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LONG TERM SCENARIOS AND THE ROLE OF FUSION POWER

Synopsis of SE0 studies, conclusions and recommendations

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Abstract

This report summarises studies carried out as part of Macro task SE0, long term scenarios, in the framework of a programme on Socio-Economic Research on Fusion (SERF). The SERF programme has been adopted by the EU, DG XII, in 1997. Fusion power is a technology with long term potential (beyond 2050) and deserves particular attention because it is a CO_2 free and virtually inexhaustible energy source. Fusion power, presumed it would be technically feasible, will have more impact for OECD countries than for developing countries. It is deemed more expensive than currently available alternatives such as fission power and coal-fired power. For the period 2070 to 2100 it comes out as an economically viable option in case of CO_2 reduction policy.

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SUMMARY

This report summarises studies carried out as part of Macro task SE0, long term scenarios, in the framework of a programme on Socio-Economic Research on Fusion (SERF). The SERF programme has been adopted by the EU, DG XII, in 1997. One of the main issues is how fusion power could fit in the group of future energy options. Fusion power is a technology with long term potential (beyond 2050) and deserves particular attention because it is a CO_2 free and virtually inexhaustible energy source.

Fusion power, presumed it would be technically feasible, will have more impact for OECD countries than for developing countries. It is deemed more expensive than currently available alternatives such as fission power and coal-fired power. Therefore, fusion power (and other CO_2 free alternatives) need some incentive like carbon taxes in order to become viable.

Among the conventional competitors to fusion power are fossil fuel based power generation (hard coal, lignite, natural gas) and fission options. Today the most economic fission options are the LWR (Light Water Reactor) and the HTR (High Temperature Reactor). Their technical-economic characteristics are well known. Intermittent renewables like wind and solar power could have considerable impact on the potential of fusion power, although they cannot be regarded as solitary competitors to fusion power, which is a base-load power option. Besides, there are several ‘exotic’ power generation concepts. Two important notions in that respect are availability and geopolitical dimensions. Some of the concepts proposed do not generate base-load power; therefore, they cannot compete fully with fusion power. Some other concepts would require power transmission from Northern Africa with its geopolitical dimensions.

Based on a large number of cost studies of fusion power, an assessment has been made of the development of investment cost and power generation cost of future fusion power plants. In the period until 2050 fusion power is in the development and demonstration stage. Costs can go down relatively rapidly in that stage. After 2050 fusion power could enter the commercial stage, which implies more moderate cost reductions linked with increased number of plants. Significant cost reductions are possible due to economies of scale: larger installed capacity, multiple units at one site.

If fusion power is assumed available in a model of the Western European energy system, it emerges as an economically viable option in case of CO_2 reduction policy. This analysis is based on various levels of global CO_2 stabilisation. Fusion power becomes competitive at a cost of ECU 30 to 70/tCO_2. Several variants with different discount rates, variants with a large potential of renewable energy or ample fossil fuel availability, etc. have been analysed. In adverse circumstances introduction of fusion power shifts to a somewhat more stringent CO_2 stabilisation level.

Rising CO_2 concentration of the atmosphere is not a short-term but a long-term global problem. It therefore requires - in addition to the more well-known short-term efforts - long-term solutions. As far as base-load power generation is concerned, such solutions should be based on CO_2 free, practically unlimited primary energy sources. Not many of such options are available. Presumed that fusion power is technically feasible, it would probably be one of the few options available.

1. INTRODUCTION

This report addresses results and conclusions from studies which have been carried as part of Macro Task SE0 (long term scenarios) in the framework of the SERF programme (Socio-Economic Research on Fusion Energy) of the EU, DG XII. The Macro tasks within this programme are:

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

One of the main issues is how fusion power could fit in the group of future energy options. Fusion power is a technology with long term potential (beyond 2050) and deserves particular attention because it is a CO_2 free and virtually inexhaustible energy source. The institutes contributing to SE0 analysed this question from different angles:

- ARGE Wärmetechnik (Graz, Austria) gave a detailed assessment of the economics of fusion power as an additional vector in the IIASA-WEC World Scenarios [1].
- FZ Jülich focused on conventional and novel power generation technologies which could compete with fusion power; they also examined long term scenario studies and gave ideas on the conditions for market introduction of fusion power [2].
- Risø National Laboratory performed an in-depth analysis of existing long term energy scenarios, showing their similarities, differences, and possible weaknesses [3].
- CEA-Lemme (Toulouse, France) examined the effects of uncertainty on the evaluation of research programmes, with special interest in the fusion programme [4].
- ECN Policy Studies also analysed the main long term energy scenarios [5], and did an in-depth analysis of the potential of fusion power in Western Europe for a number of scenarios until 2100, applying an adapted MARKAL model for Western Europe [6]. The technologies which are crucial for the evaluation of the potential of fusion power are described in [7].

Although some activities showed overlap, notably the analysis of long term energy scenarios, this proved to be more advantageous than counterproductive after all. Risø and FZ Jülich put much effort in the analysis of long term energy scenarios, particularly those developed by IIASA-WEC and IPCC. The various views on long term energy scenarios were not only partially complementary, but also useful for the design of new energy scenarios for Western Europe. This is a prerequisite for the model calculations by ECN Policy Studies.

The assessment of the economics of fusion power by Arge Wärmetechnik, which became available in an early stage of the SERF programme, served as the main source of cost data on fusion power in the study of ECN Policy Studies. In the same way, data of FZ Jülich on conventional and novel power generation technologies that could compete with fusion power have been used in the study of ECN Policy Studies.

2. VIEWS ON LONG TERM ENERGY SCENARIOS

It seems appropriate to express some hesitation with respect to long term energy scenarios. Such scenarios are inevitably influenced by current views and expectations. However, some future trends are regarded as crucial for future energy development:

- Population growth. World population will grow from 6 billion people in 1999 to about 8 billion in 2025, ending up at some 11 billion people in 2050 and beyond[1].
- Limitations of world's fossil fuel resources, notably of oil and gas. At least conventional oil resources will peak in the first half of the 21st century.
- Economic growth and growth of energy demand. Generally it is assumed that GDP of the world will increase tenfold between 1990 and 2100. World energy demand would then increase by a factor 3 to 6 compared to 1990. However, this is only one estimate within a wide range.
- Climate change. It is hard to assess future policies with respect to climate change. However, it seems a safe bet that global warming will remain an important driving force for future energy decisions.

IIASA-WEC and IPCC defined and described a number of scenarios, both for the world and for world regions. The IIASA-WEC scenarios (1995) are characterised as follows:

- Historically the consumers have been experiencing an overall increasing level of income and as a result they desire energy services that are more efficient, clean, and convenient. This trend is expected to continue and will to a large extent govern the demand side structure of the energy system.
- The development of final energy demand is to a certain extent identical in the scenarios considered. The use of cleaner end-use fuels such as electricity, gas, and synthetic fuels will increase at the expense of solids.
- Population growth is assumed identical in the scenarios, whereas the development of economic growth and energy intensity differs among the scenarios.

The IIASA-WEC scenarios (1995) have a few common elements. Growth rates for high-income economies (OECD) decline gradually. Fossil fuels are assumed to be amply available. All scenarios envisage a gradual shift away from fossil fuel sources by the end of the 21st century. This transition may not be smooth in all cases, since the cumulative energy requirements are very large. High demands for oil and gas will require substantial technological advances in oil and gas exploration and production.

The IPCC (1996) presents five so-called LESS-variants (Low CO_2-Emitting Supply Systems). The matter of consumer interests, which is a main topic in the IIASA-WEC study, is not treated separately. Instead the consumers are assumed to be part of a society with deep CO_2 reductions on the agenda. Four variants differ in the use of sources of primary energy and a fifth explores the options available given a higher level of energy demand. The four include a biomass intensive, a nuclear intensive, a coal intensive, and a natural gas intensive variant. The focus on deep CO_2 reductions and the consistence in demand side structures (unlike the IIASA-WEC study) give the IPCC study a more normative character than the IIASA-WEC study. It is interesting to put several long term scenario studies of IPCC and IIASA-WEC in perspective by comparing the CO_2 emissions expressed in GtC/year in the year 2100.

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[1] Annex A gives an overview of recent world population forecasts.

In the original ‘business-as-usual’ scenario IS92a of IPCC (1992) CO_2 emissions show a strongly increasing trend, from 6 GtC today to 20.3 GtC in 2100.

- IIASA-WEC scenarios show a range from 14 GtC in 2100 for scenario B to 2 GtC for scenario C.
- All IPCC LESS variants presume a drastic reduction to only 2 GtC.

These large differences in CO_2 emission illustrate the different scopes of the scenarios.

Considering this short overview, the following scenario categories are distinguished:

- Ecologically driven scenarios. These are scenarios with intensive development in technology and a massive focus on ecology and environmental protection.
- High-demand driven scenarios. Economy intensive scenarios focusing on high growth rates in global energy demand.

Ecologically driven scenarios presume that global warming will remain high on the political agenda, and that strict policies conforming to that priority will be put in place. High-demand driven scenarios focus on the most likely supply-side structures given that our capability of deploying global energy resources is pushed to the limits.

Especially consumers and policy makers can be expected to strongly affect the prospects for different energy sources. The choices made by such parties will decide to what extent the next century will be ecologically driven or high-demand driven.

Furthermore, consumers and policy makers will influence decisions on critical technologies like fission energy. It seems that most of the IIASA-WEC scenarios are biased towards fission energy. Considering the various words of caution mentioned in the IIASA-WEC study - breeder reactor development, public acceptance, etc. - it seems inadequate that only one out of five scenarios foresees a troublesome future for fission energy. In the IPCC LESS variants, the opposite seems to be true: the mix of one nuclear-intensive variant and four variants with a minor contribution from fission energy suggests an ample freedom of choice from non-nuclear alternatives. In all IPCC LESS variants biomass is an important part of the renewable portfolio in the 21st century. However, unlike fossil fuels biomass is not abundant in its resource base, and land use constraints will occur at some point if energy demand continues to increase.

A positive element of the IIASA-WEC scenarios is the broad range of possible futures covered by a relatively modest number of scenarios. The use of a single population forecast and several economic growth variants helps accentuate the story lines in the scenarios. The IIASA-WEC scenarios are overall more positive with respect to nuclear fission projections than the IPCC LESS variants. However, the ‘ecological’ IIASA-WEC Cases and IPCC LESS variants are comparable in this area, both representing phase-out and revival variants following similar patterns.

It seems worthwhile to give attention to the consequences of the scenarios for developing countries. In this framework we only mention some potential problems:

- The per capita income of developing countries does not seem to keep pace with that of industrialised countries.
- Even if oil and gas are relatively cheap today, it seems probable that developing countries will shift to coal as soon as oil and gas would become more expensive.
- The drive for less CO_2-intensive energy sources, which is apparent in OECD countries, could be hampered by a (partial) switch to coal in developing countries.

The potential role of fusion energy is mentioned only briefly in the IIASA-WEC and IPPC studies. The picture of fusion power is characterised by the following sentences: ‘Fusion energy would take or share the role played by breeder reactors’ (IIASA-WEC), and: ‘Fusion energy is not expected before the second half of the next century’ (IPCC). There are a few reasons for this virtual neglect of fusion energy. It is undoubtedly true that fusion energy cannot help in the first half of the 21st century. However, the IIASA-WEC and IPCC studies have a time horizon until the year 2100. Besides, the commercial introduction of fusion power could coincide with the time scale in which climate change policies should become effective. Another reason is that fusion power is not yet technically proven. However, if the scope is limited to options that are technically proven, an exaggeration of the role of e.g. breeder reactors can be expected. This is what occurs in IIASA-WEC scenarios.

All in all it seems worthwhile to include fusion power in long term energy scenarios, despite uncertainties with respect to technical-economic feasibility and the long lead time involved. If we decide to do so, it is interesting to imagine its possible impact:

- Fusion power, presumed it would be technically feasible, will have more impact for OECD countries than for developing countries. However, the global scene is dynamic: China cannot be regarded as a less developed country any longer.
- Fusion power will be more expensive than some currently available alternatives such as fission power and coal-fired power. Therefore, fusion power (and other CO_2 free alternatives) need some incentive like carbon taxes, which are contemplated in industrialised countries (the EU). From another perspective, such as the risk of proliferation, fusion power could be favoured over fission power.
- A high-demand driven scenario would at first glance seem to work in favour of energy sources with a large potential like fusion power. In a scenario with a more moderate increase in energy demand new energy sources like fusion power would face a more challenging and competitive market. However, the future level of energy demand is strongly correlated with the regional policies pursued. Sustainable energy policies are likely to induce more energy efficient and less CO_2 emitting energy structures, that can mitigate the rising demand of final energy. Being a CO_2 free energy source, fusion power could benefit from such sustainable policies, even in a market with a relatively ‘low’ level of energy demand.

3. COMPETITORS TO FUSION POWER

G. Kolb of FZ Jülich presents in his contribution to SE0 a number of possible competitors to fusion power. First the focus will be on fossil fuel based power and fission power, then on ‘conventional’ renewables, and finally on ‘exotic’ technologies.

Among the conventional competitors to fusion power are fossil fuel based power generation (hard coal, lignite, natural gas) and fission options (Light Water Reactor, LWR). Table 3.1 shows the most relevant fossil fuel based and fission options.

Table 3.1 *Fossil fuel based and fission options as competitors to fusion power*

	Net capacity [MW_e]	Inv. Cost[2] [ECU95/kW]	Oper. and maint., fixed [ECU/kW/y]	Oper. and maint., variable [mECU/kWh]	Net gen. Eff. [%]	Load factor [%]
EPR	1,450	1,900	90	0.54	34	87
SWR 1000	977	1,900	90	0.54	35	89
BoA-Plus	920	1,300	90	2.38	49	88
KoBra	1100	1,465	95	1.88	49	85
Pulv. Coal	600	1,450	80	2.10	46+	83
IGCC	823	1,415	72	1.42	49	83
Gas CC	676	580	28	0.51	60+	88
MCFC gast.	50	1,000		3.89	65	95

Source: [2]

The European Pressurised Water Reactor (EPR) and the Siemens Boiling Water Reactor (SWR) are advanced LWRs with investment costs of ECU 1900/kW_e. The option of the European Fast Reactor seems to be more disputable than the LWR. A more likely option is the High Temperature Gas-Cooled Reactor (HTR), which is rather well-known in Germany and the US. The helium cooled HTR has outstanding safety characteristics. The South-African utility Eskom developed an improved HTR design, based on a German HTR concept. Eskom is committed to build a demonstration HTR (called Pebble Bed Modular Reactor, PBMR), and to further commercial introduction[3].

Two lignite-fired power options are considered, viz. BoA-Plus and KoBra. BoA-Plus is a lignite-fired power plant with utilisation of the condensation heat of water. KoBra is the acronym for an Integrated Gasification Combined Cycle (IGCC) plant based on lignite. Investment costs (ECU 1300 and 1465/kW_e respectively) and operation and maintenance costs are comparable. Both could attain a generating efficiency of 49%.

Also coal-fired power generation options are presented (pulverised coal fired power and IGCC). Investment costs (ECU 1450 and 1415/kW_e respectively), operation and maintenance costs, and generating efficiencies (up to 50%) are roughly comparable.
A gas-fired combined cycle (CC) power plant could attain a net generating efficiency of 60% around 2000. In the near future even higher efficiencies (63%) are envisaged. A Molten Carbonate

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[2] The ECU of year 1995 is used as reference currency in all reports considered.

[3] A more remote option, the ‘Energy Amplifier’ concept of Carlo Rubbia, will be addressed later on.

Fuel Cell (MCFC) integrated with a gas turbine could attain a still higher efficiency (65%), although its investment costs are also deemed to be higher.

A more remote, albeit technically feasible, option is coal-fired power with CO_2 separation and geological sequestration. If CO_2 separation is applied to Integrated Gasification Combined Cycle (IGCC), the generating efficiency would drop with 8 percentage points (from 50%, Table 3.1). Investment costs would increase by 20-25%.

The FZ Jülich study also covers 'conventional' renewables, summarised in Table 3.2.

Table 3.2 *Characteristics of 'conventional' renewable power generation options*

	Net capacity [MWe]	Investment cost [ECU95/kW]	Operation and maintenance cost [ECU/kW/y]	Load factor [%]
Offshore wind	120	1,500	30	42
Import of solar PV[1] power from South Spain[2]	1760	4,530	22	22.5
Import of solar PV power from North Africa	1679	5,240	24	26.6
Import of solar tower power from South Spain	1760	4,240	78	41.1
Import of solar tower power from North Africa	1679	4,070	80	41.1

[1] Photovoltaic power.

[2] As Germany is the reference country, transport costs are high for South Spain and North Africa.

Source: [2]

Experience with offshore wind power - actually 'near-shore' wind power - is scarce up to now. It is also difficult to make an assessment of the costs of solar PV and the like (solar tower). Solar and wind energy, which produce intermittent power, cannot be regarded as solitary competitors to fusion power, which is a base-load power option. Nevertheless, they could have considerable impact on the potential of fusion power.

At last Kolb presents so-called 'exotic' technologies. These are defined as follows:

1. are presently futuristic, i.e. out of scope of introduced or nearly available technologies by size or by available conversion methods or by development stage,
2. are believed to promise globally or regionally and for permanent or at least for a very long time span a pronounced contribution to the energy (electricity) supply,
3. would need a long time (more than one up to several decades) for their development,
4. are not in a status to estimate or even assess especially (investment) cost figures - neither in relative nor in absolute terms, and
5. are not focus of official development efforts of any agency except (pre-)feasibility studies.

Kolb describes one nuclear and four renewable energy based 'exotic' concepts:

- The 'Energy Amplifier' (EA) concept of Carlo Rubbia.
- The 'MegaPower' Tower.
- The 'Very Large-Scale Photovoltaic Power Generation System' (VLS-PV).
- Space-based solar power.
- The Solar Energy Tower, a concept of Technion, Israel.

These concepts, except the third mentioned (VSL-PV), will be shortly addressed.

The ‘Energy Amplifier’ (EA) concept of the former Nobel prize winner Carlo Rubbia is a combination of a particle accelerator and a U^{233} breeder reactor. Fissionable U^{233} is bred from Thorium. The ‘breeder’ reaction produces an amplification of about 30 times the invested acceleration energy. This concept has some attractive features compared to convential fission options like the Light Water Reactor (LWR):

1. The threat of a core meltdown can be eliminated.
2. The amount of remaining radioactive waste could be reduced by up to 4 orders of magnitude.
3. EAs would allow production of 15,000 TWa of electricity, which is 10,000 times current world electricity production.

The ‘MegaPower’ Tower is a cable-rigged pipe, 5,000 m high and 50 m in diameter, in which the temperature difference between sea level and at great height is used to drive a thermal cycle: 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 m and a cooler at 7,500 m.

Space-based solar power seems rather futuristic. 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, reconverting 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 raised 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 Technion-Israel Institute of Technology in Haifa (Prof. Dan Zaslavsky) proposes an Energy Tower concept for the conversion of solar energy into electricity. This concept is based on the descending hot dry air of the Hadley Cell Circulation in the desert belt on both sides of the equator. Hot air is to be cooled by the evaporation of sea water at the top of the approximately 1200 m high Energy Tower. The downdraft of the cooled air will be formed by a low efficiency thermodynamic cycle within a high and large diameter shaft or tower (diameter vertical shaft: 400 m). The downward stream of air drives turbines and electrical generators located radially around the base of the shaft. Zaslavsky projects electricity costs of a Solar Energy Tower at 3.7 US¢/kWh, assuming a 7.2% interest rate and a lifetime of 30 years.

It is for sure that some exotic options will prove to be feasible. However, not all of the exotic renewables are appropriate for the latitude of Western Europe, viz. space-based solar power and VLS-PV. The MegaPower Tower poses a relatively large technical-economic risk in case of a first-of-kind plant.

Two other important notions in this respect are availability and geopolitical dimensions. The MegaPower Tower is a base-load power option, with the restriction that the power production is not constant due to seasonal fluctuations of the temperature difference between sea level and the higher atmosphere. Space-based solar power, the Solar Energy Tower proposed by Technion, and VLS-PV would require power transmission from Northern Africa with its geopolitical dimensions.

4. ANALYSIS OF FUSION POWER COST

P.V. Gilli and R. Kurz made an analysis of fusion power cost as a contribution to SE0 [1]. Their focus is on cost assessment rather than on estimates of the market potential for fusion power in the 21st century.

First Gilli and Kurz give attention to the long list of publications on fusion power costs, with special attention for recent papers on ITER or ITER-like designs. Then they address the investment cost of a first-of-kind 1000 MW fusion power plant. The investment cost depends on the type of fusion reactor, ranging from ECU 10,000/kW for an ITER-like design (conservative) to ECU 4800/kW for an advanced design.

The next step is to determine a learning ratio, going from a first-of-a-kind fusion power plant to a 10th-of-a-kind plant and beyond, based on IIASA-WEC learning assumptions. Gilli and Kurz make a distinction between the learning ratio of the fusion core and the Balance Of Plant (BOP). The learning ratio for BOP is lower than for the fusion core.

For successful technologies, learning is fast in the RD&D stage, i.e. cost degression is large per additionally installed power plant. After having reached a competitive cost level, learning is related to increasing numbers of (larger) identical fusion power plants rather than to major changes of the technology.

In the commercial stage, the major share of cost degression is due to unit size and number of units at one location. Going from 1000 MW to 1500 MW causes a cost degression of 0.794. A twin unit could show a cost degression of 0.84 compared to a single unit. Therefore, investment cost of a twin 1500 MW fusion reactor compared to a single 1000 MW unit is 0.794*0.84 = 0.67 (the same factor applies to a single 2000 MW fusion power plant).

Other relevant cost issues are:

- Operation and maintenance costs, inclusive of fuel costs and decommissioning costs. According to Gilli and Kurz these costs could decrease from 13 mECU/kWh in 2020 (for the successor of ITER, DEMO) to 10 mECU/kWh in 2070.
- Replacement charges, pertaining to the regular replacement of diverter, blanket, and first wall during operation; these charges are estimated at 53 mECU/kWh in 2020 (corresponding to DEMO) and at 14 mECU in year 2100.

Figure 4.1 shows the synthesis of the different steps for investment costs. The bottom line represents BOP cost. The cost degression is rather modest. Besides, BOP costs are assumed to level off around 2070. So, after 2070 no learning effects are assumed for BOP. Total cost shows a rather steep decline until 2050, when fusion power is assumed to enter the commercial stage. After that, cost degression is much lower.

Figure 4.2 shows a comparison of power generation cost for a commercial fusion power plant. At the right side the single 1000 MW and the twin 1500 MW power plants from the study of Gilli and Kurz are shown. The left side shows power generation costs according to Knight and Cook (Macro task E1); these are representative figures for a 'nominal' and an 'advanced' 1000 MW design. Costs refer to a discount rate of 8%.

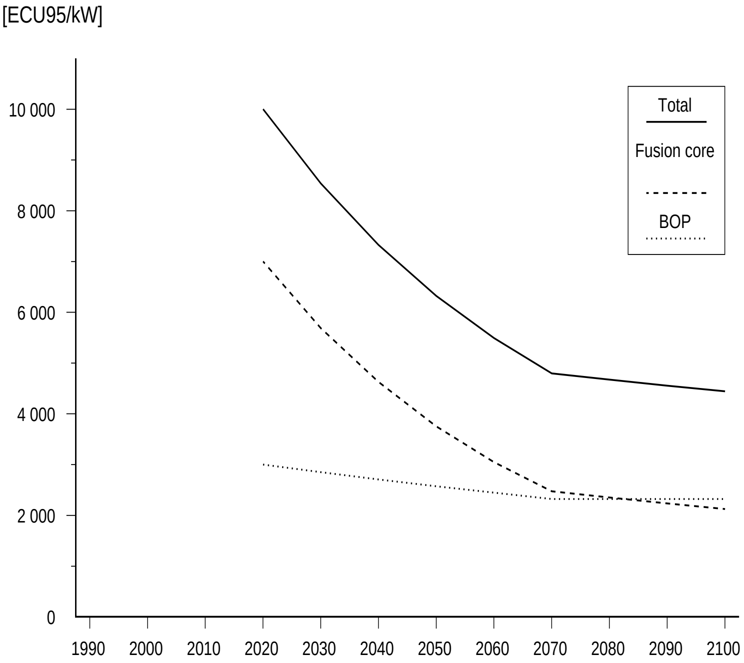

Figure 4.1 *Investment cost of an Nth-of-a-kind 1000 MW fusion power plant*

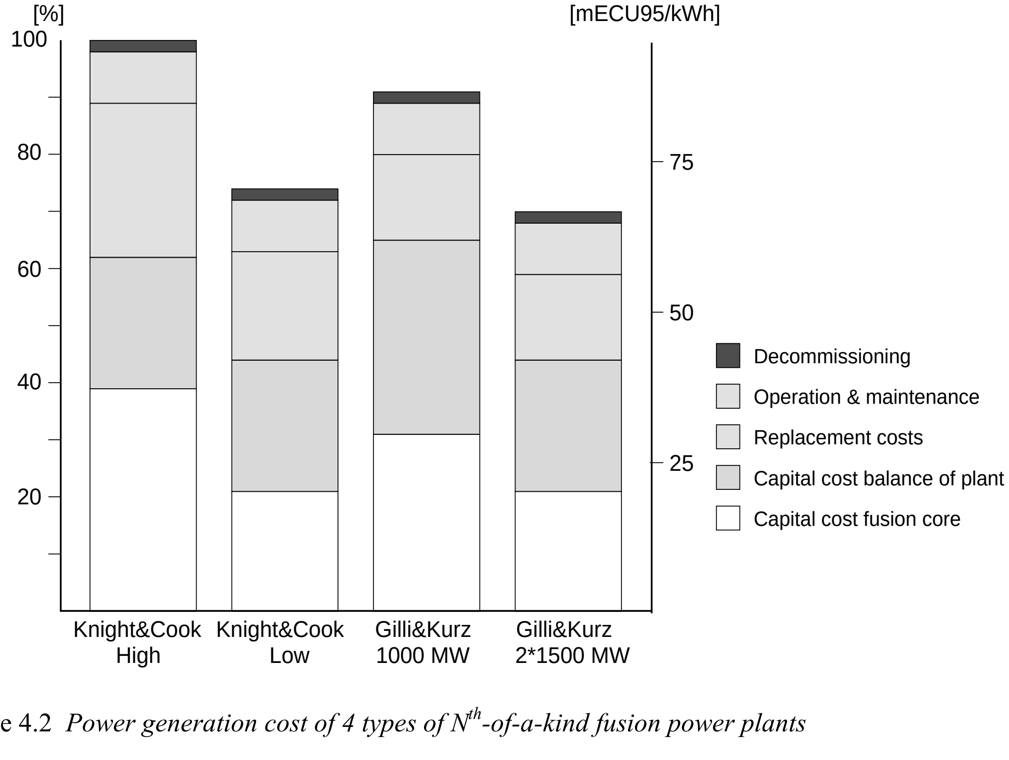

Figure 4.2 *Power generation cost of 4 types of Nth-of-a-kind fusion power plants*

5. LONG TERM POTENTIAL IN WESTERN EUROPE

This Section mainly addresses the analysis of the economic potential of fusion power by ECN Policy Studies [5]. The potential of fusion power is calculated with the technology oriented MARKAL model for Western Europe. The study has the following contents:

- methodology and scenario design,
- key parameters of scenarios,
- two scenarios without CO_2 constraints,
- scenario variants with CO_2 policy and various discount rates,
- additional sensitivity analysis.

First focus is on methodological issues related to the time horizon until the year 2100:

1. Technology assumptions in the study of ECN Policy Studies are primarily based on detailed estimates, learning effects, and expert opinions included in studies of colleague institutes contributing to the SERF programme, and other studies.
2. The issue of discounting has been solved in the following way:
   - 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. A relatively low discount rate of 2.5% per year governs the depletion of fossil fuel resources and cumulative CO_2 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.
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 CO_2 in the year 2100 (e.g. 450, 550, 650 and 750 ppm) can be translated into cumulative CO_2 emission budgets for Western Europe.

Secondly, the study addresses key parameters of scenarios. One parameter is fossil fuel resources: proven, probable, and possible reserves. For oil (conventional and unconventional) the reserve/production ratio is 130 years, for gas 190 years and for coal (only reserves) 220 years. It is acknowledged that these figures are more or less subject to changes. It is assumed that 10.5% of the resources is available to Western Europe (Table 5.1). In the 'high-demand' scenario this figure is 15%.

Table 5.1 *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

Other key parameters are the fossil fuel prices. Price trends for heavy crude oil are determined for the two main scenarios (Figure 5.1). The price trends for heavy crude oil have been translated into prices for natural gas for power generation.

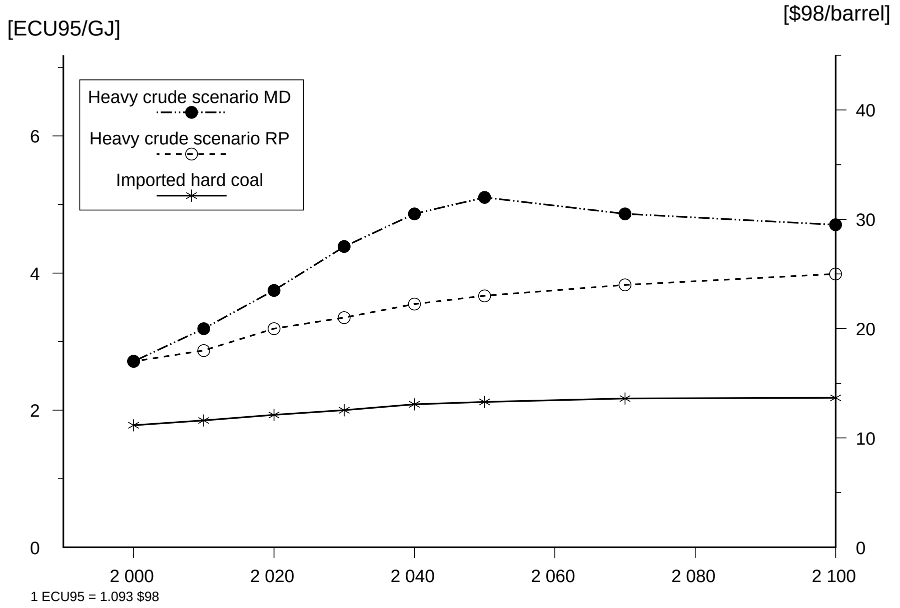

Figure 5.1 *Heavy crude oil prices and coal price for two scenarios*

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

- The price of imported hard coal rises with 0.35% per year until 2050, and stabilises after that[4].
- 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 energy demand scenario, requires higher oil prices. After a peak in 2050, heavy crude oil ends up at $ 29.5/bbl in 2100.

Table 5.2 presents characteristic differences in key parameters of the main scenarios.

Table 5.2 Ke*y 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	generally lower than in MD	generally higher than in RP
Fossil fuel availability 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, peaking in 2050; $ 29.5/bbl in 2100
Fission power	Maximum capacity declining to 70% of current capacity[5]	Maximum capacity declining to 80% of current capacity[6]

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.

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[4] Such low coal prices can only occur if coal demand is low, e.g. due to CO_2 policies.

[5] Converging to 40 GW in 2100.

[6] Converging to 40 GW in 2100.

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 produce wealth 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.

As a third step, the two main scenarios are first analysed without CO_2 constraint (base case). The resulting power generation mix for the base case scenarios is shown in Figure 5.2.

In the absence of CO_2 policies, fossil fuels are favoured for power generation. 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 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.

As fusion power is rather costly, it cannot compete with alternative base-load power options in the absence of CO_2 policies. So, irrespective of the discount rate used, fusion power needs some incentive, such as a cumulative CO_2 constraint, in order to become competitive to coal-fired power.

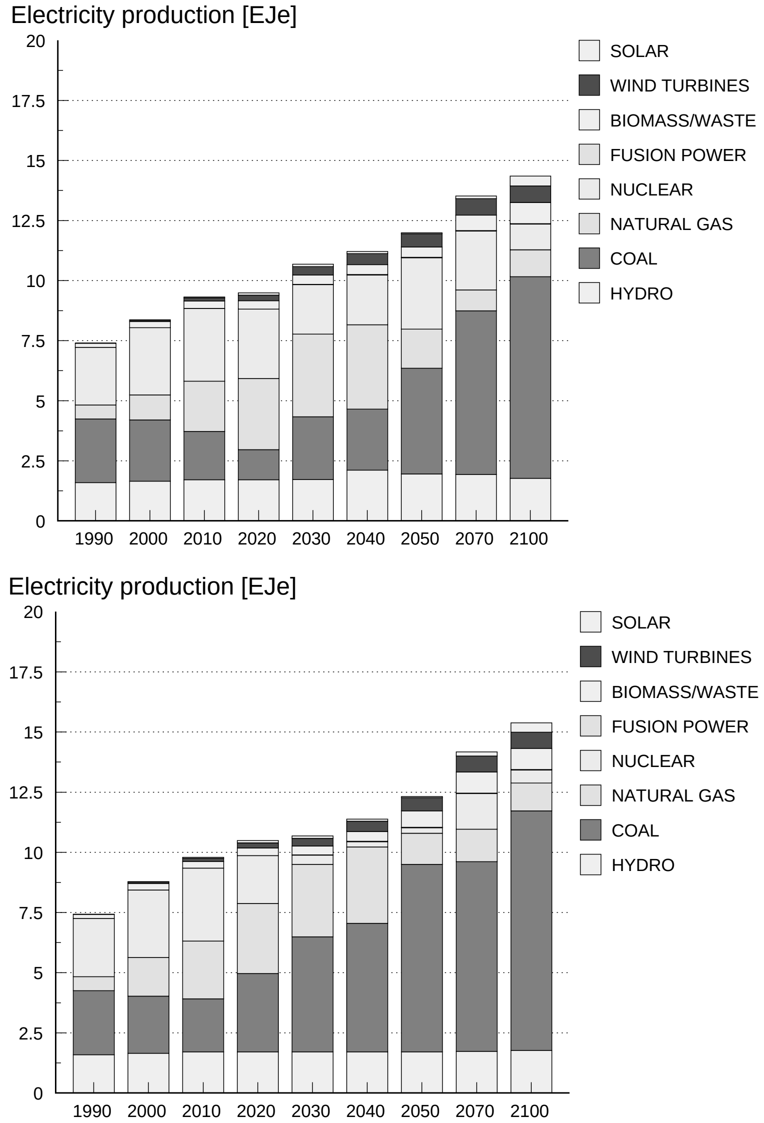

Figure 5.2 a and 5.2 b *Power generation by source for the base cases of Rational Perspective (top) and Market Drive (bottom)*

It is interesting to see what the CO_2 emissions in both of the scenarios are. Total CO_2 emissions are shown in Figure 5.3. CO_2 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, the CO_2 emission remains stable until 2050 (Figure 5.3). After 2050, coal consumption increases at the expense of oil use. Consequently, the CO_2 emission increases slowly after 2050. In 2100 the CO_2 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 fission power and new renewables increases. Coal consumption shows a surge from 2020. Therefore, the CO_2 emission increases until 2050, and remains more or less stable after that date. In 2100 the CO_2 emission is 60% higher than in 1990.

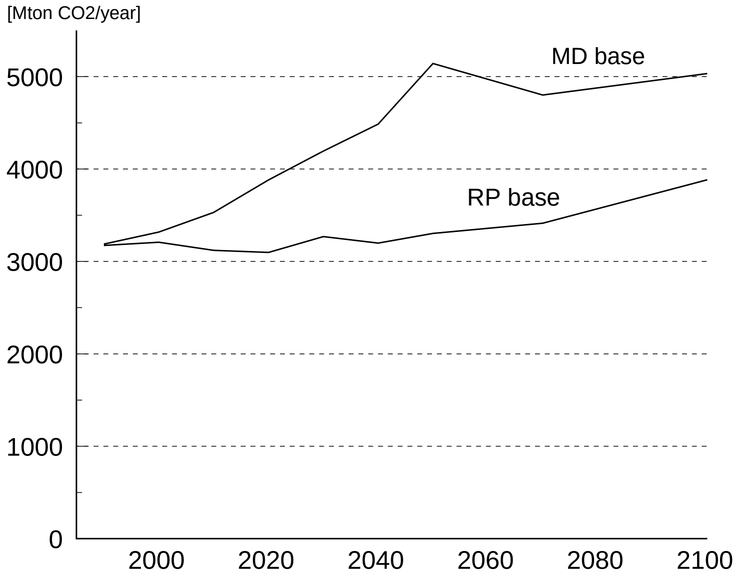

Figure 5.3 *Western European CO_2 emissions, base case scenarios Rational Perspective (bottom) and Market Drive (top)*

The fourth step is the analysis with CO_2 policies. In order to analyse the potential of fusion power under conditions of constrained CO_2 emission, cumulative CO_2 emission budgets for Western Europe have been defined, corresponding to various levels of global stabilisation of CO_2 concentration, viz. from 450 to 750 ppm (Figure 5.4 a + b).

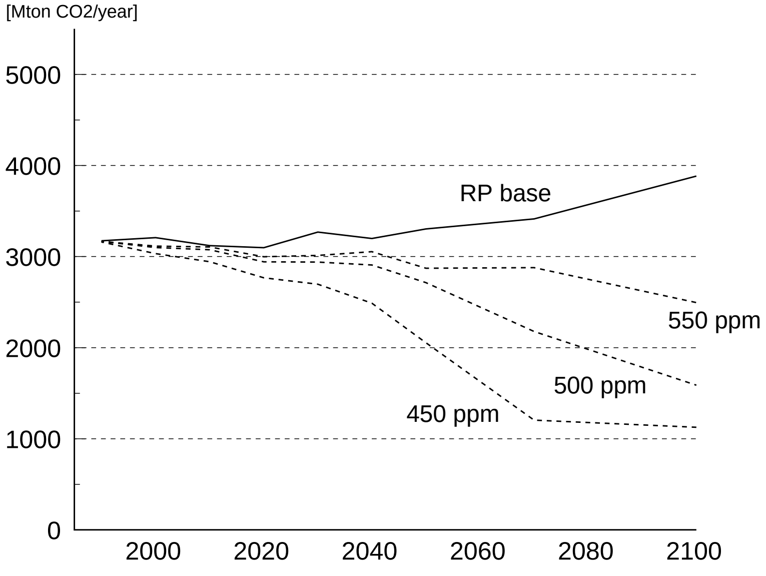

Figure 5.4 a *Western European CO_2 emissions, variants scenario Rational Perspective*

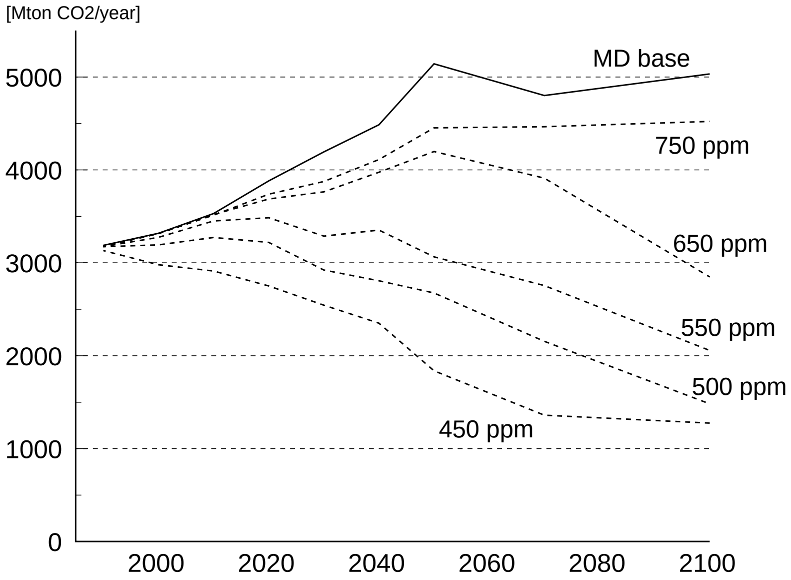

Figure 5.4 b *Western European CO_2 emissions, variants scenario Market Drive*

As the unconstrained CO_2 emission of scenario RP is almost equal to the 650 ppm level, only 550 ppm, 500 ppm and 450 ppm are shown. In case of the unconstrained MD scenario CO_2 emission is higher than any of the emission levels contemplated. Figure 5.5 shows the consequences of increasing CO_2 constraints for the power generation mix in the year 2100 in case of scenario RP and scenario MD respectively. In case of CO_2 constraints, fusion power starts to become competitive at shadow prices ranging from about 30 to about 70 ECU/tCO_2.

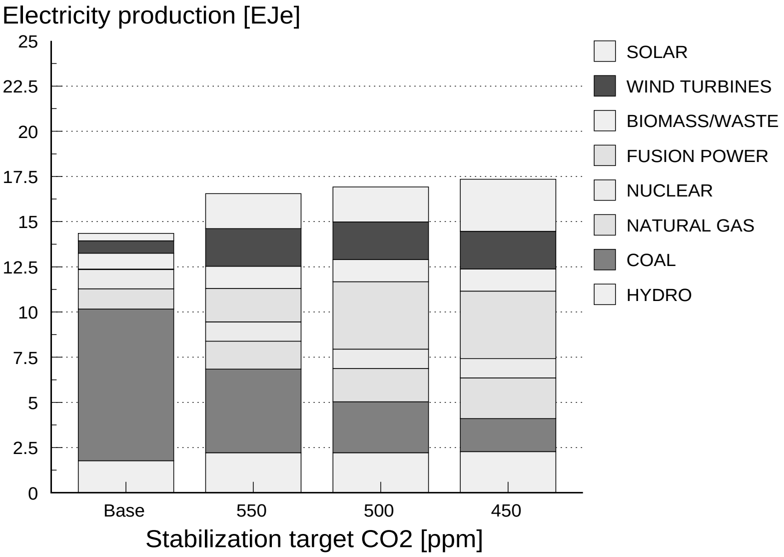

Figure 5.5 a *Power generation by source for the CO_2 variants of scenario Rational Perspective*

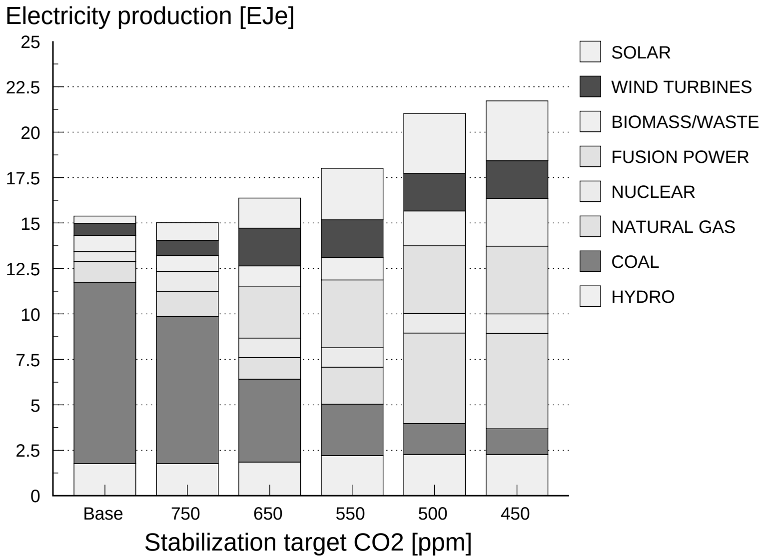

Figure 5.5 b *Power generation by source for the CO_2 variants scenario of Market Drive*

Starting with scenario RP, and going from 550 ppm down to 450 ppm, we observe the following trends:

- At 550 ppm (slightly decreasing CO_2 emission in Western Europe) fusion power gets a share in power generation which is somewhat higher than that of fission energy (which is at its upper bound), biomass-fuelled power, and gas-fired power, and comparable with that 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 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.

In case of the CO_2 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 higher 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.

As fifth and final step, a sensitivity analysis has been done 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% (like in scenario RP).
- Scenario MD with high investment cost of fusion power.
- Scenario MD with a high potential of renewable energy.
- Scenario MD with a high upper limit for fission energy (200 GW).

Installed fusion power capacity for the sensitivity cases as well as for the 'normal' CO_2 variants for the years 2070 and 2100 is shown in Tables 5.3 and 5.4 respectively.

Table 5.3 *Installed fusion power, CO_2 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 5.4 *Installed fusion power, CO_2 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 CO_2 reduction than scenario RP. Therefore, fusion power capacity is higher in case of a 'moderate' CO_2 emission level of 550 ppm in scenario MD than in scenario RP.
2. In the 550 ppm CO_2 reduction case of RP, fusion power capacity is 78 GW in 2100, about half the maximum level in the most stringent CO_2 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, but replacement costs not.
3. A 20% higher level of investment cost for fusion power does not entail a large difference in competitiveness. In the 'normal' 650 ppm CO_2 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.
4. If scenario RP is combined with the ample availability of fossil fuels of scenario MD (15% of global fossil fuel), fusion power loses competition with gas-fired power in the 550 ppm CO_2 re-

duction 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 CO_2 reduction case. In the 550 and 500 ppm CO_2 reduction cases fusion power loses market share. However, a high potential of renewables is more threatening to coal- and gas-fired power than to fusion power.
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 78 GW 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).

Another set of calculations concerns scenario variants in which it is assumed that fusion power is not available. Equal CO_2 stabilisation levels can be attained in that case, albeit at a higher cost. As the CO_2 bound is a cumulative constraint, deeper CO_2 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.

Figure 5.5 shows the results of a comparison of the capacity of fusion power under CO_2 constraints (variants of the scenario MD and RP) with the maximum global market potential estimated by Gilli and Kurz in their contribution to Macro task SE0.

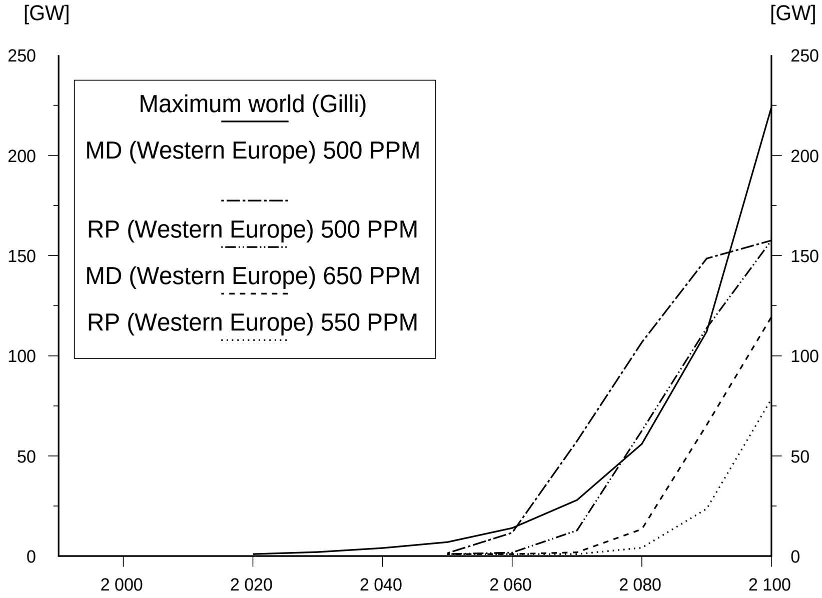

Figure 5.6 *Fusion power in Western Europe and in the World.*

In the 550 ppm CO_2 reduction case of scenario RP the Western European fusion capacity in 2100 is 35% of the global potential. In the 500 ppm case of scenario RP it is 70% of the global potential. However, in the 550 ppm case of scenario MD the Western European fusion capacity in 2070 exceeds the global potential estimated by Gilli and Kurz for that year. For the three less demanding CO_2 reduction cases the capacities in 2070 (Figure 5.5) do not exceed the global potential. It seems that the curve for the global potential is somewhat conservative for the period 2050-2070.

6. DISCUSSION

This discussion is devoted to parts of the contribution of B. Villeneuve. Villeneuve (CEA-Lemme), in his contribution to macro task SEO [5], reflects on the effects of uncertainty on the evaluation of research programmes (with special interest in the fusion programme). He discusses typical adaptations to risky contexts:

a. diversification
b. flexibility
c. experimentation.

The idea is that under uncertain conditions the economic value of a certain plan (research programme) depends on its ability to:

a. explore alternative technologies,
b. keep margins for accommodating shocks (arrival of new information and evidence), and
c. accelerate the improvement of scientific knowledge by radical procedures.

His analysis is that the tragedy with 'Big Science' is that projects are not only competitors in the sharing of funds, but it may also be the case that 'the winner takes all'. In practise, there is not a continuum of alternative options, notably when the alternative projects involve high costs. This is particularly true in the case of fusion power, where dimensional extrapolations plead in favour of large reactors. Consequently, a maximum of one project only will be implemented (at least if the idea of building a new experimental reactor is retained).

The aspect of "the winner takes all" with respect to the fusion programme, though defensible from the point of view of efficiency, seems to create a weakness in the sense that it cannot cope with the possible regret we could have in the end.

Villeneuve also examines the pros and cons of flexibility. In general, a flexible equipment is never ideal for the conditions of operations once they are known. One should be careful not to express vacuous regrets that, since *ex ante*, the decision was the best: flexibility is a form of self-insurance in a situation where purely financial operation cannot be a substitute for technological solutions. Extreme flexibility, however, like a very generous insurance, is rarely desirable. In a way, the arguments in favour of flexibility are exactly the same as the arguments in favour of status quo (wait and see): we are at a maximum of flexibility when projects are *systematically* delayed, which makes no sense.

Of course, ITER is intended to be a crucial experimental device. By building and using it, we will learn something, in particular whether a certain view of fusion power, a certain design is compatible (or possibly compatible) with commercial exploitation of fusion power. However, there is one point that should be clarified: *if* ITER were to fail, would everything be lost? Would we see better which of the other concepts would be likely to succeed? Would we learn early enough from the failure not to regret the time passed since ITER was designed and constructed?

Another important subject which Villeneuve addresses is the importance of experts and expertise. Experts are an essential part of the democratic political systems. Citizens are not able to follow in detail all the debates. Delegation to experts is a compromise in the sense that an abandonment of sovereignty is accepted in exchange for a gain in time. The more difficult the matter, the more it seems it should be delegated, whereas very arduous questions often entail crucial decisions: even though the technical analysis is difficult, the consequences are so important that delegation to experts becomes hazardous.

In a society where expertise is needed everywhere, to a large extent we observe a spontaneous specialisation: a slight comparative advantage naturally causes an individual to invest most of his activities in one rather limited domain. This does not mean that he or she is not interested in other questions, but it means that it is more efficient for him to remain specialised, given that other citizens endorse other cases. Overall, the democratic society can find a form of equilibrium in this way. As long as matters under discussion entail a low entry cost, spontaneous democratic control works well; when more expertise is needed, i.e. when experts have to be appointed and rewarded for their services, serious precautions have to be taken. Unfortunately, questions that are more technical in certain stages (they always become political at others) need particularly qualified experts. Now it is crucial for society to institute norms, rules or mechanisms for naming experts, et cetera, in order to direct the choices in the most appropriate direction.

7. CONCLUSIONS

Long term energy scenarios including fusion power were not available before the European Commission (DG XII) started the SERF programme. Fusion power has largely been neglected in long term energy scenarios because:

- Fusion power will not become commercially available before 2050.
- It has to be demonstrated that fusion power is technically feasible.

A distinction is made between ecologically driven and high-demand driven scenarios. If scenarios cover the entire 21st century, fusion power can be included because it is a CO_2 free and virtually inexhaustible power generation option.

Base-load power options like coal-fired power and fission power (LWR) are economically viable competitors to fusion power in the second half of the 21st century. Intermittent renewables - solar power, wind energy - are gaining importance. Although they could have considerable impact on the potential of fusion power, they cannot be regarded as solitary competitors to fusion power, which is a base-load power option.

'Exotic' concepts are the 'Energy Amplifier' concept of Carlo Rubbia (a combination of a particle accelerator and a U^{233} breeder reactor, using Thorium as fuel), the 'MegaPower' Tower (using the temperature difference between sea level and at great height), space-based solar power, and the Solar Energy Tower proposed by Technion in Israel for desert regions on both sides of the equator (using a downdraft of air cooled by a spray of sea water at the top of a 1200 m high tower to generate power at the base of the 400 m diameter shaft). None of these concepts can be developed in short course. However, they promise globally or regionally a pronounced contribution to the electricity supply, presumed they would be technically feasible.

The investment cost of fusion power can be estimated, starting with first-of-a-kind fusion reactors (ITER-like) and estimating the effects of technical improvement (including larger unit size and multiple units at one site) and increasing numbers of plants. Between 2020 - 2030 (DEMO, the successor of ITER) and 2050 fusion power is in the demonstration stage, and costs could come down rapidly. After 2050 cost degression is largely linked with increased numbers of plants: costs will come down slowly.

Investment cost of a twin 1500 MW fusion power plant is estimated at ECU 3000/kW (ECUs of year 1995) in 2100. Power generation costs could be 68 mECU/kWh for a commercial 1000 MW fusion power plant (discount rate 5%). Such costs come up from independent cost assessments within the SERF programme.

The long term potential of fusion power (in Western Europe) depends on the priority of climate change policies. As fusion power is rather costly, it cannot compete with alternative base-load power options in the absence of CO_2 policies. However, it seems a safe bet that global warming will remain high on the agenda. Therefore, fusion power would be an economically viable option if climate change remains a dominant issue.

Scenario calculations with an updated MARKAL model for Western Europe (1990-2100) show that coal-fired power is notably favoured in absence of CO_2 policies. CO_2 emission in Western Europe would increase by 20 or 60% in 2100 compared to 1990.

In case of CO_2 constraints, fusion power starts to become competitive at shadow prices ranging from about 30 to about 70 ECU/tCO_2. 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 CO_2 at 550 ppm would be needed (slightly decreasing CO_2 emission in Western Europe). In case of a ‘high-demand’ driven scenario, fusion power becomes already competitive in 2070, if stabilisation of atmospheric CO_2 at 650 ppm is aimed for. Fusion power is introduced at the expense of coal-fired power.

Sensitivity analysis shows that higher discount rates (8 or 10%) are not detrimental to fusion power, supposed fusion power has some market share due to CO_2 constraints in case of a 5% discount rate. This is because some renewable power options - notably photovoltaic power in the northern part of Western Europe - have a higher capital cost component in their generation costs than fusion power. A case with 20% higher investment cost of fusion power does not show much difference with the case with the above mentioned cost level of ECU 3,000/kW.

Fusion power would face competition from gas-fired power in case of ample availability of fossil fuels (15% of global resources available to Western Europe) and an ecologically driven scenario. This case shows that availability of oil and gas affects the competitiveness of fusion power to a certain extent. If a high potential for renewables is assumed, fusion power would lose market share under moderate CO_2 reduction conditions. However, a high potential of renewables is more threatening to coal- and gas-fired power than to fusion power.

If a complete phase-out of fission power in 2080 is presumed, fusion power could profit somewhat in a moderate CO_2 reduction case. If fission power is allowed to grow (from 125 GW up to 200 GW), fusion power is less prominent in the 650 ppm CO_2 reduction case (of the high-demand driven scenario).

Within the time horizon of the year 2100, equal CO_2 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 CO_2 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 CO_2 reduction levels the benefits of fusion power are relatively small.

It has been demonstrated in the IIASA-WEC study of 1995 (and in other studies as well) that the rising CO_2 concentration of the atmosphere is not a short-term but a long-term global problem (of the second half of the 21st century and even the 22nd century). It therefore requires - in addition to the more well-known short-term efforts - long-term solutions. As far as base-load power generation is concerned, such solutions should be based on CO_2 free, practically unlimited primary energy sources Not many of such options are available. Presumed that fusion power is technically feasible, it would probably be one of the few options available.

ANNEX A WORLD POPULATION FORECASTS

Some recent world population forecasts are shown in Table A.1.

Table A.1 *World population forecasts (billion people)*

	UN 98 low	UN 98 medium	UN 98 high	World Bank 96	IIASA 96 low	IIASA 96 med.	IIASA 96 high
1995	5.7	5.7	5.7	5.7	5.7	5.7	5.7
2000	6.062	6.091	6.123	6.065	6.110	6.140	6.170
2005	6.409	6.491	6.581		6.480	6.573	6.665
2010	6.726	6.891	7.060		6.850	7.012	7.168
2015	6.962	7.286	7.554		7.221	7.451	7.678
2020	7.265	7.672	8.062		7.547	7.879	8.191
2025	7.474	8.039	8.581	7.926	7.838	8.289	8.715
2030	7.625	8.372	9.100		8.072	8.672	9.247
2035	7.715	8.670	9.614		8.239	9.019	9.779
2040	7.746	8.930	10.12		8.371	9.341	10.30
2045	7.725	9.159	10.63		8.456	9.627	10.80
2050	7.662	9.367	11.16	9.199	8.488	9.874	11.30
2055					8.465	10.08	11.78
2060					8.391	10.25	12.25
2065					8.275	10.39	12.71
2070					8.121	10.49	13.14
2075				9.929	7.933	10.56	13.54
2080					7.714	10.59	13.90
2085					7.466	10.58	14.22
2090					7.174	10.53	14.53
2095					6.850	10.46	14.81
2100	5.6	10.4	17.5	10.32	6.507	10.35	15.07
2150	3.6	10.8	27.0	10.77			

Source: Risø

The UN publishes every second year with a time frame to 2050. A long term projection has been made available early 1998, which means a 5-6 year cycle since the last publication in 1992. The projection of 1992 was used in some of the IS92 scenarios of IPCC.

The World Bank has published projections every second year until 1994/95 but has stopped publishing since they use much of the basic data from the UN. The data in the table has not been published, but usage is permitted.

The number of regions used in the projections is not identical:

- The World Bank projections are country based.
- The UN projections are based on nine regions but country based projections until 2050 are also published.
- The IIASA projections uses 13 regions.

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