THE ROLE OF FUSION POWER IN ENERGY SCENARIOS

Proposed method and review of existing scenarios

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Preface

This is the interim report of the ECN study in the framework of the programme of socio-economic research on the prospects of fusion energy (SERF). This study is carried out on behalf of the European Union, DG XII and two Dutch Ministries: the Ministry of Economic Affairs and the Ministry of Education, Culture and Science. (ECN project number 77.119)

Abstract

The European Commission wishes more insight in the potential role of fusion energy in the second half of the 21st century. Therefore, several scenario studies are carried out in the so-called macro task Long Term Scenarios to investigate the potential role of fusion power in the energy system. The main contribution of ECN to the macro task Long Term Scenarios is to perform a long term energy scenario study for Western Europe with special focus on the role of fusion power. This interim report gives some methodological considerations for such an analysis.

A discussion is given on the problems related to the long time horizon of the scenario study such as the forecast of technological innovations, the selection of appropriate discount rates and the links with climate change. Key parameters which are expected to have large effects on the role and cost-effectiveness are discussed in general terms. The key parameters to be varied include level and structure of energy demand, availability and prices of fossil energy, CO2 reduction policy, discount rates, cost and potential of renewable energy sources, availability of fission power and CO2 capture and disposal and the cost and the maximum rate of market growth of fusion power.

The scenario calculations are to be performed later in the project with the help of an existing cost minimisation model of the Western European energy system. This MARKAL model is briefly introduced. The results of the model calculation are expected to make clear under which combinations of scenario parameters fusion power is needed and how large the expected financial benefits will be. The present interim report also gives an evaluation of existing energy scenarios with respect to the role of fusion power.
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1. FRAMEWORK OF THE STUDY

1.1 Background

Fusion energy research during the last decades made remarkable but not always noticed progress in scientific and technical respect, in realising a technique with enormous potential for energy production. However, such progress is a prerequisite, not a warrant, for commercial fusion energy. During the next decades substantial investments are needed in order to develop, demonstrate and commercialise fusion energy. Investments in projects like the next experimental fusion reactor ITER require international funding. Up to now the international community has proved to be able to generate the funds required for fusion research and development. International co-operation will remain the cornerstone of the development of fusion energy. In some countries governments are more inclined to invest in (long term) energy research and development than in other countries. If decisions with large financial impacts are at stake, e.g. the timing and location of ITER, it could be worthwhile to reconsider the motives for the development of fusion energy. This is the rationale for the programme of socio-economic research on fusion energy (SERF) on behalf of the European Commission. The European Commission wishes that the potential role of fusion energy in the second half of the 21st century is analysed. Within the framework of this research programme the following Macro tasks will be carried out:

- long term scenarios (SE0),
- production costs (E1),
- external costs and benefits (E2),
- fusion as a large technical system (S1),
- fusion and the public opinion (S2).

This interim report of ECN is the result of one of the studies being carried out in the framework of Macro task SE0. This interim report presents the points of departure for new scenario calculations. Chapter 2 gives methodological considerations, chapter 3 an analysis of existing scenarios. At last, some preliminary conclusions are formulated in Chapter 4.

First, Section 1.2 contains a general discussion on some of the factors that determine the prospects of fusion power.

1.2 Factors determining the prospects of fusion energy

Fusion energy could become commercially available in the second half of the 21st century. In order to become an economically viable option, fusion technology should be developed and demonstrated in the meantime. Not all of the economic and political factors favour the development of fusion energy. Some main factors with regard to the prospects of fusion energy are the political priority of greenhouse gas abatement policies or sustainable energy policies, the rather gloomy prospects for fission energy, and the limits to the deployment of renewable energy.
Sometimes political and economic developments seem to be unfavourable for the development of fusion energy, e.g. budgetary constraints preceding the introduction of the Euro, and liberalisation of electricity markets. However, even a seemingly 'muddling through' scenario could result in introduction of fusion energy in the second half of the 21st century. It is quite conceivable that a growing concern about climate change due to global warming would create enough momentum to decide on fusion energy projects. This is because concern about climate change would favour energy technologies which do not cause emission of greenhouse gases. Fusion energy, if technically feasible, is one of the most important long term options. Although an undertaking like the development of commercial fusion energy requires a high degree of political and economical stability in the financing countries, the rise of the EU as a political and economic main point could be another significant circumstance in that respect. Taking into account our reliance on fossil fuels with their threat of global warming and geopolitical risks, investment in fusion energy could be considered as more than an insurance premium.

Although the road to commercial fusion energy seems to be powdered with technical, economic and political obstacles, there is growing attention for sustainable economic and energy policies. Sustainable energy policies are generally focused on decreasing the reliance on fossil fuels by energy conservation and deployment of renewable energy technologies. An all-out switch from fossil fuels to fusion energy is generally no longer considered as a viable long term option. This is because public acceptance has become a matter of concern. Public acceptance of the nuclear breeder technology is virtually absent. More than current Light Water Reactors breeder reactors appear to be teased by safety concerns. This could reduce the role of fission energy to a transition technology. Issues like safety, radioactive waste, proliferation, and public acceptance, seem to be less relevant in case of fusion energy: fusion energy can be considered as an abundant and clean energy source, presumed it would be technically feasible. It is generally acknowledged that the radioactive waste issue is much more critical for fission reactors than for fusion energy.

If sustainability would become a prime driving force in energy policies, this would create much more momentum for energy conservation and renewable energy than already available today. However, the economic costs and benefits of energy conservation and renewable energy would be exposed by such policies. If we focus on renewable energy the following limitations seem to be most significant:

- The world potential of wind energy is huge, but only a modest fraction of it can be exploited, mostly in (populated) coastal regions. Its intermittent nature limits the contribution without energy storage. Even considering energy storage, a really large contribution would necessitate large scale production and storage of hydrogen.
- The potential of solar energy is really tremendous, although its application up to now is limited by economic constraints. Even if photovoltaic energy would become much cheaper than today, the distribution of solar energy over the planet is uneven. Therefore, in the coming decades its economic potential will be largely restricted to the southern latitudes and developing countries with weak or absent central electricity grids. Photovoltaic power is a highly intermittent energy source. Therefore, a large contribution to the future energy demand necessitates energy storage and at last hydrogen production and storage.
Framework of the study

- Biomass energy is an environmentally friendly CO₂ neutral source of energy. It can be applied on short notice, if sufficient agricultural or forestry residues are in place. A growing contribution from biomass requires the transition to the growing of energy crops, which is not only rather costly but also limited by competing land use claims. Biomass energy could have a fair share in the future energy supply, if the demand for food crops could be curtailed, e.g. by changing human nutrition patterns.

These are a few examples of limitations of renewable energy sources. Sustainable energy policies could favour renewable energy applications in conjunction with energy conservation technologies, e.g. solar thermal energy combined with heat pumps, photovoltaic and wind energy in combination with electrical heat pumps and electrical vehicles, etc. Generally, a growing contribution from renewables will increase the importance of electrical energy compared to direct use of fossil fuels. The penetration of renewable energy technologies depends on cost reduction for such renewables as on-shore and offshore wind energy and photovoltaic energy. Also exotic renewable energy options like the Megatower or import of power and hydrogen from solar power generation in other regions (Sahara) could become economically competitive. At last, separation and geological storage of CO₂ from the flue gas or syngas of coal fired power plants could be a competitive technology in the next century.

Long term scenario studies, based on multi period optimisation models of the energy economy of Western Europe, allow to analyse the diffusion of energy conservation, renewable energy and fusion energy in competition with conventional supply and demand options. In this way the potential of fusion energy and the complex interactions and synergy with other options could be quantified to some extent.
The role of fusion power in energy scenarios
2. METHODOLOGICAL CONSIDERATIONS

This chapter presents some methodological considerations for the scenario based analysis of the long term prospects of fusion power. In Section 2.1 the elements of work of the present study are given. Some considerations for the selection of scenario variants are presented in Section 2.2. Section 2.3 contains a brief discussion on the problems that are linked with a long time horizon. This discussion focuses on long term technological changes, discounting and climate change. In Section 2.4 the energy model MARKAL, which will be the main analysis tool in the ECN contribution to the overall SE0 study is presented and limitations and specific features of MARKAL are discussed in Sections 2.5 and 2.6.

2.1 Elements of work of the present study

The objective of the macro task on long term scenarios is to analyse the role of fusion power, viewed in the long term perspective for the development of society at large, with special emphasis on the environment and on energy systems.

The objective of the ECN contribution to the macro task is to provide an assessment of the comparative prospects of fusion in long term scenarios (second half of next century) and to provide insight in the sensitivity of the prospects of fusion to the relevant parameters.

In the present study of ECN two approaches will be followed to analyse the long term role of fusion power.
1. Analysis of the role of fusion power in existing long term energy scenarios.
2. Construction of new long term energy scenarios for Western Europe to analyse the future role of fusion power under a range of scenario conditions.

The emphasis is on the second approach.

Analysis of existing long term scenarios

Several long term energy scenarios have recently been published. Those which are considered most appropriate for studying fusion power have been selected and a first review is presented in Chapter 3. The key questions for this part of the analysis have been: 'What are the main differences between the scenarios?', 'How reasonable are the scenario assumptions?' and 'What role is projected for fusion power?'.

New long term energy scenarios for Western Europe

There are various reasons to construct new energy scenarios in addition to the existing scenarios to analyse the prospects of fusion power. First, the existing long term scenarios have not been designed with the aim to analyse fusion power. Instead, the objective of the long term scenario studies was to explore future development paths of the entire energy system and fusion power has been considered as only one of the power generation options in some of these scenarios. In general little attention was paid to the option of fusion power. Second, the existing scenario studies only describe
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future developments with respect to some general aspects. In order to explore the prospects of fusion power, it is preferred to analyse a large number of scenarios under a range of conditions. Third, the analyses that have been performed so far have focused too much on the entire world and they provided too little detail on regional energy systems. Since energy systems of world regions differ substantially with respect to energy demand levels, availability of energy resources, technology level and environmental policy, prospects of technologies differ also substantially per region. Finally, the cost and performance assumptions for fusion power are not transparent for most of the existing scenario studies.

The new scenarios will be prepared for Western Europe (the EU, Norway, Switzerland and Iceland) for the period 1990-2100. This period is covered in steps of 10 years. The existing technology processing model MARKAL [1] has been adjusted to cover such a long time frame. An existing MARKAL database for Western Europe [2,3] is used as a starting point for the scenario analysis. This MARKAL model facilitates the calculation of a consistent development path of the energy system of Western Europe. Further information on the MARKAL model is presented in Sections 2.4, 2.5 and 2.6.

The point of departure in choosing scenarios and variants is that fusion power may become available as a power generation option with its specific characteristics (relatively high investment cost, large unit size, base load power generation, long lifetime and long construction schedule). It is noted that the probability that fusion power will become available as a technical option will not be discussed. As fusion power is definitely not among the least cost options for power generation, its economic attractiveness depends on other factors. The other factors can be divided in factors which enhance the prospects of fusion power and factors that reduce the prospects of fusion power. In the modelling part of this study the factors that enhance or reduce the prospects of fusion power are combined. The resulting balance of factors results in either no, or a smaller role or larger role for fusion power in the long term energy system of Western Europe. Since all factors that affect the prospects of fusion power have significant uncertainties, the factors need to be varied in the variants. It is expected that fusion power will have a role in part of the variants but by now it is unclear how large this part will be. For these variants, the financial benefits of fusion power being available as a technical option will be estimated. These benefits will be calculated by comparing the cost of the energy system of Western Europe between a case in which fusion power is assumed available and a case in which fusion power is not available.

The construction of new energy scenarios for Western Europe requires five sets of elements. These elements include:

1. Design of the methodology. Since the time horizon of the study differs substantially from the time horizon of most scenario studies, several factors, such as discount rates, technical change and inertia in the energy system need to be considered.

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The production and availability of several key energy sources varies widely between different world regions. North America has e.g. large reserves of coal and natural gas, the US has sites with high solar radiation without large seasonal differences which is favourable for solar PV. On the other hand Western Europe has limited reserves of natural gas, oil and coal and the region is less suited for solar PV as annual production per square meter of PV system will be limited and the production per season will show large differences. Japan has again a different situation. Due to such differences in regional circumstances, fusion power is preferably analysed on a regional level.
Methodological considerations

2. Key scenario parameters. This means identification of the key scenario parameters that determine scenario results for Western Europe. This identification will partly be based on the results of the analysis of existing scenarios. The scenario parameters both include factors that can enhance the prospects of fusion power (e.g. high demand for electricity and drastic CO₂ emission constraints) and factors that reduce the prospects of fusion power (e.g. low fossil fuel prices).

3. Characteristics of fusion power. This includes estimates of the future cost of fusion power and limits to its availability and potential at various moments in time. The lower the (estimated) cost of fusion, the better are the prospects.

4. Characteristics of technologies that compete with fusion power for a place in the energy system. Future cost of alternatives (fossil fuels, renewables, fission) and limits to their potentials. Low cost and ample availability of alternative technologies will reduce the prospects of fusion power.

5. Synthesis. Structured analysis to combine the above mentioned elements to construct scenarios for Western Europe. The analysis can be characterised as 'an energy model based cost-effectiveness analysis'. Key steps of this part of the analysis are the design of the scenario variants, the actual scenario calculations, presentation of the results and the transfer of the scenario results into conclusive insights.

2.2 Selection of scenario variants for Western Europe

Figure 2.1 gives a schematic view of the technical energy system and its environment. The technical part of the energy system consists of energy technologies for extraction, conversion, transportation/transmission/distribution and end use, together with the flow of energy through and between these technologies. The technical energy system uses different energy sources to satisfy useful energy demands. The useful energy demand depends on the energy demand driving factors, such as economic growth. Technology development determines which technologies are available in the technical energy system and what their cost and performances are. The physical environment puts constraints on emissions and land use. The technical energy system takes different configurations depending on the objective function such as minimal total costs or dependence on external energy sources. The objectives are translated to the energy system via criteria, e.g. the (maximum) total CO₂ emission in a year or the maximum cumulative CO₂ emission. The results of the model of the technical energy system encompass the development of capacities, energy flows and emissions and cost over time. All elements outside the technical energy system are inputs.
There is considerable uncertainty about various inputs. The specific combination of each of the assumptions determines the development path which the model calculates as being optimal for the Western European energy system. Depending on the inputs, fusion power will have a role or not. Since most factors that affect the prospects of fusion energy have significant uncertainties, the factors need to be varied in the sensitivity cases. Due to time and resource constraints the number of scenario calculations needs to be limited. At this moment in the project it is not yet possible to precisely select the scenario variants. However, some considerations for the scenario selection can already be given:

- The level of energy demand and the share of electricity in energy demand will be important scenario parameters. High energy demand and a large share of electricity will enhance the prospects of all electricity generating technologies including fusion power. It is less relevant for the present analysis to know what factors drive the level of energy demand as long as the useful energy demand projections cover a representative range.

- Policies to reduce future emissions of carbon dioxide (CO₂) can have a very large impact on the development of the future energy system [2,5,6,7]. Since both the long term global targets for CO₂ emissions and the distribution of emission rights across the globe are uncertain, it is uncertain how much CO₂ is allowed to be emitted from Western Europe. Various emission targets for the period 1990-2100 need to be considered.

- Various carbon free electricity sources and technologies other than fusion power can contribute to power generation. Among the most important options are nuclear fission, hydro power, wind turbines, solar PV systems, fossil fired power plants with CO₂ recovery and storage and possibly some speculative new energy technologies (e.g. PV systems in space, Megatower). The prospects of fusion power decrease if the cost of these carbon free electricity sources is low and if the availability is high. An efficient way to analyse the sensitivity of the prospects of fusion power is by performing a set of sensitivity runs spanning the full range of figures for cost and potential of carbon free energy sources. This sensitivity analysis should also in-
clude the uncertainties in technological innovation. This approach is more efficient than consecutively varying cost and availability of each carbon free electricity source.

- Especially, for scenarios with modest or no limits to the emissions of CO₂ it is reasonable to perform sensitivity analysis with different availability of fossil fuels.
- The discount rate to compare alternative investment decisions will be varied.

2.3 Time horizon of the study

Fusion power is expected to become available as a power generation option by the year 2050. Because of limits to the rate of growth of fusion power, it will take several decades more before fusion power would significantly contribute to power generation. Therefore, the analysis of the future role of fusion power with the help of energy scenarios, needs to have a time horizon that includes the second half of next century.

![Figure 2.2 Stages in the development of fusion power](image)

Most existing energy scenario studies deal with general energy and environmental issues [8], such as forecasts of future energy demand, analysis of security of supply and comparison of strategies to mitigate acidifying emissions or emissions of greenhouse gases. These existing studies have a time horizon between 10 and 30 years and national governments are the primary clients. Studies which analyse the prospects of energy technologies are usually performed for organisations responsible for energy technology R&D. These studies usually have a somewhat more distant time horizon (20 to 40 years ahead). Only few existing energy scenario studies have a time horizon until the year 2100. Most of these very long term scenarios have been constructed to make projections of greenhouse gas emissions. The greenhouse gas emissions results of the long term energy scenarios are serving as inputs for models that calculate the effects on climate.

Energy scenario analysis with a very distant time horizon is not straightforward. Assumptions on technological innovation are different for scenarios with various time horizons. Other issues which need further clarification as a result of a long time horizon are discounting and climate change. These three issues will be discussed below.
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Technological change
Most energy scenarios with a relatively short time horizon assume some technological innovation but the technological innovation is assumed to be exogenous. The assumption not to endogenize technological changes is founded by one or more of the following arguments:

- Too little is known about the driving forces for technological innovation to process in a numerical model (e.g. the relation between cumulative sales of a technology, the cumulative R&D investments and the progress in cost and performance).
- The spatial scale of the scenario study is too limited to analyse technological innovation.
- For a limited time horizon, it is believed that technological change can be forecasted more precisely in an exogenous way.
- The effects of scale effects on accelerated technological innovation are modest in the short term.
- The transparency of the technology assumptions is reduced if technology development is endogenized.
- The basis for drawing policy recommendations from the results of the analyses will become too uncertain.

Some recent long term scenario studies, e.g. studies by Shell [9], IIASA [10], Mattson [11] and Poles [12] try to endogenize technological innovation. In each of these studies a simple relationship is assumed between the cumulative world-wide sales of an energy technology and the investment cost of the technologies. With each doubling of the cumulative sales of a technology the investment cost drop by a certain percentage. The cost reduction per doubling of sales is estimated between 0% and 30% [13]. The cost reduction is believed to result from ‘learning by doing’. In several of the studies this approach has led to undesired feed forward effects in the results of energy system models with one technology gaining the entire market while continuously becoming cheaper.

Our understanding of the dynamics of technology in the long term is limited. How will the current technologies have evolved? What energy technologies will become available in the next 100 years from now? It may well be that technologies may have emerged which have currently not or hardly been envisaged. The kinds of questions are very similar to the question to people 100 years ago to forecast the technologies at the end of the twentieth century. Technology forecasting is increasingly receiving attention. Some relationships between technology driving factors, conditions required for technology development and innovation are under investigation. The notion that technologies that seem at first most promising for technical reasons are not always the ones adopted by the market is getting through. Lock in and lock out effects are also considered important factors. The dynamic development of relation networks between research institutes, industries, funding agencies etc. is also considered relevant. However, a grand theory to give robust forecasts of technology development is not available.

The approach that will be followed in this study is to take exogenously estimated assumptions for technology development. The technology assumptions will primarily be based on expert judgements and estimated learning effects. The technology characteristics of several existing studies [2,7,14,15], for which forecasts of the development
Methodological considerations

of energy technology have been made, will be used. If applicable, the technology estimates of the SERF macro task on external costs and benefits will also be considered.

**Discount rates and interest rates**
The following two paragraphs have largely been taken from [5]:

1. The discount rate allows economic effects occurring at different moments in time to be compared. It plays a vital role in public policy analysis of actions with varying time paths of costs and benefits. It is particularly important for issues with a long time horizon. Then the choice of a discount rate strongly affects the net present value of alternative actions.

2. Two major approaches are used to determine the appropriate discount rate for climate change analysis. On the one hand, the social rate of time preference (or prescriptive approach) is linked with normative questions such as 'How should impacts on future generations be valued?'. The social rate of time preference is derived from the rate of growth of consumption per capita and the greater distance we feel to generations further away from us. On the other hand, the descriptive discount rate derives the discount rate from interest rates which are common on the capital market. The social rate of time preference tends to be relatively low (between 2 and 3%). The descriptive approach (or opportunity cost approach) tends to generate somewhat higher discount rates which may also differ per country, sector and as a function of the risks involved in the investment. Economists continue to debate which of the two approaches is correct.

Many quantitative studies have dealt with the discount rate issue. Frequently, it was decided to take an intermediate discount rate which amounts to 4-7% [6]. In several studies sensitivity analysis have been performed with higher and lower discount rates [14].

For the present analysis on the prospects of fusion power, a slightly different approach will be followed with two different kinds of discount rates being simultaneously applied in one analysis. The present study requires a time horizon until the year 2100. Within this time horizon two inter generation environmental budgeting issues are relevant: depletion of fossil fuel reserves and CO₂ emission budget. For these inter generation issues a discount rate based on the social rate of time preference is suggested (2.5% per year). For the energy investment decisions it is considered appropriate to use interest rates which are currently common. Several interest rates will be applied: 5, 8 and 10% per year.

**Climate change**

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

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

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

2.4 Energy model applied

The model that will be used and further developed for this study is based on MARKAL-EUROPE 1.0 [2]. MARKAL-EUROPE is based on a frequently used linear programming model (MARKAL). The 1.0 version of the model has been defined for Western Europe (European Union member countries and Norway, Switzerland and Iceland). The time span covers the period from 1990 to 2070 (although results are only reported until the year 2050). For this study, the time horizon will be extended to 2100.

MARKAL is a widely applied linear optimisation model [6]. The main characteristic of an optimisation model for the energy system is the concept of a predefined network of demands, sources and technologies of energy interconnected by flows of energy carriers. The networks typically cover the various stages from Primary Supply (mining, import) of energy carriers through Conversion and Processing (power plants, refineries, etc.) to obtain user-ready energy products to End-Use Devices (boilers, cars, light bulbs, etc.) that serve to satisfy Demands for Energy Services broken down by (sub-)sectors and functions (residential lighting, commercial air conditioning, industrial drive power, etc.). The interconnected network of energy flows and technologies is also referred to as the reference energy system (RES).

All prespecified branches between sources, technologies and demands can be selected by the optimisation model. The costs and conversion efficiencies of all technologies are defined exogenously. On certain energy-flows cost- and emission factors are attached. With special functions the total costs or emissions of the energy system can be calculated. With an l.p. algorithm the value of a function can be minimized by an optimal configuration of the energy system with minimal costs that meets the specified energy demand. If total costs is the objective function there is no solution with lower costs. The model applies an integrated approach. This implies that synergy and competition between technologies at the supply side and the demand side of the energy system are explicitly considered.

New technologies to satisfy demands for energy services that consume less energy and/or other types of energy carriers will be indispensable to cut back future greenhouse gas (GHG) emissions. Technology oriented models like MARKAL aim to identify which are the options of choice and how big their role could become over time. The system-wide (all sectors, from primary source to energy service) and dynamic (capital stock changes; load patterns) scope implies that systemic interactions like
synergies, competition and load management are considered. Synergies can occur between supply and demand options, for example better prospects for electric cars if more (affordable) low emission power generation would be possible.

The dynamic nature implies that past decisions and future constraints are taken into account in decisions to expand or decrease capital stocks at any point in the time horizon considered in the analysis. Structural changes are thus allowed, but the rate at which the potential flexibilities are exploited are limited to what is both technically and economically viable. Future expectations are taken into account fully with every decision; this is called 'perfect foresight' as uncertainties play no role in these decisions.

Environmental considerations can be addressed in various ways, such as through sectoral or system-wide emission limits on an annual basis or cumulative over time. An alternative is imposing fees on emissions, e.g. reflecting carbon taxes or external costs of pollutants.

If constraints are placed on the penetration of technologies or on the total level of emissions of pollutants linked to the use of energy, the configuration of the energy system will change. In such a situation, MARKAL will again seek the configuration that has the lowest cost and that meets the constraints.

Maximum penetration of technologies can be regulated in the model by imposing maximum bounds on total capacities and/or maximum bounds on new capacity. Examples of technologies that have bounds in MARKAL-EUROPE 1.0 are wind turbines, PV systems, geothermal energy and district heat. The bounds can be justified on the basis of different real constraints: public planning constraints (e.g. wind turbines), limited (growth of) manufacturing capacity (e.g. PV systems), physical constraints (geothermal resources), heat demand in areas with high heat load (district heating), etc.

The overall optimisation ignores stakeholders with conflicting interests operating on markets in real life situations. Allocation of benefits and losses is thus no issue. The capability of MARKAL to mimic 'real world' behaviour, for instance as observed in the past, is limited. This kind of model is typically more suited to explore alternative, cost-effective strategies (for example to meet quantified emission targets) than to estimate the effectiveness of policy instruments.

MARKAL-EUROPE takes the overall overview of Western Europe as the perspective for model calculations. This assumes a situation that only one actor decides how the structure of the energy system will look like. The model assumes free competition of the technologies fully based on the cost-effectiveness of the technologies. With its dynamic nature, MARKAL performs an optimisation of the energy system for the full period 1990-2100 in one set of iterations. This implies that perfect foresight applies.

Western Europe does not have a homogeneous energy system; there are large differences between the kinds of end use and the primary energy mixes of the various countries. Up to a certain level, regional detail has been included in the model definition. Space heating and hot water demand has been considered for three regions North, Middle and South. Renewable energy potentials have been considered in
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tranches depending on the site-specific energy production. It is viewed that differences between countries will become less important over time with the liberalisation of the electricity market in Western Europe, the gradual integration of the economy and policy making within Western European and globalisation of energy technology markets.

MARKAL has much detail in the modelling of the end-use sectors. An overview of the kinds of energy end-uses considered in MARKAL-EUROPE 1.0 is given in Table 2.1.

Table 2.1 Overview of the kinds of useful energy demand in the model for Western Europe

<table>
<thead>
<tr>
<th>Industry</th>
<th>Households</th>
<th>Transport</th>
<th>Commerce</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium production</td>
<td>Space heating</td>
<td>Passenger car</td>
<td>- Space heating</td>
</tr>
<tr>
<td>Bricks production</td>
<td>houses:</td>
<td>Van</td>
<td>- North Europe</td>
</tr>
<tr>
<td>Chlorine production</td>
<td>- North Europe</td>
<td>Truck</td>
<td>- Middle Europe/large</td>
</tr>
<tr>
<td>Steel production</td>
<td>- Middle Europe/old</td>
<td>Bus</td>
<td>- Middle Europe/small</td>
</tr>
<tr>
<td>Polyethylene production</td>
<td>- Middle Europe/new</td>
<td>Rail Transport</td>
<td>- South Europe</td>
</tr>
<tr>
<td>Ammonia production</td>
<td>- South Europe</td>
<td>Water Transport</td>
<td>Other commercial</td>
</tr>
<tr>
<td>Olefine production</td>
<td>Space heating</td>
<td>Inland</td>
<td>electricity demand</td>
</tr>
<tr>
<td>Styrene production</td>
<td>apartments:</td>
<td>Air Transport</td>
<td></td>
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<tr>
<td>Cement clinker production</td>
<td>- North Europe</td>
<td>Bunkers</td>
<td></td>
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<tr>
<td>Paper production</td>
<td>- South Europe</td>
<td>Water heating:</td>
<td></td>
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<tr>
<td>Non Energy Use: Lubricants-Butumens</td>
<td>- North Europe</td>
<td></td>
<td></td>
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<tr>
<td>Other industry:</td>
<td>- Middle Europe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- large high temp. heat</td>
<td>- South Europe</td>
<td>Dishwashers</td>
<td></td>
</tr>
<tr>
<td>- small high temp. heat</td>
<td></td>
<td>Lighting</td>
<td></td>
</tr>
<tr>
<td>- large low temp. steam</td>
<td>Refrigerators/freezers</td>
<td>Tumble dryers</td>
<td></td>
</tr>
<tr>
<td>- small low temp. steam</td>
<td>Washing machines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- electricity</td>
<td></td>
<td>Other electric appliances</td>
<td></td>
</tr>
</tbody>
</table>

The currently existing stock of capital and the associated energy use is considered as the starting point for the development of the energy system. The model has been calibrated to reflect the historic energy balances in the year 1990. It has been assumed that electricity can be freely traded in Western Europe from the year 2010 onwards.

2.5 Limitations of the energy model

The choice to use MARKAL-EUROPE includes several (implicit) limitations to be aware of. The most important ones are:

- Largely exogenous specification of: energy demand levels, technology dynamics, fossil fuel prices.
- Assumptions: perfect foresight, no distinction between individual market parties.
- Exclusion of: emissions of NOx and SO2, and of non-CO2 GHGs and indirect emissions outside the borders of Western Europe.
Most of these limitations pertain to other energy models based on the RES approach (e.g. [16]). Linking of the energy model with macro-economic models is the usual way to endogenize the energy demands (e.g. MARKAL-MACRO [17]).

*Endogenous technology dynamics:* experiments for relative small energy models have recently been conducted [6,12,18]. The recently started EU sponsored project Energy Technology Dynamics (endogenous) aims at extending models like MARKAL, MESSAGE, POLES, and PRIMES with endogenized technology dynamics.
The role of fusion power in energy scenarios
3. ANALYSIS OF LONG TERM ENERGY SCENARIOS

3.1 Introduction

Most energy scenario studies for Western Europe and the world have a relatively modest timeframe, e.g. the period 1990-2020. Analysis of the role of fusion energy serves a timeframe until year 2100. Only a few energy scenarios with such a distant time horizon have been reported. One of the most detailed studies is an IIASA-WEC study dated 1995 [10]. In the same year the Intergovernmental Panel on Climate Change (IPCC) published a study containing outlines of different sustainable energy futures for the world [5]. At last two less detailed scenarios of Shell [9] cover a large part of the 21st century. Although these studies differ in scope and detail, the views on long term energy supply and demand they present could be helpful in the analysis of the future role of fusion energy.

3.2 Global energy perspectives to 2050 and beyond IIASA-WEC 1995

In ‘Global energy perspectives to 2050 and beyond’ [10] IIASA presents six scenarios with alternative views on world energy demand and supply until year 2100. Three scenarios are ‘high growth’ scenarios of the family Case A. One scenario is called Case B, or ‘middle course’, with more modest growth assumptions. At last, two scenarios, of the Case C type, are considered as ‘ecologically driven’. The scenarios are disaggregated to eleven world regions. World population in all of the scenarios increases to 10.1 billion in 2050 and 11.7 billion in 2100, conform the single scenario developed by the World Bank in 1992.

Case A is characterised by enormous increases of productivity and wealth. World GNP increases by 2.7 percent per year to 2050, and by 2.2 percent per year thereafter. Case A is technology and resource intensive. A1 is challenging in that it goes beyond the conventional wisdom on the availability of oil and gas beyond 2020. A2 scenario provides a contrasting and more conservative strategy both with respect to technological change and resource availability. Technological progress is more gradual along the lines of current supply technologies and resource availability. Consequently, the development strategy is coal-intensive. A3 scenario is also ‘technology intensive’ but with a different direction compared to the other two variants. New renewables and new nuclear combine to form a ‘bio-nuc’ technology cluster that permits the transition to a post-fossil age.

Case B is based on a more cautious approach regarding economic growth prospects, rates of technological change, and energy availability. World GNP increases by 2.2 percent per year to 2020, and by 2.0 percent per year thereafter. Case B does not rely on drastic changes in current institutions, technologies, and current perception of
The role of fusion power in energy scenarios

availability of fossil fuel resources. Energy supply and demand patterns are also closer to the current situation for a longer period in Case B than in Cases A and C.

The two Case C scenarios present challenging global perspectives. World GNP increases by an average of 2.2 percent per year to 2020, and by 2.1 percent per year thereafter (which is almost equal to GNP growth in Case B). Ambitious policy measures accelerate energy efficiency improvements and develop and promote environmentally benign, decentralised energy technologies. The goal is to reduce CO₂ emissions to 2 GtC by 2100 (corresponding to one-third of current emissions or the 60 percent fall from 1990 levels indicated by the IPCC's Scientific Assessment as required to stabilise atmospheric concentration). In C1 nuclear energy is a transient technology that becomes virtually phased out by 2100 together with most of the fossil fuel contribution. In C2 a new generation of inherently safe, small scale (150-250 MWe) reactors is developed and finds widespread social acceptability, particularly in areas of scarce land resources and high population densities that limit the contribution from renewables.

These different scenarios have common elements. Growth rates for high-income economies (OECD) decline gradually in all three cases. Fossil fuels are assumed to be amply available. All six scenarios envisage a gradual shift away from fossil energy sources by the end of the next century. This transition may not be smooth in all cases since the cumulative energy requirements are indeed very large. For example, the three variants of Case A result in between 1300 to almost 2000 Gtoe fossil energy being consumed by 2100. The cumulative demands on oil and gas, ranging from 950 (A2) to 1200 (A1) Gtoe, will require substantial technological advances to ensure the replenishment of needed reserves from the resource base.

The IIASA-WEC study gives a very broad view on possible energy demand and supply patterns in the world, considering an increasing world population and different GNP growth rates. The scenarios are transparent, and most of the assumptions are clear and arguable. However, some issues deserve comment:

- Most of the scenarios seem to be very optimistic with regard to fission energy. In the scenarios A1, A3, and B, nuclear power surges from 350 GWe in 1997 to about 1900 GWe in 2050. Also in scenario C2 nuclear power shows a sharp increase to more than 1200 GWe in 2050. In scenario A2 installed nuclear capacity increases to 800 GWe in 2050. The future of fission energy depends on how current controversies concerning safety, waste disposal, and proliferation will be resolved. The nuclear industry must develop and demonstrate not only new, convincingly safer, possibly smaller-scale reactor designs incorporating 'inherently safe' and 'walk away' features but also efficient and 'robust' fuel cycles and waste disposal solutions. International agreements, enforceable regulations, and comprehensive accounting of nuclear materials should be in place. However, the IIASA-WEC study only addresses these controversies and solutions in general terms. For most of the scenarios breeder reactors appear to be inevitable from a resource depletion point of view. However, public acceptance of breeder reactors is low, even in countries with large numbers of nuclear power plants like France and Japan. Therefore, fission energy appears to be most likely an intermediate energy source rather than a plentiful energy resource based on an all-out breeder strategy.
In all cases, energy options that are not technically feasible today are excluded. Nuclear fusion, for example, is not taken into account. This is a crucial assumption. If fusion energy would have been included as an energy option, the large and increasing dependence on fission energy in five of the six scenarios could have been avoided. Options which are feasible today are included, e.g. fuel cells and photovoltaic power. However, CO₂ sorption at coal fired power plants and CO₂ disposal in geological reservoirs is not included.

The two Case C scenarios are considered as normative, because they presume aggressive efforts to advance international economic equity and environmental protection. However, in view of current efforts to curtail worldwide CO₂ emissions (Kyoto), the environmental protection in Case C scenarios seems to be more in line with current global policies than Case A and Case B. Note that global carbon emissions in scenario A3 amount to 9 GtC by 2050 and 7 GtC by 2100, compared to 6 GtC today. In Case B CO₂ emissions steadily rise to about 15 GtC in 2100. For the scenarios A1 and A2 the ultimate CO₂ emission in 2100 is about 15 GtC and about 22 GtC respectively. However, from the perspective of today (Kyoto) a decreasing trend for CO₂ emissions in industrialised countries seems to be inevitable.

The IIASA-WEC study assumes that (additional) hydro power and ‘new’ renewables will be transferred from industrialised to developing countries, mainly after 2020. Indeed, hydro power schemes in developing countries are sometimes curtailed by economic and environmental constraints. However, wind energy can be implemented fairly rapidly if sufficient financial incentives are in place, as shown in India. ‘New’ renewables at the threshold of widespread application will become available for industrialised countries and for developing countries as well: there is room for a more reassuring view on the deployment of hydro power and ‘new’ renewables in the period until 2020.

3.3 Climate change 1995, contribution of working group II to the second assessment report of the Intergovernmental Panel on Climate Change

In Chapter 19 (Energy Supply Mitigation Options) of the IPCC Working Group II report [5] five ‘scenarios’ are defined. To assess the potential impact of combinations of individual measures at the energy system level, variants of a Low CO₂-Emitting Energy Supply System (LESS) are described, based on eleven world regions. World population in all of the scenarios increases to 9.5 billion in 2050 and 10.5 billion in 2100. The LESS constructions are ‘thought experiments’ exploring possible global energy systems. GDP is assumed to grow 7-fold by 2050 and 25-fold by 2100, relative to 1990. Because of emphasis on energy efficiency, primary energy consumption rises much more slowly than GDP. The energy demand levels of the LESS constructions are consistent with the energy demand mitigation chapters of the IPCC report. The main conclusions of Chapter 19 are:

- Deep reductions of CO₂ emissions from energy supply systems are technically possible within 50 to 100 years, using alternative strategies.
- Many combinations of the options identified could reduce global CO₂ emissions from fossil fuels from about 6 GtC in 1990 to about 4 GtC/yr by 2050, and to about
The role of fusion power in energy scenarios

2 GtC/yr by 2100. Cumulative CO₂ emissions, from 1990 to 2100, would range from about 450 to 470 GtC in the alternative LESS constructions.

- Higher energy efficiency is underscored for achieving deep reductions in CO₂ emissions, for increasing the flexibility of supply side combinations, and for reducing overall energy system costs.
- Interregional trade in energy will grow conforming to the LESS constructions compared to today’s levels, expanding sustainable development options for Africa, Latin America, and the Middle East during the next century.

The five ‘scenarios’ are a biomass-intensive variant, a nuclear-intensive variant, a natural gas-intensive variant, a coal-intensive variant and a high-demand variant. The IPCC report is very instructive with respect to the technologies thought to be available. However, closer examination shows the following pitfalls:

- The relation between the presumed economic growth (3% per year) and the growth in primary energy demand (0.5-1.0% per year) is highly questionable. The scenarios are not based on economic optimisations. Drastic energy conservation would have economic consequences and would result in considerably lower GNP growth rates than suggested by the IPCC study. This means that either the projected GNP growth rates or the very low primary energy demand levels are unrealistic.

- Stringent CO₂ reductions could be an option to industrialised countries, albeit at a cost, reflected in low GNP growth rates. If energy conservation in industrialised countries would be drastic (as suggested by the IPCC study), in order to make room for economic growth and increased CO₂ emissions in developing countries, GNP growth in industrialised countries could be stagnating for a long period. Alternatively, CO₂ emissions in developing countries would have to be curtailed, which would jeopardise their economic growth perspectives. Anyhow, a low level of primary energy demand in 2100 seems to be at odds with a relatively high GNP growth during the next century.

- 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. Particularly the biomass-intensive variant seems to be biased with respect to the potential of biomass, considering the growth of world population, the higher level of nutrition in developing countries, and the corresponding demand for food crops and agricultural land.

- Most of the scenarios are highly dependent on the implementation of CO₂ capture and disposal in depleted gas reservoirs, an option which has not been demonstrated until now. The availability of depleted gas reservoirs seems to be not so common as suggested by the IPCC study; if large scale pipeline transport of CO₂ would be required, this would have considerable economic consequences. Therefore, the economic potential seems to be much more limited than suggested by the IPCC study. Moreover, public acceptance, which could be problematic in case of CO₂ pipelines in density populated areas, is disregarded.

- The nuclear-intensive variant is very optimistic with regard to the perspectives of fission energy. One reason could be that this is the only variant with a substantial share from nuclear energy. It is acknowledged that the continuing concern of many members of the general public and many policymakers with regard to safety and proliferation issues may remain a severe constraint on nuclear power generation in many countries. However, reliance on uranium alone (thermal reactors) without
fast-breeder development could introduce constraints in the longer term if demand for nuclear power were to increase substantially. Indeed, an increase of the installed nuclear capacity from 350 GWe in 1997 to 1450 GWe in 2050 and even 3300 GWe in 2100 (in the nuclear-intensive variant) is so tremendous that breeder reactors would have to be deployed soon and on a large scale. Even considering that there is only one out of five variants which is nuclear-intensive, such a scenario seems to be unlikely.

- **The role of fusion energy in the nuclear-intensive variant is not clear.** The IPCC study suggests that fusion energy could be used instead of fission energy in the longer term. Recovery of uranium from seawater and fusion energy are alternatives (possibly available from 2050) to the deployment of breeder reactors. Fusion power plants would be less likely to contribute to the acquisition of nuclear-weapons capabilities by subnational groups and would be easier to safeguard against clandestine use for fissile material production by governments. This is one of the obvious advantages of fusion energy compared to breeder reactors, according to the IPCC study.

### 3.4 Shell scenarios (‘the evolution of the world’s energy system 1860-2060’) 1995

In ‘The evolution of the world’s energy system 1860-2060’ [9] Shell presents two contrasting views on the world’s energy supply and demand until 2100, both based on an average world GNP growth of 3% per year. World population is assumed to increase to 11 billion people in 2100. Both scenarios are based on an optimistic view on technological change. Current energy options - fossil fuels, nuclear energy, and hydro power - are considered as the ‘first wave’. From 2020 wind energy, photovoltaic energy, and ‘modern’ biomass could cause a ‘second wave’. After that, around 2050, a ‘third wave’ could occur, e.g. the introduction of fusion energy. The results of the scenario study have been published only in a short article. Therefore, the analysis is rather superficial.

The first scenario is called ‘Sustained growth’. In 2060 the average GNP per capita could be $17,000, four times the current world average. Energy consumption would grow by 2% per year. Energy consumption per capita in 2060 would amount to 25 barrels of oil equivalent, equal to the energy consumption in Japan today. From 2020 incremental energy demand will be met by non-fossil options: nuclear energy and renewables. Global CO₂ emissions show an increasing trend, from 6 GtC today to a peak level of 10 GtC around 2020; after that, CO₂ emissions show a declining trend, ending up at 4 GtC in 2100.

The second scenario is called ‘Dematerialization’. This scenario is characterised by a different lifestyle, much more based on clean and efficient technologies than the ‘Sustained growth’ scenario. Energy consumption increases by 1% per year until 2050, and by 0.5% thereafter. In 2060 energy consumption per capita would amount to 15 barrels of oil equivalent on average, 40% below the level of ‘Sustained growth’ in 2060. In 2100 global energy consumption would be 3 times the current level. Cumulative consumption of oil and coal would be approximately 15% lower than in ‘Sustained growth’, and cumulative gas consumption would be approximately 10% higher than for ‘Sustained growth’. Global CO₂ emissions show an increasing trend,
The role of fusion power in energy scenarios

from 6 GtC today to a peak level of 9 GtC around 2020; after that the CO₂ emissions decline, ending up at 4 GtC in 2100.

The two scenarios provide an interesting view on successive transitions in the global energy system from 1995 to 2100. Although the energy demand projections show large differences, GNP growth in both scenarios is equal (3% per year on average). Also the CO₂ emission is almost equal. However, the view on long term energy demand and supply seems to be somewhat unbalanced:

- In the 'Sustainable growth' scenario energy demand grows by 2% per year. For the period until 2020-2030 incremental energy demand is met by oil and gas. However, when oil and gas peak, alternative energy sources should come in fast. The speed of introduction of new energy sources has to accelerate in order to keep up with energy demand. Around 2040 even up to now unknown energy sources would be introduced. This path of introduction and growth of alternative energy sources (nuclear and renewable energy) seems to be too optimistic. In other words, a growth of primary energy demand of 2% per year until 2100 seems to be unrealistically high.

- The 'Dematerialization' scenario shows an increase of energy demand of 1% per year until 2050, and a growth of 0.5% per year after that. This enables a more smooth transition to alternative energy sources compared to the 'Sustained growth' scenario. However, GNP growth in the 'Dematerialization' scenario seems to be largely decoupled from the growth of energy demand. It is questionable if and how such a decoupling could be achieved. Most probably, GNP growth should be lower than 3% per year on average; if so, the scenario would be more ecologically driven. Both of the scenarios are based on the view that CO₂ emissions can be reduced (at least after 2020) by accelerated introduction of alternative energy sources. Not only the speed of introduction of those alternatives (some of which are unknown) seems to be unrealistically high for the 'Sustained growth' scenario, but it is questionable whether renewable energy sources could be introduced fast without any carbon taxes. The Shell scenarios are based on the view that alternative energy sources will be plentiful and cheap. A more realistic view seems to be that they could be plentiful if one is prepared to pay a tough price (for instance in case of photovoltaic power), which means that some financial incentive or carbon tax should be in place. From the moment that carbon taxes are imposed in order to speed up the introduction of renewables, the higher level of energy prices will reduce energy demand.
### Table 3.1 Overview of characteristics of long term energy scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>IIASA/ WEC A</th>
<th>IIASA/ WEC B</th>
<th>IIASA/ WEC C</th>
<th>IPCC Biomass-Intensive</th>
<th>IPCC Nuclear-Intensive</th>
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</thead>
<tbody>
<tr>
<td><strong>Population [billion]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2050</td>
<td>10.1</td>
<td>10.1</td>
<td>10.1</td>
<td>9.5</td>
<td>9.5</td>
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<td>2100</td>
<td>11.7</td>
<td>11.7</td>
<td>11.7</td>
<td>10.5</td>
<td>10.5</td>
</tr>
<tr>
<td>**GWP(^1) [10(^{12}) US(1990)$]$</td>
<td></td>
<td></td>
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<tr>
<td>2050</td>
<td>100</td>
<td>75</td>
<td>75</td>
<td>150</td>
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</tr>
<tr>
<td>2100</td>
<td>300</td>
<td>200</td>
<td>220</td>
<td>500</td>
<td>500</td>
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<tr>
<td>**GWP/capita(^2) [1000 US$/cap]$</td>
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<td></td>
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<tr>
<td>2050</td>
<td>9.9</td>
<td>7.4</td>
<td>7.4</td>
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<td>48.2</td>
<td>48.2</td>
</tr>
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<td>high</td>
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<td><strong>Primary Energy Demand [Gtoe]</strong></td>
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<td>45</td>
<td>35</td>
<td>21</td>
<td>17</td>
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<td><strong>Resource Use [Gtoe]</strong></td>
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<tr>
<td>1990-2050</td>
<td>A(_1)</td>
<td>A(_2)</td>
<td>A(_3)</td>
<td>B</td>
<td>C(_1)</td>
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</tr>
<tr>
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<td>no</td>
<td>no</td>
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<td><strong>Biomass availability [10(^6) ha]</strong></td>
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<td>2050</td>
<td>390-690</td>
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<td>690-1350(^3)</td>
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<td><strong>Renewables 2050 [EJ]</strong></td>
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<td>B</td>
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<td>250</td>
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<tr>
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<td>other</td>
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1 GWP 1990: 21.2 x 10\(^{12}\) US(1990)$]
2 GWP/capita 1990: 4000 US$
3 Biomass output up to 10 t.o.e./ha = 420 GJ/ha
### Table 3.1 (continued) Overview of characteristics of long term energy scenarios

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<td>Natural Gas-</td>
<td>Coal-</td>
<td>High-</td>
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<td>Intensive</td>
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### 3.5 Synopsis

The most important assumptions for long term energy scenarios concern the level of economic growth and that of future energy demand. Decoupling of economic growth and growth of energy demand has been observed to a certain extent. However, deep reductions of energy demand could incur economic penalties. Therefore, a balanced view on the potential for economic growth without undue increase of energy demand in the world is needed.

Internationally co-ordinated policies to reduce the emission of greenhouse gases, notably in industrialised countries, become more and more visible since the Kyoto Conference. Even if the consequences for the western world are not known in detail, this
Analysis of long term energy scenarios

development casts serious doubts on the usefulness of some of the scenarios presented before. The need for sustainable energy policies will most probably intensify the efforts to reduce CO₂ emissions from fossil fuel combustion by energy conservation and use of renewable energy sources. The extent to which costs of renewable energy could be reduced should be part of the analysis.

Aggressive policies to reduce CO₂ emissions, based on energy conservation and renewable energy, would not be a guarantee for a sustainable energy development. At one hand continued large scale use of oil, gas and coal could result in too high levels of CO₂ emission. At the other hand a radical shift from coal and oil to natural gas (with its inherently lower CO₂ emission) could prove to be infeasible, at least on the long term. Therefore, a careful analysis of the availability of fossil fuel resources as well as alternative energy supply options is indispensable.

Sustainable energy policies also require analysis of the environmental consequences and risks of future energy options. It is doubtful whether fission energy could be considered as a real long term option. However, environmental and public acceptance constraints could be relevant for other alternatives too. Therefore, long term energy studies should take into account the most probable outcomes of the development of long term energy options including fusion energy.

Long term energy studies should carefully consider the timeframes of different energy options. The depletion of low cost oil and gas reserves remains a matter of concern in view of the time horizon of year 2100. It is quite possible that fission energy should be regarded as a transition energy option in that timeframe. New renewable energy options could come up. And, last but not least, fusion energy could become available as an economical and environmentally benign energy supply option around 2050.
The role of fusion power in energy scenarios
4. CONCLUSIONS

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

Only few existing scenario studies have a time horizon until the year 2100, which is a prerequisite for analysis of the prospects of fusion power. They deal with long term projections of greenhouse gas emissions, serving as inputs for models that calculate the effects on climate. The model to be used and further developed here, is based on MARKAL-EUROPE 1.0, a technology oriented optimisation model with a time horizon of year 2100. The system-wide (all sectors, from primary source to energy service) and dynamic (capital stock changes; load patterns) scope implies that systemic interactions like synergies, competition and load management are considered.

Energy scenario analysis with a very distant time horizon is not straightforward. Assumptions on technological innovation are different for scenarios with various time horizons. Other issues which need further clarification as a result of a long time horizon are discounting and climate change. Many quantitative studies have dealt with the discount rate issue. For the present analysis a specific approach will be followed, with two different kinds of discount rates being applied simultaneously in one analysis:

- A discount rate based on the social rate of time preference, derived from the rate of growth of consumption per capita and the greater distance we feel to generations further away from us; this relatively low discount rate (between 2 and 3%) governs the depletion of fossil fuel resources and the emission of CO₂ over time, given a cumulative emission of CO₂ allowed for the period until 2100.
- A higher interest rate -5, 8 and 10% - for energy investment decisions.

Environmental targets for CO₂ emissions are defined in terms of stabilisation levels for CO₂ in the year 2100 (450 to 750 ppm), linked to global cumulative emission levels.

The most important assumptions concern the level of economic growth, that of future energy demand and the technical economic development of certain energy technologies. Decoupling of economic growth and growth of energy demand has been observed to a certain extent. However, deep reductions of energy demand could incur economic penalties. Therefore, a balanced view on the potential for economic growth without undue increase of energy demand in the world is needed. The process of internationally co-ordinated policies to reduce the emission of greenhouse gases becomes visible since the Kyoto Conference. Even if the consequences are not known in detail, this development casts serious doubts on the usefulness of some of the existing
scenarios. The need for sustainable energy policies will most probably intensify the efforts to reduce CO₂ emissions from fossil fuel combustion by energy conservation and use of renewable energy sources. The extent to which costs of renewable energy could be reduced should be part of the analysis.
REFERENCES


