsheim et al: *Norway rises to the challenge*. Petroleum Economist, August 1997, 7-8.
- [23] Energy policies of IEA countries, Norway 1997 review, 102-104.
- [24] N.J. Smith et al.: *Technology pushes reserve 'crunch' date back in time*. Oil&Gas Journal, 7 April 1997, 43-50.
- [25] J. Inciarte: *Technology pushes Venezuela's heavy-oil projects ahead*. Oil&Gas Journal, 8 December 1997, 52-54.

- [26] *Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen*, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, June 1989.
- [27] G. Warfield: *Oil, gas, coal, uranium, tar sand resource trends on rise*. Oil&Gas Journal, 4 September 1995, 104-111.
- [28] *OPEC bulletin*, March 1997, 14.
- [29] E. Verbricke: *A growing and viable alternative to conventional oil*. Petroleum Economist, January 1998, 21-22.
- [30] M.M. Carson: *Natural gas central to world's energy mix*. Oil and Gas Journal. August 11 1997, 37-47.
- [31] *International Gas Research*, 30 May 1997.
- [32] *International Gas Research*, 11 July 1997.
- [33] T.S. Collet et al.: *Hydrates contain vast store of world gas resources*. Oil & Gas Journal, May 11 1998, 90-95.
- [34] www.fe.doe.gov/remarks/hydrate_052198.html.
- [35] *BP Statistical Review of World Energy*. June 1994.
- [36] J.C. Jansen et al: *Long term prospects for fossil fuel prices*. ECN-C--95-046, Petten, 1996.
- [37] H. Gruss: *Entwicklung von Angebot und Nachfrage auf dem Steinkohlen-weltmarkt (1995)*. Zeitschrift für Energiewirtschaft, 1/96, 1-36.
- [38] H. Gruss: *Entwicklung von Kosten und Preisen auf dem Steinkohlenweltmarkt*. Zeitschrift für Energiewirtschaft, 2/96, 159-175.
- [39] A. Faussat et al: *The French national inventory of radioactive waste*. In: 'The nuclear power option', Proceedings of an International Conference, Vienna, 5-8 September 1994, IAEA, 1995, 419-427.
- [40] P. Lako, A.J. Seebregts: *Characteristics of power generation options for the 21st century*. ECN-C--98-085, Petten, 1998.
- [41] G. Kolb: *Contributions to the Socio-Economic Research on Fusion (SERF)*. Interner Bericht FZJ-STE-IB-17/98, FZ Jülich, October 1998.
- [42] P.C. Rühland: *Modernes 500-Megawatt Kraftwerk Rostock eingeweiht*. Energiewirtschaftliche Tagesfragen, 11, 1994, 726-727.
- [43] *Energiewirtschaftliche Tagesfragen*, 3, 1997, 183-184.
- [44] P.T. Alderliesten et al: *An attractive option for CO₂ control in IGCC systems: water gas shift with integrated H₂/CO₂ separation (WIHYS) process. PHASE I: proof of principle*. CEC project JOU2 CT92-0158.
- [45] J. Ewers et al: *Braunkohlenforderung und Verwendung*. BWK, April 1998, 46-51.
- [46] J-G. Kim: *Wirtschaftlichkeitsanalyse der in der Bundesrepublik Deutschlands gebauten Kernkraftwerke und Vergleich mit Steinkohlekraftwerken*. Universität Essen, February 1991.
- [47] G. Frederic et al: *Competitiveness of nuclear power in Belgium*. In: 'The nuclear power option', Proceedings of an International Conference, 5-8 September 1994, IAEA, Vienna, 1995, 505-523.
- [48] D.J. Gielen et al: *Prospects for bioenergy in the Netherlands*. ECN-C--97-103, Petten, 1998.
- [49] P. Lako et al: *European biomass scenarios and the need for import of biomass*. ECN-R--97-009, Petten, 1997.
- [50] G. Brakmann: *Das solarthermische 50-MW-Kraftwerk Theseus*. Energie-wirtschaftliche Tagesfragen, 4 (1998), 249-251.
- [51] F. Trieb et al: *Markteinführung solarthermischer Kraftwerke*. Energiewirtschaftliche Tagesfragen, 6 (1998), 392-397.
- [52] *An assessment of renewable energy in the UK*. ETSU, Harwell, 1994.
- [53] P. Breeze: *Power generation technologies*. Financial Times Energy, 1998.

-
- [54] Energie & Milieuspectrum, March 1996, 27.
- [55] *MegaPower. Concept description*. IJmuiden, March 1996.
- [56] D. Zaslavsky: *Solar energy without a collector for electricity and water in the 21st century*. 8th Sede Boqer Symposium on Solar Electricity Generation. November 1997.
- [57] *IPCC, Stabilization of atmospheric greenhouse gases: physical, biological and socio-economic implications*, Technical Paper III, 1997
- [58] *BP Statistical Review of World Energy 1997*
- [59] L.W.M.M. Rademakers et al.: *Physical model testing for characterising the AWS*. European wave energy conference EWEC '98, Patras, (Greece) 30 sept. - 2 oct. 1998.
- [60] *Climate change 1992*. The Supplementary Report to the IPCC Scientific Assessment. The 1992 report of the IPCC Scientific Assessment Working Group.
- [61] IIASA-WEC: *Global Energy Perspectives*, Cambridge University Press, 1998
- [62] M. Kaltschmitt, M. Fishedick: *Wind- und Solarstrom im Kraftwerksverbund - Moglichkeiten und Grenzen*, C.F. Muller Verlag GmbH, Heidelberg, 1995.
- [63] P.J. Knight, I. Cook: *Draft final report on fusion electricity costs, scalings and uncertainties*. UKAEA, September 1998.