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LONG-TERM SCENARIOS AND THE ROLE OF FUSION POWER

Executive Summary of SE0 studies

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Acknowledgement

This study contains the results of studies carried out as part of Macro task SE0, long-term scenarios. The ECN study has the project number 7.7119. The following authors and institutes/companies contributed to this study:

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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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1. INTRODUCTION

Macro Task SE0 of SERF-1 addressed long-term scenarios. Primary aim of the task was to investigate how fusion power could fit in the group of future energy options by exploring the prospects in a systemic analysis. 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 (Gilli and Kurz, 1998).
- 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 (Kolb, 1998).
- Risø National Laboratory performed an in-depth analysis of existing long-term energy scenarios, showing their similarities, differences, and possible weaknesses (Lemming and Morthorst, 1998).
- CEA-Lemme (Toulouse, France) examined the effects of uncertainty on the evaluation of research programmes, with special interest in the fusion programme (Villeneuve, 1998).
- ECN Policy Studies also analysed the main long-term energy scenarios (Lako et. al., 1998a), 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 (Lako et. al., 1998b). The technologies which are crucial for the evaluation of the potential of fusion power are described in (Lako and Seebregts, 1999).

The assessment of the economics of fusion power by Arge Wärmetechnik, which became available in an early stage of SERF, is the main source of cost data on fusion power. In the same way, data of FZ Jülich on conventional and novel power generation technologies that could compete with fusion power have been used. The systemic analysis was performed at ECN with a specifically adapted version of the MARKAL model for the OECD-Europe region[1] to cover the period up to 2100. This model is a technology-oriented model of the energy system that enables dynamic optimisation, producing the least-cost solution over a number of time periods and under specific circumstances (fossil fuel prices, CO_2 constraints, etc.) The model was developed within the cooperative research partnership ETSAP (Energy Technology Systems Analysis Programme) under the auspices of the Internal Energy Agency in Paris. Today the MARKAL toolbox, which was gradually expanded with many optional features, is used by over 55 institutes in over 35 countries for a variety of purposes. At ECN, where MARKAL was used for a range of national studies from the mid eighties onwards, the database for the OECD-Europe region was developed from 1995 as part of a study on new energy and material options for the period up to 2050 (Kram et. al., 2001). Further enhancements and extensions were made for application in a comprehensive biomass potential study for the EU (Gielen et. al., 2000) and a study for the OECD.

MARKAL calculates a development path minimising (in a properly discounted way) the time-integrated expenditures (over the interval, and for the region considered) for energy provision. It is thus a rigorous procedure, following well-defined mathematical rules. It does require, however, in its input base-line assumptions regarding the future energy demand, and the technical and economic prospects of all technologies and primary supply sources. One can also take into account environmental constraints, by imposing limits on the total CO_2 emission budget, and the share of it allotted to Western Europe. This has been done in the ECN study.

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[1] The EU-15 countries, Norway, Switzerland, and Iceland.

2. VIEWS ON LONG-TERM ENERGY SCENARIOS

It seems appropriate to express some hesitation with respect to long term-energy scenarios, as these are inevitably a construct of current views and expectations. However, in (Lemming and Morthorst, 1998) Risø National Laboratory regards some future trends as crucial for future energy development:

- Population growth. The world population will grow from 6 billion people in 1999 to approximately 8 billion in 2025, ending up at some 11 billion people in 2050 and beyond.
- 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. It is widely assumed that GDP of the world will increase by an order of magnitude between 1990 and 2100. Here a tenfold increase is assumed. The associated world energy demand would then increase by a factor 3 to 6 compared to 1990. However, this is only an estimate within a wide range.
- Climate change. It is hard to assess future policies with respect to climate change, notably the balance between adaptation and mitigation. However, in light of growing consensus on climate change and the role of human activities as assessed by the IPCC, it seems a safe bet that global warming will remain an important driving force for future energy decisions.

Before developing the scenarios for the purpose of the SERF programme, the literature on existing studies with a similar scope was analysed.

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. 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.

There are large differences in CO_2 emissions. Most scenarios show an increase from the current global level of 6 GtC, some ending up at a trebling of that level in 2100.

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 or high-demand driven.

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.

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 in passing in the IIASA-WEC and IPPC studies. 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: for example China cannot be regarded a less developed country any longer over the time period considered.
- Fusion power will be more expensive in terms of direct costs than some currently available alternatives such as fission power and coal-fired power. Therefore, fusion power - and other CO_2 free alternatives - need some additional incentive to become a viable option. Carbon taxes reflecting the concerns over climate change could be such an incentive. Carbon taxes are contemplated in industrialised countries, e.g. the EU. From other perspectives, such as risk of proliferation and long-lived radioactive waste, 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 (partly) offset 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

Clearly an assessment of the prospects for fusion power cannot be made without considering what alternative options could be considered and how the various attributes of all options can be compared.

G. Kolb of FZ Jülich presents in his contribution to SE0 (Kolb, 1998) 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.

The European Pressurised Water Reactor (EPR) and the Siemens Boiling Water Reactor (SWR) are advanced Light Water Reactors (LWRs), characteristics of which are shown in Table 3.1. The option of the European Fast Reactor seems to be more disputable than the LWR. A more likely option is the High Temperature Reactor (HTR). The helium cooled HTR has excellent safety characteristics.

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%.

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

	Net capacity [MW$_e$]	Investment. costs[2] [ECU95/kW]	Operation/ maintenance, fixed [ECU/kW/y]	Operation/ maintenance, variable [mECU/kWh]	Net generating efficiencies [%]	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

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 is deemed to attain a net generating efficiency of 60% around 2000. In the near future even higher efficiencies (63%) are envisaged.

A more remote, albeit technically feasible, option is coal-fired power with CO$_2$ separation and geological sequestration. If CO$_2$ separation would be applied to IGCC, the generating efficiency would drop by 8 percentage points (from 50%) while capital costs would increase by 20-25%.

The FZ Jülich study also covers ‘conventional’ renewables. 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. Therefore, unless renewables would be so cheap that they would

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

enable large-scale energy storage - e.g. in the form of hydrogen - in order to mitigate supply fluctuations over the seasons, some type of back-up power remains necessary. Nevertheless, renewables could have considerable impact on the potential of fusion power.

At last Kolb presents several as yet not demonstrated or even ‘exotic’ technologies, four of which based on renewable energy:
- 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.

One of the ‘exotic’ concepts is the ‘Energy Amplifier’ concept of Carlo Rubbia, which is a combination of a particle accelerator and a U^{233} breeder reactor, using Thorium as fuel. Another ‘exotic’ option is the ‘MegaPower’ Tower, using the temperature difference between sea level and at great height. The Solar Energy Tower proposed by Technion in Israel for desert regions on both sides of the equator is based on a downdraft of air, cooled by a spray of sea water at the top of a 1200 m high tower, generating power at the base of the 400 m diameter shaft).

It is hard to imagine that none of these options will prove to be feasible, even though the specific prospects for each are highly speculative. 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 (Gilli and Kurz, 1998). 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 4,800/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 (Figure 4.1).

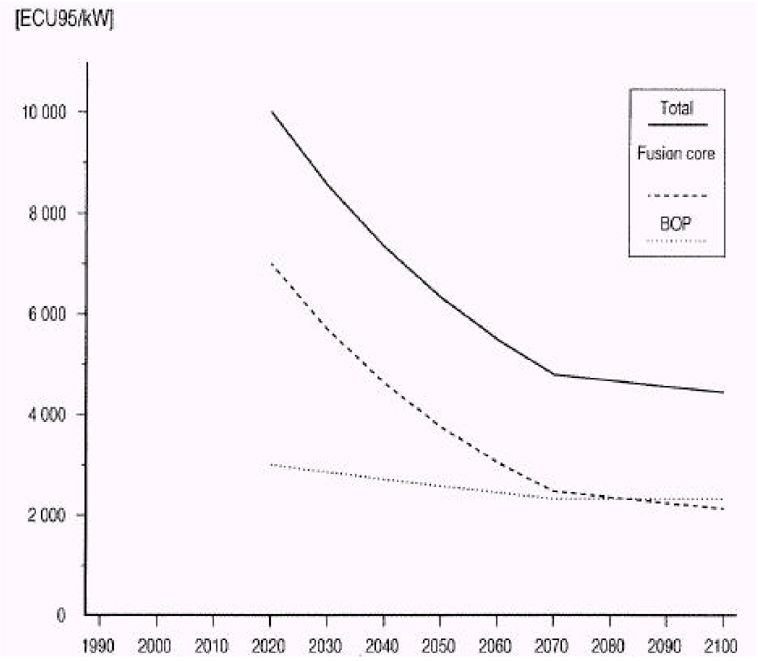

Figure 4.1 *Investment cost of an N^{th}-of-a-kind 1000 MW fusion power plant*

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 x 0.84 = 0.67 (the same factor applies to a single 2000 MW fusion power plant).

5. LONG-TERM POTENTIAL IN WESTERN EUROPE

ECN Policy Studies analysed the economic potential of fusion power in Western Europe with a specifically designed MARKAL model (Lako et. al., 1998b). The model contains a large number of supply side and demand side technologies that can be called upon depending on their competitiveness under various conditions (fuel prices, CO_2 constraints, etc). The study has the following contents:

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

With respect to methodological issues the following points are highlighted:

- Technology assumptions are mainly based on detailed estimates, learning effects, and expert opinions included in studies of colleague institutes contributing to SERF and other studies.
- The issue of discounting has been solved in the following way:
    - A relatively low discount rate of 2.5% per year governs the depletion of fossil fuel resources and cumulative CO_2 emissions (if applicable).
    - A higher interest rate from 5 to 10% per year is used for energy investment decisions.
- Climate change is driven by the increased concentration levels of greenhouse gases. Stabilisation levels for CO_2 in the year 2100 (e.g. 450 to 750 ppm) can be translated into cumulative CO_2 emission budgets for Western Europe. This will be explained later on.

With regard to fossil fuel resources the following assumptions have been made:

- reserve/production ratio of oil: 130 years,
- reserve/production ratio of gas: 190 years,
- reserve/production ratio of coal: 220 years,
- availability of fossil fuels to Western Europe: normally 10.5% of global resources.

Price trends for imported hard coal and heavy crude oil are assumed to be as follows (Figure 5.1):

- The price of imported hard coal rises by 0.35% per year until 2050 and stabilises after that.
- 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.

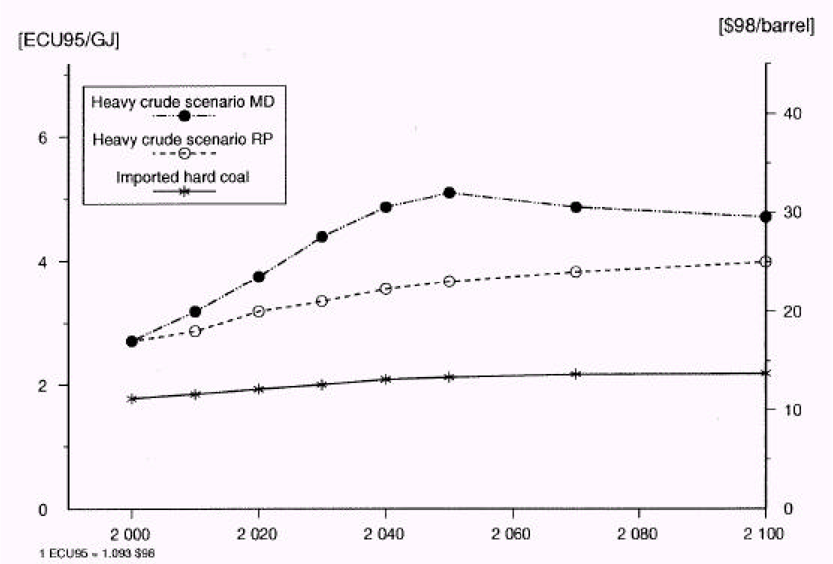

Figure 5.1 *Heavy crude oil prices and coal price for two scenarios*

Key input parameters of scenarios *Rational Perspective* and *Market Drive* are shown in Table 5.1.

Table 5.1 *Key input parameters of scenarios Rational Perspective (RP) and Market Drive (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 available to 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 energy.	Maximum capacity declining to 70% of current capacity and 40 GW in 2100	Maximum capacity declining to 80% of current capacity and 40 GW in 2100

Note that fission energy is assumed to decline to 70-80% of its current capacity in 2070 and to one third of its current capacity in 2100. This is how a technology with particular problems with regard to public acceptance may be constrained (or not, as will be shown in the sensitivity cases).

Rational Perspective is the ecologically driven scenario. 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.

In the 'high growth' scenario *Market Drive*, the market mechanism is seen as the best way to produce wealth and handle complexity in uncertainty. The penetration of more efficient demand and supply technologies totally depends on market forces and the behaviour of the actors. Energy policy is driven by the desire 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.

CO_2 emission in Western Europe would increase by 20% (scenario *Rational Perspective*) to 60% (scenario *Market Drive*) in 2100 compared to 1990. This summary focuses on the power generation mix, e.g. the base-case of scenario RP (the case without CO_2 constraint, Figure 5.2).

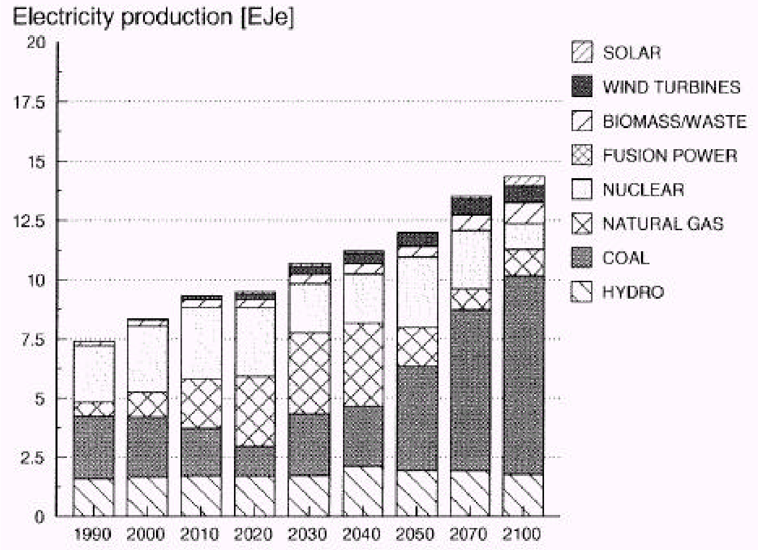

Figure 5.2 *Power generation by source for scenario Rational Perspective without CO_2 constraint*

MARKAL calculations show that fossil fuels are favoured for power generation in the absence of CO_2 policies. In scenario RP, gas-fired power grows strongly until 2040, after which coal gets a competitive edge. Fission energy declines slowly until 2040. After that, a (temporary) revival of nuclear energy occurs. Because of ongoing technological development, some renewable power generation options, particularly onshore wind and biomass, become more or less competitive without CO_2 policies. Other renewables - offshore wind, PV - and fusion power cannot compete with conventional power generation options in the absence of such policies.

Figure 5.3 shows the power generation mix of the base case of scenario *Market Drive*.

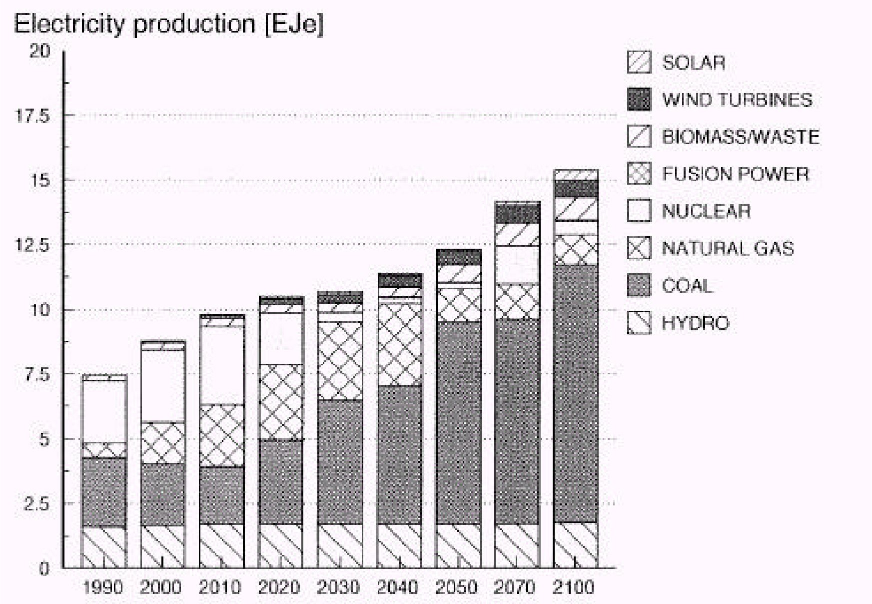

Figure 5.3 *Power generation by source for scenario Market Drive without CO_2 constraint*

In scenario MD, coal-fired power remains stable until 2020. After that, coal becomes more and more dominant due to relatively high gas prices. Fission energy shows a steep decline towards 2030, and it recovers not earlier than in 2070 because of the relatively high discount rate for capital costs. Just like in case of scenario RP, onshore wind and biomass are more or less competitive, whereas other renewables and fusion power cannot compete without CO_2 policies.

The potential of fusion power has also been analysed under conditions of constrained CO_2 emission. The pre-industrial atmospheric CO_2 content was 280 ppm. The current atmospheric CO_2 content (1999) is 367 ppm. The IPCC has calculated global CO_2 emission budgets for the period 1990-2100, corresponding to atmospheric CO_2 levels from 450 to 750 ppm in 2100. As the emission share of Western Europe in IPCC's 1992 scenarios proved to be 10% on average, this percentage has been used for Western Europe's share in IPPC's cumulative CO_2 budgets.

Figure 5.4 shows the patterns of CO_2 emissions corresponding to scenario *Rational Perspective* and variants from 450 to 550 ppm in 2100. Similar patterns emerge in case of scenario MD.

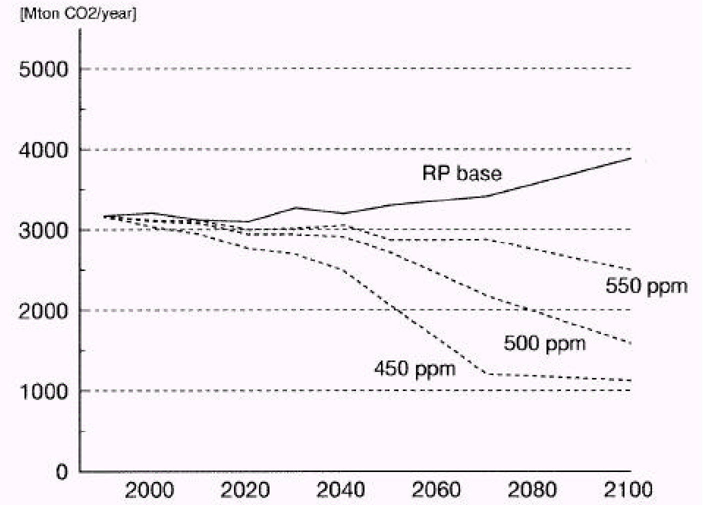

Figure 5.4 *Western European CO_2 emissions, variants scenario Rational Perspective*

Figure 5.5 and 5.6 show the impacts of increasing CO_2 constraints for the power generation mix in the year 2100 in case of the scenarios Rational Perspective and Market Drive respectively.

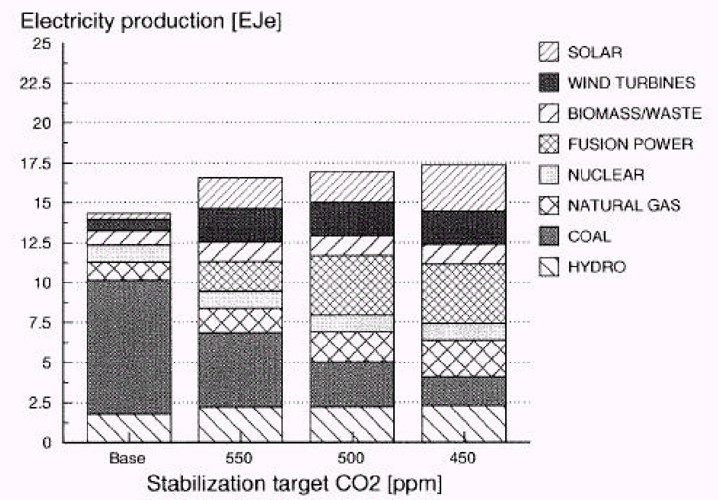

Figure 5.5 *Power generation by source in 2100, CO_2 variants of scenario Rational Perspective*

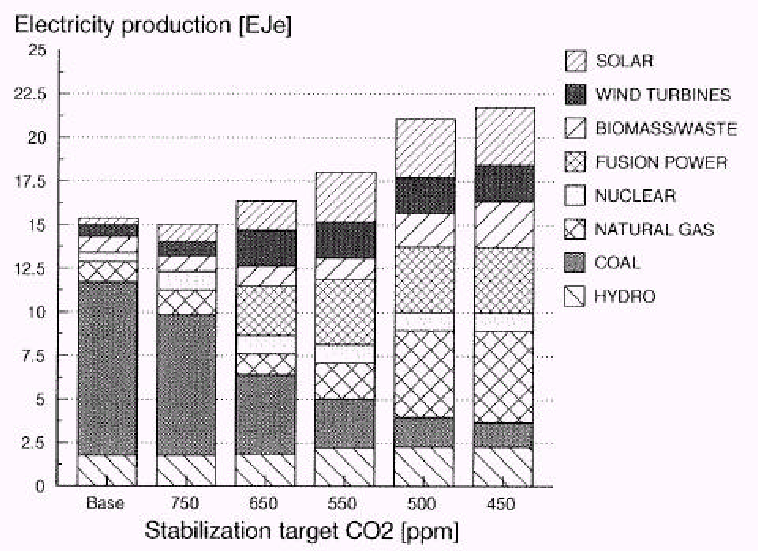

Figure 5.6 *Power generation by source in 2100, CO_2 variants scenario of Market Drive*

MARKAL contains options to conserve electricity and options to substitute electricity for gas (electric heat pump) or oil (electric car). Figure 5.6 shows that some electricity is conserved in the 750 ppm case. New electricity options - electric heat pump, electric cars - become competitive under demanding CO_2 constraints, whereas the potential for electricity conservation is depleted.

MARKAL optimisations show that fusion power is maximised at a level of 500 ppm in scenario RP, at the expense of coal-fired power. Fusion power is compatible with renewables like wind and PV. It is the least-cost optimisation within MARKAL which determines their market shares.

According to the MARKAL optimisations, fusion power is maximised at a CO_2 level of 550 ppm in scenario MD, at the expense of coal-fired power. Scenario MD is more demanding from the point of view of CO_2 reduction. Gas fired-power gets a boost in the more ambitious CO_2 reduction cases (500 and 450 ppm), because fusion power is already at its upper limit. Note that a default maximum introduction path for fusion power has been imposed from 2050 to 2100.

Figure 5.7 shows the power generation mix of a variant of scenario *Market Drive* with a large potential for fission power, viz. 200 GW (an increase of 60% compared to its current capacity).

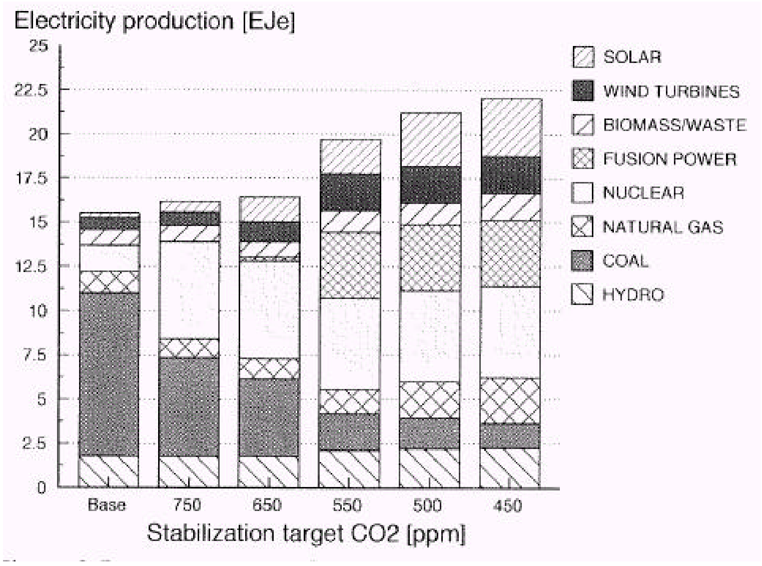

Figure 5.7 *Power generation by source in 2100, MD variant 'High Potential Fission'*

In this case, which is highly optimistic with regard to fission power, fusion power remains economically viable in case of CO_2 reduction, although its market share is really small in the 650 ppm case. As a matter of fact, in this particular case the marginal CO_2 reduction cost is ECU 67/tCO_2, which is about twice the 'normal' level of some ECU 30/t CO_2.

In order to exclude potential pitfalls, sensitivity analysis has been for a number of cases, viz.:

- 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 power (200 GW).

Table 5.2 and 5.3 show fusion power capacity for the 'normal' scenario variants and for the sensitivity cases for the years 2070 and 2100 respectively.

Table 5.2 *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 Potential 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 5.3 *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 Potential 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:

- Scenario MD is more demanding from the point of view of CO_2 reduction than RP. So, fusion power is more important at moderate CO_2 emission levels in case of scenario MD.
- 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 in 2100 in the 550 ppm case of RP (instead of 78 GW). This is because some renewables - notably PV at northern latitudes - have a higher capital cost component in their generation cost than fusion power, although the latter has high replacement cost (diverter, blanket, first wall).
- A 20% higher level of investment costs for fusion power has some impact, although the impact is not decisive for its competitiveness. In the 650 ppm CO_2 case of MD, fusion power capacity in 2100 is 119 GW; 20% higher investment costs cause a decline to 56 GW.
- If scenario RP is combined with ample availability of fossil fuels, fusion power loses competition with gas-fired power in the 550 ppm CO_2 reduction case. However, it remains an economically viable option at 500 and 450 ppm.
- If a high potential of renewables is assumed for MD, fusion power loses market share in the 550 and 500 ppm CO_2 reduction cases. However, a high potential of renewables is more threatening to coal- and gas-fired power than to fusion power.
- Under alternative conditions that are deemed plausible, fusion power is rather insensitive to the fate of fission power. In case of an early phase-out of fission energy, fusion energy takes over its market share in 2100 in the 550 ppm case. In case of a steep growth of fission energy (from 125 GW today to 200 GW), fusion energy suffers only in the 650 ppm case.

Another set of calculations concerns variants in which fusion power is unavailable. Equal CO_2 stabilisation levels can be attained, albeit at a (substantially) 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 unavailable anyhow) would provide natural gas for gas-fired power as a substitute for fusion power. Increased use of renewables only gives relief under moderate CO_2 constraints.

In the MD scenario the total, discounted cost associated with 550 ppm increases from 810 to 900 billion ECU. In the 450 ppm case, the total discounted costs increase from around 3,900 to 4,700 billion ECU. The difference, viz. 90 billion ECU and 800 billion ECU respectively, constitutes the discounted shadow value of the fusion power option available to Western Europe in the 21st century (not counting the value for the rest of the world and for the next centuries).

Finally, the potential of fusion power under various conditions from the MARKAL optimisations is compared to the global potential estimated by Gilli and Kurz (1998) in Figure 5.8.

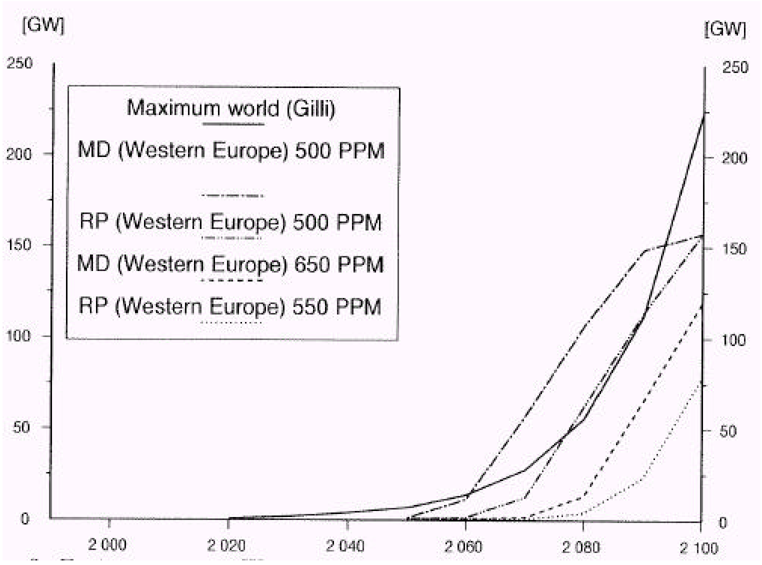

Figure 5.8 *Fusion power in Western Europe and in the World*

Figure 5.8 shows that the capacities from the MARKAL calculations are not excessive compared to the global potential calculated by Gilli and Kurz for 2100. Indeed, their curve may be even somewhat conservative for the period 2050-2070 in case of CO_2 reduction policies.

6. DISCUSSION

This discussion is devoted to the contribution of B. Villeneuve (CEA-Lemme, 1998). The author 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:

- diversification
- flexibility
- experimentation.

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

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

Villeneuve discusses various aspects of the effects of uncertainty on evaluation of research programmes. 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, 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.

Also the importance of experts is discussed. Experts are an essential part of the democratic political systems. Citizens are not able to follow 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 and it may become available in the second half of the 21st century.

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.

There are several ‘exotic’ concepts, most of which are based on renewable energy sources. 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 electricity production by 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 3,000/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 an independent cost estimate made at the start of the SERF programme. Power plant studies conducted later came to somewhat higher estimates, which were included in the sensitivity analysis of the ECN study.

The long-term potential of fusion power 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. Under these conditions (absence of CO_2 policies), the 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 30 to 70 ECU/tCO_2. In a scenario with relatively low energy demand, fusion power obtains a share in power generation in 2100 that is slightly higher than the share of fission power, if global stabilisation of CO_2 at 550 ppm would be needed (slightly decreasing CO_2 emission in Western Europe). In both of the main scenarios, fission power is assumed to decrease to 40 GW in 2100 (one third of its current level) due to presumed problems with public acceptance.

In case of a ‘high-demand’ driven scenario, fusion power obtains a substantial share in power generation in 2100, viz. 119 GW, if stabilisation of atmospheric CO_2 at 650 ppm is aimed for. In order to reach such a level, fusion power is already introduced in 2070. Fusion power mainly competes with coal-fired power.

Sensitivity analysis shows that high discount rates (e.g. 8 or 10%) are not detrimental to fusion power, if fusion power has some market share due to CO_2 constraints in case of a discount rate of 5%. 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 aforementioned 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. In the high demand scenario MD the total discounted cost to meet the 550 ppm target rises from 810 to 900 billion ECU. The gap widens with lower stabilisation levels: for 450 ppm the discounted cost rises from 3,900 to 4,700 billion ECU. In case of a scenario with low energy demand like RP and/or moderate CO_2 reduction levels the economical 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.

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