ECN-C--97-051, December 1997

SCENARIOS FOR WESTERN EUROPE ON LONG TERM ABATEMENT OF CO_2 EMISSIONS

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This project was carried out in the framework of the Dutch National Research Programme on Global Air Pollution and Climate Change; registered under nr. 77018, entitled: the MATerial TEchnologies to Reduce CO_2 emissions (MATTER). The Ministry of Economic Affairs is also acknowledged for providing financial support. We thank Ad Seebregts for providing useful comments.

ABSTRACT

An energy model for Western Europe has been constructed based on the MARKAL model to analyze future development of CO_2 emissions from Western Europe and the possibilities to limit these emissions with technological measures. This report describes two baseline scenarios for Western Europe for the period 1990 to 2050 which have clear differences in orientation of economic production and assumptions with respect to criteria for making energy investment decisions. The differences in points of departure result in distinctly different base levels of CO_2 emissions ranging from almost stable CO_2 emissions to a continuous growth. Several cases with a range of CO_2 emission taxes have also been calculated to identify cost-effective strategies for CO_2 emission reduction and to assess the potential contribution of energy technologies and sectors to CO_2 reduction. It appears that energy efficiency improvements have the highest potential to contribute to CO_2 emission reduction. Fossil fuel switching and nuclear energy are relatively cost-effective ways to reduce CO_2 emissions. The contribution of renewables to CO_2 reduction is relatively small with low CO_2 taxes but it is substantial with high CO_2 tax levels.

SUMMARY

Energy technologies will play a key role in reducing future CO_2 emissions. In this report the potential role of different energy technologies is assessed to reduce the CO_2 emissions from Western Europe in the long term (until the year 2040).

An energy model for Western Europe has been constructed to analyze the future development of CO_2 emissions and the possibilities to limit these emissions with technical measures. This report describes two baseline scenarios for Western Europe for the period 1990 to 2050 which have a different orientation of economic production and criteria for energy decisions. The Market Drive scenario has a continuously increasing demand in transport, industry and appliances while the Rational Perspective scenario has a more modest growth in demand for energy services. Moreover, the Market Drive scenario projects barriers to the penetration of cost-effective efficiency improvements to persist while the Rational Perspective scenario assumes disappearing barriers as a result of successful government intervention.

Both total primary energy requirements and CO_2 emissions are projected to increase rapidly in the Market Drive scenario. In the Rational Perspective scenario the growth in CO_2 emissions remains limited. Without imposing limitations to the growth in CO_2 emissions several structural changes are projected to take place. The role of nuclear power is projected to drop. Natural gas will first replace coal but over time coal will revive and reduce the role of natural gas again. New renewables will penetrate until a less significant level (Market Drive) or a more significant level (Rational Perspective) is reached. The penetration of efficient technologies depends on the scenario. The penetration is large in Rational Perspective but limited in Market Drive. The role of electricity will continue to grow in both scenarios but the rate of growth will decrease over time.

Taxes linked to the emissions of CO_2 induce changes in the mix of fuels and technologies. More efficient end-use energy technologies will increasingly penetrate. Coal and oil become less attractive. Nuclear power and renewables become more cost-effective. Large reductions (up to 60%) in the level of CO_2 emissions compared to the 1990 emission levels appear possible for the Rational Perspective scenario. For Market Drive, however, stabilisation of CO_2 emission already requires substantial efforts. Reduction of CO_2

emissions appears most attractive in electricity generation. Drastic emission reduction appears most difficult for the transport sector.

It is concluded that a mix of energy technologies is required to reduce the emissions of CO_2. Near term reduction of CO_2 emissions will have to rely on energy efficiency improvements and fossil fuel switch. In the longer term energy efficiency improvements continues to give a large contribution to emission reduction. Additional emission reduction will have to come from renewables and, depending on the social acceptance, from CO_2 removal technologies or nuclear power.

The model that has been developed (MARKAL-EUROPE 1.0) appears a flexible tool to analyze the possible role of energy technologies under various scenario assumptions. As a next step within the MATTER project, the model will also be used to analyze options to reduce CO_2 emissions by substituting materials in products, by increased material efficiency (product redesign or lifetime extension of products), by recycling, by renewable feedstocks and by waste management.

CONTENTS

1. INTRODUCTION

1.1 Background

New and improved energy technologies are expected to play a key role in abating future emissions of greenhouse gases [1,2,3]. Various technologies comprise the capacity to significantly contribute to the reduction of CO_2 emissions. How large the role of individual technologies will ultimately be depends among others on:

- the success of technologies to make progress in performance and cost;
- the market potential of the technologies at various moments in time;
- development of prices of fossil fuels;
- the level of future energy demand;
- environmental policy;
- the level of integration of the European energy system;
- the support for energy technologies by the actors in the energy system;
- barriers for the introduction and deployment of technologies.

To assess the possible role of technologies to the energy system and to the limitation of future CO_2 emission requires the use of energy technology scenarios. Energy technology scenario studies (e.g. [2,3]) which aim to analyse the contribution of energy technologies to CO_2 reduction have been been performed in different countries.

None of these studies has focused on Western Europe. For several reasons the geographical scope of Western Europe[1] is becoming increasingly important. For energy affairs, the Western European level is gaining importance. In economy and finance the borders between countries are gradually disappearing, the European Union (EU) is more and more becoming integrated. Environmental policy is increasingly dealt with at the EU level especially with respect to international environmental issues. Furthermore, the European electricity market is becoming liberalized and this will most likely result in an increase of

[1] The study covers Western Europe. This includes the countries of the European Union (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom) and Iceland, Norway and Switzerland. This group of countries is equivalent to OECD Europe minus Turkey.

electricity trade within Europe. Finally, the development of new and improved energy technologies via R&D activities continues to take place at the international level.

1.2 Objective and scenarios

The objective of the study reported here is to forecast possible autonomous trends in CO_2 emissions from Western Europe and to assess the potential role of energy technologies in the future Western European energy system to limit future CO_2 emissions. This is done by creating several energy scenarios for Western Europe and by analysing CO_2 abatement under a range of scenario conditions. As such, an assessment is made of the potential for individual energy technologies to reduce the emissions of CO_2.

The emphasis of this study is on the technical possibilities to reduce the emissions of CO_2 in the longer term while considering the cost consequences of emission mitigation technologies. It is recognized that technology is not the only means to reduce emissions of CO_2 and that non-technical aspects are also of key importance. To become successfully implemented, technology needs to be embedded in society and the new more sustainable energy technologies have to picked by the various actors involved in decisions on energy use. However, for constructing strategies for emission reduction, the technical possibilities and the possible contribution have to be known first. Once these are known, the implementation issues can be considered. Therefore, the identification of attractive emission mitigation technologies in this study should be regarded as a key step in the development of emission mitigation strategies. Complete mitigation strategies should include also a selected package of policies and measures to implement the energy technologies and include estimates of the macro-economic costs.

For this study, four scenarios have been prepared for Western Europe starting from the year 1990 and going in steps of 10 years to the year 2050. The scenarios include two levels of energy demand and two kinds of energy technology availability. The ‘technology availability’ refers to two different sets of constraints for technology with uncertain social development paths, such as nuclear power and CO_2 removal. In addition, each scenario has been analyzed with different rates of CO_2 emission abatement (CO_2 variants). A wide range of energy technologies is included in the scenarios of this study and the possible role of these technologies has been assessed for each scenario and for each variant.

Western European 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. In general this study treats Europe with an aggregate approach. Differences between the regions of Europe which are relevant for energy technical reasons, such as climate related energy demands and location dependent production (renewables) have been treated explicitly. On the other hand, indvidual countries have not been modelled. This is a main difference with the recent energy modelling work of the European Commission [4], which treats all countries of the European Union explicitly.

Another difference with the study of the European Commission [4] is the time horizon. The present study has a time horizon of 2050[2] while the European Commission has a time horizon of 2020. Over longer time frames structural changes in the energy system become increasingly important. That is one of the reasons why an integrated energy system approach is adopted in this study in which energy supply and energy demand technologies are treated simultaneously. The study of the European Commission uses an econometric approach for the demand side of the energy system and it is does not treat demand technologies explicitly.

This report has been prepared as part of the MATTER[3] project. The objective of the MATTER project is to improve the understanding of the processes responsible for CO_2 emissions in production and use of both energy and materials and products and to analyze strategies to reduce these emissions. Two phases can be considered in the scenario work of MATTER. In the first phase more or less conventional energy system scenarios have been constructed and analyzed without analysis of the materials system. The present report covers the main results of this first phase. The scenarios for this analysis have been constructed between February 1996 and December 1996. Three other reports cover more

[2] It is noted that the model has calculated scenarios until the year 2070. The results for 2060 and 2070 have not been reported.

[3] MATTER stand for MATterial TEchnologies to Reduce CO_2 emissions.

specifically the outline, assumptions and results for three sectors, i.e. electricity generation [5], transport [6] and the building sector (residential and commercial) [7].

In the second phase of the MATTER project, the analysis of the energy system will be expanded with the analysis of the material and product system[4]. Then, flows of materials and products will simultaneously be analyzed with an analysis tool that is fit for the combined analysis of the energy and the material system. A similar analysis with the energy system and the material system simultaneously analyzed has been done earlier for the Netherlands [8].

1.3 Contents of the report

This report contains 7 chapters. Chapter 2 contains a discussion of the recent historic development of energy consumption in Western Europe. In Chapter 3 the scenario inputs are described and the methodology that was used to construct scenarios is explained. The results for the base case scenarios (the scenarios without constraints for the emissions of CO_2) are presented in Chapter 4. In Chapter 5 the results of emission abatement scenarios are given and explained. Chapter 6 contains the results of two scenario variants. Chapter 7 contains a discussion of the results and a comparison with the results of other scenarios. In Chapter 8 conclusions are drawn and recommendations are given.

[4] The material system refers to the system that ranges from material production (e.g. steel, plastics, glass) to product manufacturing (e.g. cars, machinery, buildings) and waste material management. For this purpose a combined energy and material flow model is being built for Europe. The model is a tool to structure and analyze the developments in energy and material flows for the time period 1990 to 2050.

2. HISTORIC DEVELOPMENTS IN ENERGY USE IN WESTERN EUROPE (1970-1993)

2.1 Main trends

The main trends that have occurred in energy use in Western Europe between 1970 and 1993 are summarized below:

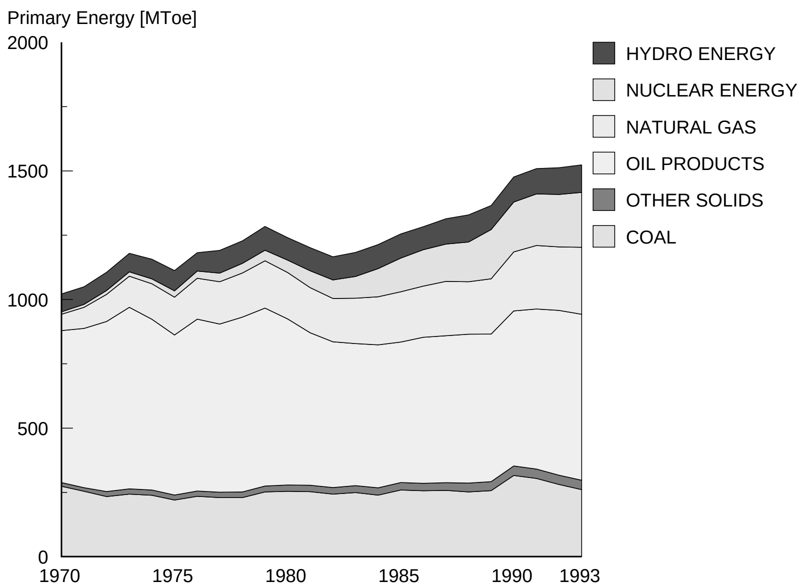
- Total primary energy requirements (TPER) have increased significantly with an average rate of 1.3% per year.
- The shocks in the prices of fossil energy carriers havehad an impact on total energy consumption pulling the rate of growth downwards.
- The consumption of coal, oil and hydro power has not changed much.
- The use of natural gas and nuclear power has shown a large increase.
- The supply of renewables other than hydro power has remained small.
- Due to the net switch towards less carbon intensive fuels, CO_2 emissions have almost remained constant while TPER has increased.
- The largest sectoral growth in energy use has taken place in transport and in electricity generation.
- Final energy use in industry has remained constant. Growth in production has been balanced by efficiency improvements.

2.2 Primary energy

Over the last 25 years considerable changes have occurred in the level of energy use in Western Europe and the contribution of the different fuels to this fuel consumption. The development of total primary energy supply between 1970 and 1993 is shown in Figure 2.1. Total growth in the period 1970-1993 is more than 30%. On average the growth amounted to 1.3% per year. This growth is modest in comparison with an average GDP growth of 2.6% per year over this period. Population growth was on average 0.38% per year.

The effects of the two energy price shocks in 1973 and 1979 on total energy consumption can clearly be observed. Both prices shocks have resulted in a decreasing trend of energy consumption that lasted for several years. From 1982 to 1993 total energy supply has increased. The increase of energy supply in 1990 largely results from the expansion of OECD Europe with Eastern Germany after the reunification of Germany.

Figure 2.1 Total primary energy requirements in Western Europe between 1970 and 1993. Until the year 1990 emissions from East Germany are excluded.

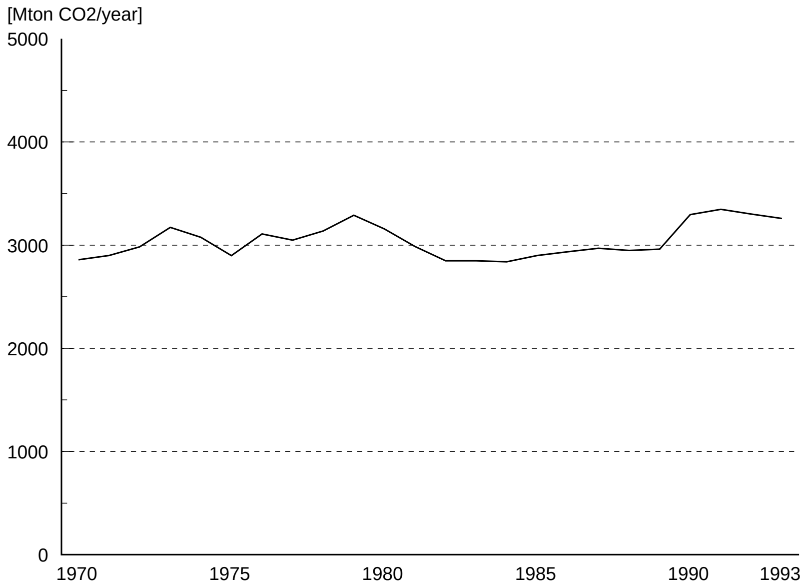


Natural gas and nuclear energy took most of the net growth in energy supply during the period considered. The growth of nuclear energy has been very strong between 1975 and the end of the eighties but after 1990 nuclear supply stabilized. The growth in natural gas supply has been more gradually and growth of natural gas consumption is still continuing.
Oil is the most important energy source in Western Europe. Except for the effects of price shocks, the level of consumption of oil has remained relatively constant between 1970 and 1993. The last 8 to 10 years show a modest but steady increase of oil supply. The consumption of coal has even been more stable during the period considered than the role of oil; only in the last few years the supply of coal has been decreasing. The small peak in

coal consumption in 1990 results from the uptake of East Germany in Western Europe and the subsequent phasing out of the East German coal consumption.

Total CO_2 emissions from Western Europe have not changed much between 1970 and 1993 as can be seen from Figure 2.2, despite the considerable increase in total primary energy consumption. This is a result of a shift over time toward energy sources with lower carbon contents such as natural gas and nuclear power.

Figure 2.2 CO_2 emissions from Western Europe between 1970 and 1993. Until the year 1990 emissions from East Germany are excluded. The emissions have been calculated on the base of IEA energy balances.

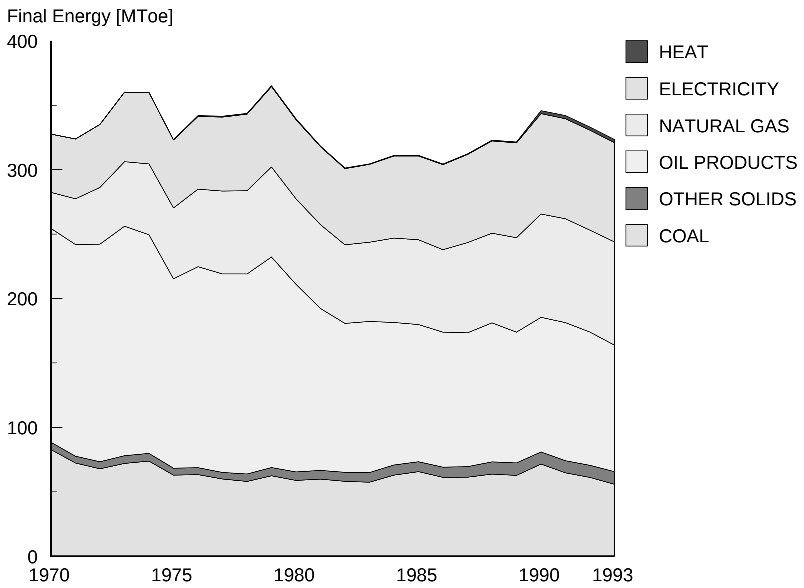


2.3 Sectoral developments

Industry

Total energy consumption in industry has remained relatively constant between 1970 and 1993 (see Figure 2.3), although the shocks in energy prices had clearly impacts on total energy use.

Figure 2.3 Breakdown of energy consumption in Western Europe by fuel in industry between 1970 and 1993. Until the year 1990 emissions from East Germany are excluded.

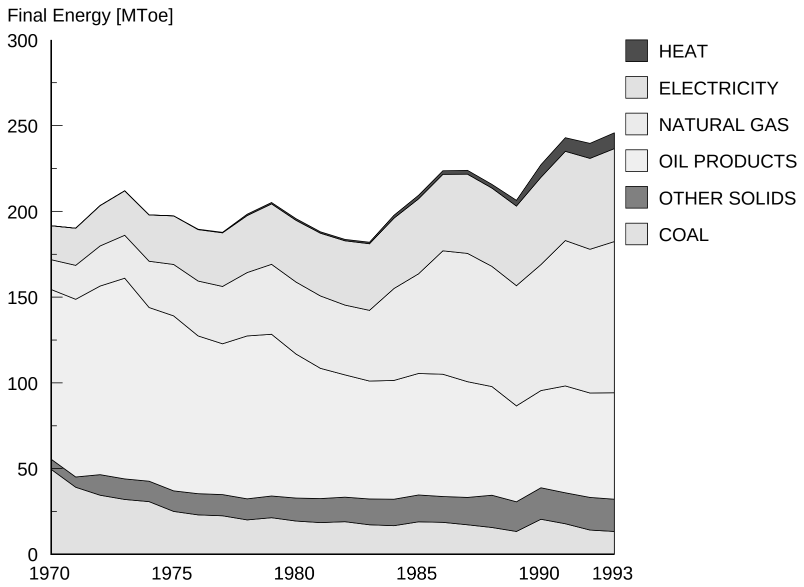


The contribution of coal has slightly decreased between 1993 and 1970. The share of oil products in total industrial energy use has decreased considerably. Oil products are used less for heating purposes but the use of oil products for feedstock production has not decreased. Natural gas has been the primary substitute for oil products and coal in the production of process heat and steam. Electricity use in industry has continuously increased and it almost doubled in the 25 years considered.

Residential sector

The changes in fuel consumption in the residential sector have been larger than in the industry sector. While total consumption of fossil fuels remained more or less constant, substitution between fuels has been more pronounced. By 1993 the use of coal has decreased with about 75% compared to the 1970 consumption level and the use of oil products has decreased with almost 40%. At the same time the consumption of natural gas has increased with more than 500% and for heating purposes natural gas is now the most important fuel in the residential sector. Direct heat distribution to the residential sector via district heat systems has become significant in the last 10 years and it contributes now to over 4% of energy consumption.

Figure 2.4 Breakdown of energy consumption in Western Europe by fuel in the residential sector between 1970 and 1993. Until the year 1990 emissions from East Germany are excluded.

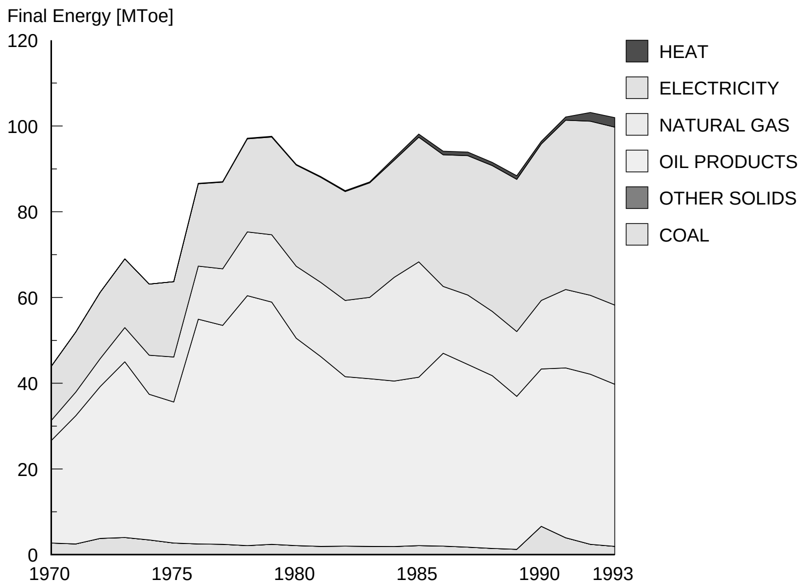


Electricity consumption in the residential sector has increased continuously. By the year 1993 the electricity consumption of the residential sector is 2.7 times the electricity consumption in 1970. However, the rate of growth of electricity consumption has decreased. Between 1970 and 1975 the average rate of growth was 7.4% per year, while the annual growth between 1990 and 1993 amounted to only 2.1%. This decreasing growth of electricity consumption results from emerging saturation effects in the penetration of appliances and from the shift towards more efficient electric equipment.

Commercial and service sectors

Between 1970 and 1980 energy consumption in the commercial and service sectors has increased strongly (see Figure 2.5). After 1980 the final consumption of fossil fuels has decreased slightly. Electricity consumption has continuously increased and it is currently accounting for 45% of total energy consumption in the commercial sector. The commercial sector is the sector for which the effect of the energy price shocks on energy consumption can best be observed. The energy price shocks had a lasting effect on the consumption of fuels.

Figure 2.5 Breakdown of energy consumption in Western Europe by fuel in the commercial and service sectors between 1970 and 1993. Until the year 1990 emissions from East Germany are excluded.

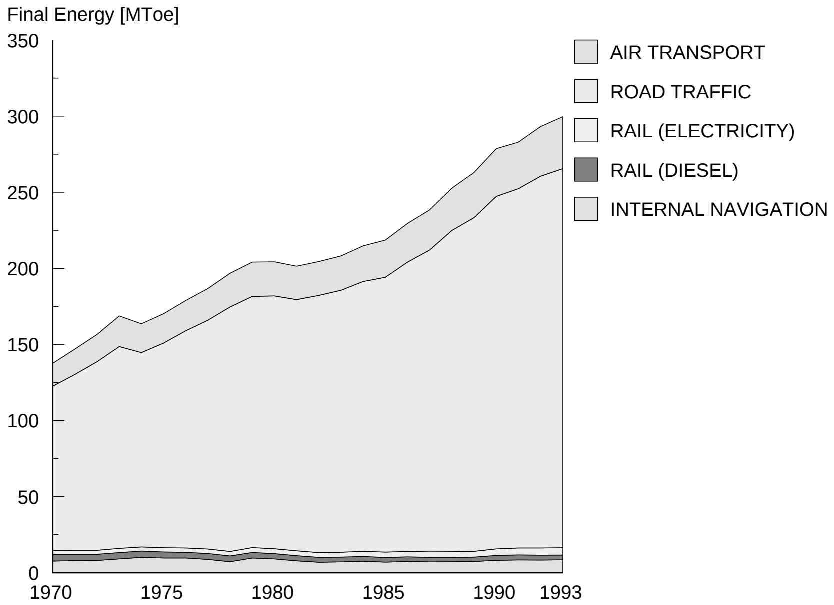


In 1990 the contribution of coal to commercial energy consumption has increased as an effect of the reunification of Germany. East Germany had a significant final consumption of coal in the commercial sector, however, this consumption is clearly decreasing as can be noted from Figure 2.5.

Transport sector

Compared to the other sectors, transport energy consumption has increased most strongly over the last two decades at a rate of 3.7% per year. The increase took entirely place in road and air transport. Total energy consumption does not seem to stabilize as yet. Total energy consumption for rail transport remained almost constant although diesel has been substituted for by electricity. Energy use for internal navigation also remained constant.

Figure 2.6 Breakdown of energy consumption in Western Europe by transport mode in the transport sector between 1970 and 1993.



Electricity generation

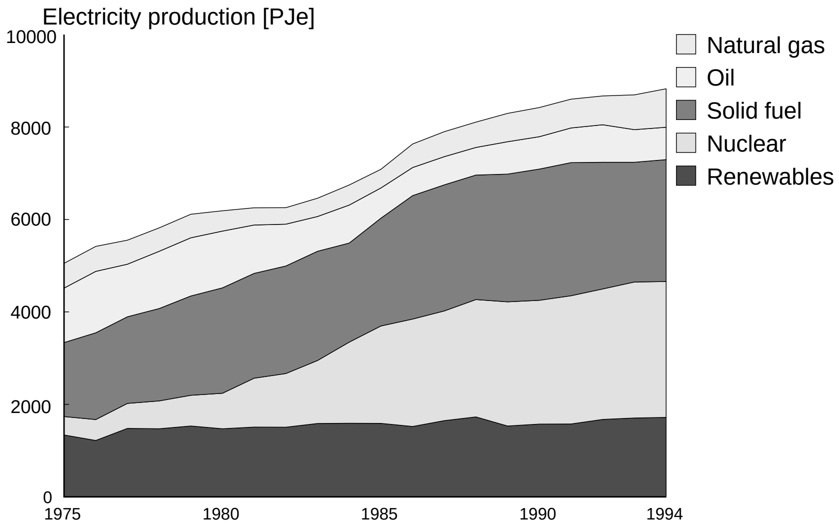
Figure 2.7 shows the development of power generation in Europe during the last twenty years. The average growth of electricity consumption during this period was about 2.5% per year. During the period 1975-1985 average growth was about 3% per year, and during the last ten years somewhat less than 2% per year.

Twenty years ago the three main sources of power in Western Europe were solid fuel (hard coal and lignite), hydro power, and residual oil. These energy sources represented more than 80% of power generation. Nuclear power was far less important than today.

Hydro power has showed an increase of about 1.5% on average. In 1994 its share of total power production was about 19%. Nuclear power has increased very fast until about 1993, ending up at about 33% of power generation in 1994. Production from solid fuels, mainly hard coal and lignite, as a percentage of total power generation has increased slightly from 32% in 1975 to 37% in 1980. After that, coal fired power lost some market share to

nuclear power, although power from solid fuels has increased in absolute figures until 1991. In 1994 solid fuels represented 30% of power generation.
Oil fired power, which supplied 23% of power in 1975, lost against nuclear power and coal fired power, both in relative and absolute terms. In 1994 oil fired power supplied 8% of power in Europe, and gas fired power about 9%.

Figure 2.7 Electricity production in Western Europe between 1975 and 1994 per source of power. Waste and biomass are considered under solid fuels.



The renewables other than hydro are comprised in Figure 2.7 in ‘renewables’. Such ‘new’ renewables are geothermal power, tidal power, and wind energy. Their contribution is very small up to now.

3. METHODOLOGY AND SCENARIO ASSUMPTIONS

This chapter describes the approach that has been followed in this study. First, the general approach and the modelling tool are explained (Sections 3.1 and 3.2), then the assumptions for the scenarios are given (Section 3.3). Finally, the selection of the technologies that are included in the model is explained (3.4).

3.1 General approach

To meet the objective of this study energy scenarios of Western Europe are required in which the potential role of energy technologies can be assessed with various levels of CO_2 emission abatement and under a range of scenario conditions.

Energy technologies will compete with one another if they can deliver the same type of energy carrier or the same type of energy service. Economic considerations are crucial for decisions on the use of one technology or an alternative. As the pattern of energy use changes with seasons and with time of day, as cost of fuels vary over time, and as technologies in different areas in the energy system interact, the identification of the most optimal investment decisions for energy technologies is not simple. If energy decisions are considered for the entire energy system, one needs to use integrated energy models that can incorporate such aspects. This study applies the MARKAL model (see Section 3.2). This models allows to study the competition of technologies within a level playing field.

The level of energy demand, energy price development and environmental policy will affect the potential role of energy technologies. Each of these factors is uncertain. With two different scenarios, this study covers the uncertainty in energy demand and in energy prices (see section 3.3). Uncertainty in future environmental policy is comprised in this study by different levels of CO_2 taxes. Emissions of CO_2 will be reduced more and more with increasing CO_2 tax levels.

The potential for further development of energy technologies varies with the current status of the technology. On the one hand, technologies which have already been applied on a large scale lack in general the possibility for large efficiency or cost improvements. On the other hand, technologies in the demonstration phase have much larger room for improvement. In this study, the technologies compete at moments in time with the technical and economic specifications that are expected for these dates in time.

3.2 Modelling tool

The model that has been developed for this study is called MARKAL-EUROPE 1.0, and it is based on a frequently used linear programming model (MARKAL). 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).

MARKAL is a widely applied linear optimization model [9]. The main characteristic of an optimization 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 optimization model. The costs and conversion efficiencies of all technologies are defined exogenously. The optimal solution found by the model is the configuration of the energy system with minimal costs that meets the specified energy demand. 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 national 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 electricity generation were possible.

The **dynamic** nature implies that past decisions and future expectations 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.

Environmental considerations can be addressed in various ways, such as through sectoral or national 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 or maximum bounds on new capacity. Examples of technologies that have bounds in MARKAL-EUROPE 1.O are wind turbines, PV systems, geothermal energy and district heat. The bounds can be justified on the base of different real constraints: public planning constraints (e.g. wind turbines), limited manufacturing capacity (e.g. PV systems), physical constraints (geothermal reserves), heat demand in areas with high heat demand (district heat), etc.

The overall optimization **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 policies and measures.

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 optimization of the energy system for the full period 1990-2050 in one set of iterations. This implies that perfect foresight applies. This means for instance that the structure of energy system in 2020 anticipates on the constraints that have to be met in 2030.

Western European 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 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 Western European economy and policy 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 3.1.

Table 3.1 Overview of the kinds of useful energy demand in the model for Western Europe.

Industry	Households	Transport	Commerce
Aluminium production Bricks production Chlorine production Steel production Polyolefine production Ammonia production Olefine production Styrene production Cement clinker production Paper production Non Energy Use: Lubricants+Bitumen Other industry: - large high temp. heat - small high temp. heat - large low temp. steam - small low temp. steam - electricity	Space heating single houses: - North Europe - Middle Europe /old - Middle Europe /new - South Europe Space heating apartments: - North Europe - Middle Europe - South Europe Water heating: - North Europe - Middle Europe - South Europe Dishwashers Food preparation Lighting Refrigerators/freezers Tumble driers Washing machines Other electric appliances	Passenger car Van Truck Bus Rail Transport Water Transport Inland Air Transport Bunkers	Space heating - North Europe - Middle Europe/large - Middle Europe/small - South Europe Other commercial electricity demand

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.

3.3 Scenario assumptions

To frame the analysis of the energy and material system, one or more scenarios are required. For this study two new energy scenarios have been developed but they include certain similarities with existing EU scenarios. The two scenarios are named **Rational Perspective** and **Market Drive**. The differences between the two scenarios relate to their perspective towards decision criteria on energy investments by individual actors (represented by different discount rates), the level of energy demand and energy price projections. Assumptions for the cost and performance of technologies are the same for the two scenarios. The maximum and minimum potentials of supply technologies are - in absolute meaning - the same for the two scenarios.

General scenario background

Rational Perspective is the ecologically driven scenario. The process of global economic integration will lead to more collective public action in this scenario. The cooperation between countries will be more efficient in order to deal with complex shared problems. Heavy polluters and energy intensive industries will decline relatively to more environmentally friendly sectors like services. Strong penetration of new, more efficient demand and supply technologies is facilitated. This strong penetration will be reached by setting efficiency standards, removing existing barriers for the introduction of efficient technologies and active energy service companies which carry out cost-effective efficiency improvements for end-users, etc. The above mentioned policy shifts are driven by environmental concerns and concerns about efficiency throughout society.

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

Growth of population and economy

Most population projections for Western Europe show very little differences in the results for the next 30-50 years. Therefore, the development of population is also assumed to be equal for Market Drive and Rational Perspective. The population projection of the European Union is based on data of the Worldbank [10]. The number of households have been estimated by division of population per country by the average number of persons per household per country. It is assumed that the average number of persons per households in Western Europe will decline gradually, but will not become less than 2.2 person per household.

From 1990 to 2020 the growth rate of GDP is higher in Market Drive than in Rational Perspective. This is caused among others by the restructuring process in Rational Perspective towards more environmentally friendly economic sectors like services and less heavy polluters like energy intensive industries. However, in 2020 GDP in Rational Perspective and in Market Drive have almost the same level, due to stagnation in Market Drive caused by among others too much privatization, which will cause economic inefficiencies. Some of these privatizations will be reversed and afterwards the economic growth is higher in Market Drive than in Rational Perspective. To a certain extent energy demand becomes decoupled from economic growth. By the year 2040 high economic growth rates are not any more in line with ecological objectives in the Rational Perspective scenario. On average economic growth over the time horizon amounts to 2.4% per year in both scenarios.

Discount rates

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

In one of the two scenarios a single uniform discount rate has been applied. By applying a uniform rate to all technologies, all technologies at the demand side of the energy system are allowed to compete with energy supply technologies as if in a perfect market. The scenario where this is allowed has been named the **Rational Perspective** scenario, as this scenario assumes a market that works rational without barriers and with perfect information so that any difference in pay back opportunities will automatically be removed. The discount rate in Rational Perspective amounts to 5% per year.

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

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

Sector	Discount rate
Power generation Industrial cogeneration Refineries Industrial processes Biomass conversion	15%
Space and water heating in residential sector, commercial sector and greenhouses	20%
Boilers in industry Trucks and buses	25%
Passenger cars and vans Electric appliances	50%

End-use energy demand levels

For most kinds of energy end-use, demand for energy services has been assumed higher in the Market Drive scenario than in the Rational Perspective scenario. The Rational Perspective scenario assumes a world where growth in energy demanding services which have important negative external effects on environment and health is limited. In the Market Drive scenario this is not the case. Therefore, demand in road transport, air transport and the heavy industry is significantly lower in Rational Perspective than in Market Drive. Energy demand in the residential sector is assumed the same for most kinds of energy services that are discerned in the residential sector. Table 3.3 gives the energy demand projections for selected energy demands in the year 2010 and in 2040. It is noted that demands refer to physical outputs, e.g. in tons of aluminium and are not specified in financial terms. The projection of the demand for individual materials in industry was based on expected trends in volume and substitution between materials. Energy demand is the commercial sector and transport has been related to growth in GDP. The demand in the residential sector is driven by the number of households and the penetration level of end uses.

Table 3.3 Useful energy demand for selected energy demands in the scenarios Rational Perspective and Market Drive in the years 2010 and 200

	useful energy demand as index of demand in 1990				
		rational perspective		market drive	
	1990	2010	2040	2010	2040
Industry					
aluminium	100	147	167	183	250
steel	100	98	90	102	106
polyolefines	100	135	153	153	190
olefines	100	144	167	156	200
styrene	100	138	138	155	175
ammonia	100	120	153	127	140
paper	100	138	169	162	200
other electricity use	100	127	168	138	194
Commercial sector					
space heating North	100	125	154	140	187
space heating South	100	132	177	148	217
electricity	100	133	178	149	217
Residential sector					
space heating North	100	108	116	108	116
space heating South	100	115	126	115	126
refrigerators/freezers	100	111	120	111	120
tumble dryers	100	267	342	267	342
other electricity	100	233	378	269	435
Transport					
passenger cars	100	128	176	157	240
trucks	100	124	164	166	355
rail	100	180	409	134	213

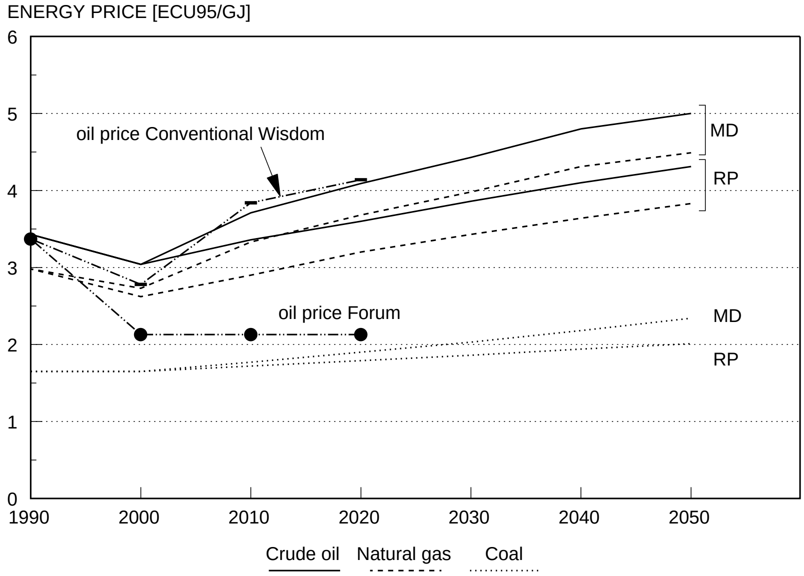
Energy price projections

From the past oil crises (1973, 1979) it is evident that oil prices can vary with wide margins. The same holds for gas prices, as far as they are linked with oil product prices, which is common until now. The *level of* fossil fuel prices, and the *margins* between the prices of oil and gas on the one hand and the coal price on the other hand, have a large influence on the cost-effectiveness of energy technologies. With a high energy price level, technologies that can reduce fossil fuel use - energy conservation, renewables, nuclear energy - become more cost-effective than with low fossil fuel prices. At a low level of energy prices, energy conservation and substitution of coal or nuclear energy for oil and gas are not very attractive. The margin between the price of fuel oil or natural gas versus the price of coal is determining for the question if coal or gas fired power generation is economically attractive.

With the experience of falling oil prices since the mid eighties, energy analysts are more and more confused about the future energy price development. Some expect oil and natural gas prices to pick up, as soon as the current glut is over; others tend to favour relatively flat energy price projections. Another phenomenon is the relatively short time span of energy price projections: 2015, 2020. If they would be used for this study, some extrapolation to the year 2050 is needed.

The reasons behind the uncertainty with respect to future energy prices, are different assessments of magnitude and production costs of fossil energy carriers, different views on energy demand, and other issues such as the costs of energy supply over large distances. Moreover, energy analysts have different opinions on the room for and probability of fossil fuel substitution, energy conservation potential, and future environmental policy.

Figure 3.1 Energy price projections for scenarios Market Drive and Rational Perspective. The projections refer to real prices in ECUs of 1995. Carbon taxes are not included in the projections.



Taking into account these views, two energy price projections have been chosen both with slowly but steadily rising fossil fuel prices (see Figure 3.1). These two developments of fossil fuel prices are both considered as fairly central energy price projections. Energy prices are somewhat higher in Market Drive than in Rational Perspective. This is related to the differences between the scenarios in energy prices and the differences in required pay back times of capital investments. Each of the energy price scenarios is equally plausible from different views on energy supply and demand in Europe and the world in general.

It is assumed that the supply of coal and oil (which can easily be transported by ship) is unlimited. The supply of gas, however, has been limited. In the Rational Perspective scenario it is assumed that under CO_2 reduction variants the price of natural gas will increase for the natural gas that will be consumed in addition to the base case natural gas consumption. A first tranche of about 1 EJ has a 10% higher price. A second tranche is 20% more expensive. In Market Drive the supply of natural gas is restricted from 2030 to 2050 to 10 EJ natural gas per year. In a scenario variant with extended supply options (see Chapter 6) this restriction is removed.

For comparison, the oil price projections up to the year 2020 of a recent study for the European Commission [4] are also included in Figure 3.1. The price projections for crude oil in the Market Drive scenario and the Conventional Wisdom scenario are very similar. The price projection of the EC's Forum scenario is lower than the price projections of the present study. Considering recent literature on energy price expectations, the Forum price projection are regarded as unrealistically low.

3.4 Energy technologies

A wide range of energy technologies has been considered in this study. The technological substitution options for the different sectors are represented in a balanced way. A balance has been aimed at establishing a model with a manageable size which is flexible to use and a realistic representation of the technological alternatives. To give an impression of the technological detail, energy technologies are listed for several end-uses in Table 3.4 (end-use sector) and Table 3.5 (energy conversion).

Table 3.4 Selection of energy technologies in end-use sectors considered in the European MARKAL model.

Space heating		
floor, wall and roof insulation heat recovery coated glass gas-filled glass	gas boiler condensing boiler oil boiler coal boiler wood boiler	electric resistance electric heatpump district heat heat from small cogeneration
Appliances		
water heaters based on gas, coal, oil, wood electric boilers electric heatpump boiler solar boiler with various back-up systems	cookers on gas, LPG, wood, electricity IR impingement cokr.	conv. refrigerator refrigators with levels of insulation, efficient compressors
Industry		
For each of the main energy consuming industries various alternative processes	cogeneration use of waste heat various boilers	extra recycling fuel switching
Transport		
Improved internal combustion engines, modified frames regeneration of brake energy, impr. transmission	Fuels: gasoline, diesel, LPG, CNG, ethanol, methanol, hydrogen	Hybrid car Various electric cars Fuel cell vehicle

Table 3.5 Selection of energy conversion technologies considered in the European MARKAL model.

Electricity generation	
Existing pulverised coal power plant	SOFC/gas turbine comb. for R&C
New pulverised coal power plant	Wood gasification/small indust. cog.
Integrated coal gasification power plant	Wood gasification/STAG power plant
Existing gas fired power plant	Wood gasification/ISTIG+reheat
Existing STAG power plant	Medium and high head hydro
New STAG power plant	Low head hydro
Existing lignite fired power plant	Waste to energy plant (incinerator)
New lignite fired power plant	LWR power plant
Integr. lignite gasification power plant	Solar PV in Middle Europe
Coal FBC CHP plant	Solar PV in South Europe
Existing oil fired power plant	Solar PV from South Eur. for rest Eur.
New oil fired power plant	geoThermal energy
Gas turbine peaking plant	Large onshore wind turbine
Existing gas turbine CHP plant	Large onshore wind turbine/storage
Existing STAG CHP plant	Large offshore wind turbine/storage
Exist. gas eng. gen. set for R&C	Existing windturbines onshore
New gas turbine CHP plant	Hydro pumped storage
New STAG CHP plant	Hydro pump stor. (2nd cost tranche)
New gas engine gen. set for R&C	
Refinery	
Catalytic reformer	Hydrocracker
Fluid catalytic cracker	Hycon
Flexi coker	Distill. light crude
Distill. heavy crude	Visbreaker
Biomass	
Biomass/briqu. plant	Biomass/wood short rot.forests Middle
Biomass/methanol from straw	Biomass/diesel from rapeseed South
Biomass/diesel from rapeseed Middle	Biomass/ethanol from wheat South
Biomass/ethanol from wheat Middle	Biomass/ethanol sugarbeet South
Biomass/ethanol from sugarbeet Middle	Biomass/straw from miscanthus South
Biomass/straw from miscanthus Middle	Biomass/wood short rot. forests South

The technology assumptions are for the larger part reported in [5,6,7,11]. Characterizations of technologies were largely taken from the database of the Dutch SYRENE study [3], although it has been extended with technologies which are relevant for other countries in Western Europe than the Netherlands. For most of the technologies considered a further technological development has been assumed resulting in improved efficiency, higher technical availabilities and reduction of cost. The technology development has not been endogenized by e.g. relating the cost of technologies to the capacity that has cumulatively been manufactured. Since Western Europe is only a limited part of the world market for energy technologies, applying such a relationship on the scale of Western Europe is not appropriate. Instead, the technology data are based on the open technology literature, expert opinions and peer review.

Several remarks need to be made about the assumed availability of technological options in the model for Western European model:

- In first instance, certain technologies with large uncertainties about their further development with respect to the technical concept and costs have not been considered in the analysis. This is the case for e.g. breeder reactors, fusion power, super conductors and fuel cells.
- It is noted that the list of energy conservation options is not exhaustive. For some end-uses the substitution options are still absent or incomplete. This is the case with end-uses which are small in terms of absolute energy consumption such as coffee makers, micro waves etc. In a few cases the substitution options have not been considered since technical descriptions of alternatives were not available. This is the case with e.g. aircraft and trains.
- Changes in the transport infrastructure have only been considered as different points of departure for the two scenarios, not as technological choices. Rational Perspective assumes a shift towards a larger role for electricity driven passenger transport. In Market Drive the modal split remains constant.
- The role of nuclear power is assumed to remain between its current role and 50% of this capacity in the two scenarios. It is noted that two scenario variants have been calculated with extended potential for nuclear power. The results of these variants are discussed in Chapter 6.
- CO_2 removal from fossil fuels at electric power plants or at hydrogen production is not considered in the two scenarios. However, the variant with extended technological potentials in Chapter 6 includes such CO_2 removal options.
- Import of renewables from other continents, e.g. import of electricity from PV systems located in North Africa has not been considered as an option.

4. RESULTS IN THE BASE CASES

4.1 Main results

This chapter describes the results of the scenario calculations for the two base case scenarios Market Drive and Rational Perspective. The calculations suggest various developments. First, the main emerging trends are listed:

- Market Drive and Rational Perspective substantially differ with respect to growth of total primary energy requirements (TPER) between 1990 and 2050. TPER remains almost constant in Rational Perspective at a level of 60 EJ while it increases to 80 EJ in Market Drive.
- The difference in TPER between Market Drive and Rational Perspective primarily results from the much higher use of oil products in Market Drive for the transport sector (15 EJ higher). Energy use in most other sectors is also slightly higher in Market Drive.
- The emissions of CO_2 in Rational Perspective will remain close to the current emission level. In Market Drive, however, CO_2 emissions will increase steadily with a rate of 1% per year on average.
- Market Drive and Rational Perspective show similar trends in time for the relative contribution of most primary fuels.
- Oil remains the most important primary fuel in both scenarios.
- Until the year 2020 both scenarios suggest a smaller role for coal than presently. After 2020 the consumption of coal increases substantially.
- The consumption of natural gas increases strongly until 2020. After 2020 the use of natural gas decreases slightly.
- Combined cycle power plants based on gas or coal are the dominant technologies for fossil based power generation.
- After the year 2020 the role of nuclear power will decrease substantially. The contribution of hydro remains constant.
- "New" renewables, such as wind turbines and biomass, will increasingly penetrate but their total contribution remains limited to 3.5% of TPER in Market Drive and 7% in Rational Perspective.

- The developments in the mix of energy carriers within sectors differs between Market Drive and Rational Perspective.
- Penetration of efficient end-use technologies, such as efficient vehicles and appliances, insulation and process changes in industry is much larger in Rational Perspective than in Market Drive.
- The growth in the share of electricity in final energy use continues, but not as strongly as recent historic trends.

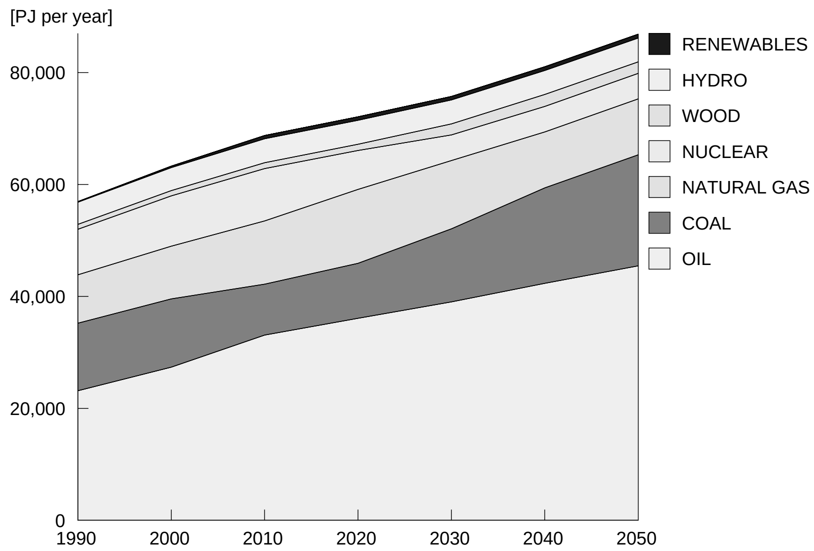
The following sections of this chapter give more detailed descriptions of the base case results. Section 4.2 shows the development of the primary energy mix in the two scenarios and the trends in CO_2 emissions. Section 4.3 presents some sectoral results. It is noted that the results for the different sectors are described in more detail in two other reports [6,7]. The results for energy conversion at the supply side of the energy system (electricity generation and refineries) are given in Section 4.4.

4.2 Primary energy mix and CO_2 emissions

Market Drive

In the first 30 years of the projection period primary energy demand increases at a rate of almost 1% per year in the Market Drive scenario (see Figure 4.1). The growth of primary energy demand is lower between 2020 and 2050 (0.7% per year). Oil remains the most important kind of primary energy supply. The relative importance of oil even increases over time as the growth in the demand for oil products is relatively high; between 1990 and 2050 it amounts on average to 1.1% per year. This is mainly due to a large growth in the demand of the transport sector combined with relatively small efficiency improvements in this sector. The role of coal continues to decrease between 1990 and 2010 but after 2020 a revival takes place in the role for coal. For natural gas we see the opposite pattern. Its role increases between 1990 and 2020 up to a level of 13 EJ, but afterwards it goes down and stabilizes at a level of 10 EJ. The relative cost advantages of natural gas and coal reverse over time. Between 1990 and 2020 natural gas has a cost advantage and most new electricity generation plants are gas-based. However, between 2020 and 2050, the situation has turned around due to the assumed larger rise in the price of natural gas than in the price for coal.

Figure 4.1 Primary energy demand in the Market Drive scenario between 1990 and 2050. The primary energy equivalent for hydro, nuclear and renewables has been calculated using a fossil equivalent efficiency factor of 40%.



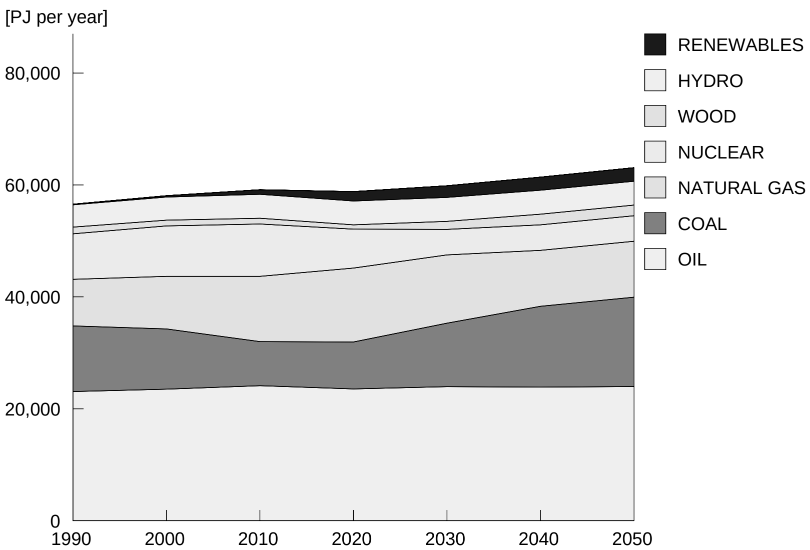
The contribution of hydropower remains almost constant over the projected time horizon; only a marginal expansion of generation capacity occurs. The role of nuclear energy decreases until the assumed lower bound of 50% of the current production. The contribution of biomass and waste doubles between 1990 and 2030 and then it remains almost constant. Its share in total primary energy in 2030 is 2.6%. The role of new renewables, predominantly wind energy, shows a fivefold increase between 1990 and 2010. This large growth does not continue after 2010 in the baseline and the role of the new renewables stabilises at a share of almost 1% of total primary energy demand.

Rational Perspective

The development of primary energy demand in the Rational Perspective reference scenario shows certain similarities and some clear differences compared with the development in the Market Drive scenario.

Growth in total primary energy demand is very modest in Rational Perspective, on average it amounts to only 0.2% per year. The amount of oil consumed is extremely constant; it amounts to 24 EJ per year during the full time period 1990 to 2050, see Figure 4.2. This is a continuation of the development between 1970 and 1990 where oil consumption was also fairly stable. Between 1990 and 2010 the demand for coal drops to a level below 8 EJ. After 2020 the role of coal increases again and by the year 2030 it reaches again the demand level of the year 1990. This pattern is similar to the development in Market Drive. For natural gas, the opposed pattern can be observed in Rational Perspective. Until 2020 the demand for natural gas increases; the maximum consumption in 2020 amounts to 13 EJ. After 2020 natural gas demand drops to a level of 10 EJ in 2040/2050.

Figure 4.2 Primary energy demand in the Rational Perspective scenario between 1990 and 2050. The primary energy equivalent for hydro, nuclear and renewables has been calculated using a fossil equivalent efficiency factor of 40%.



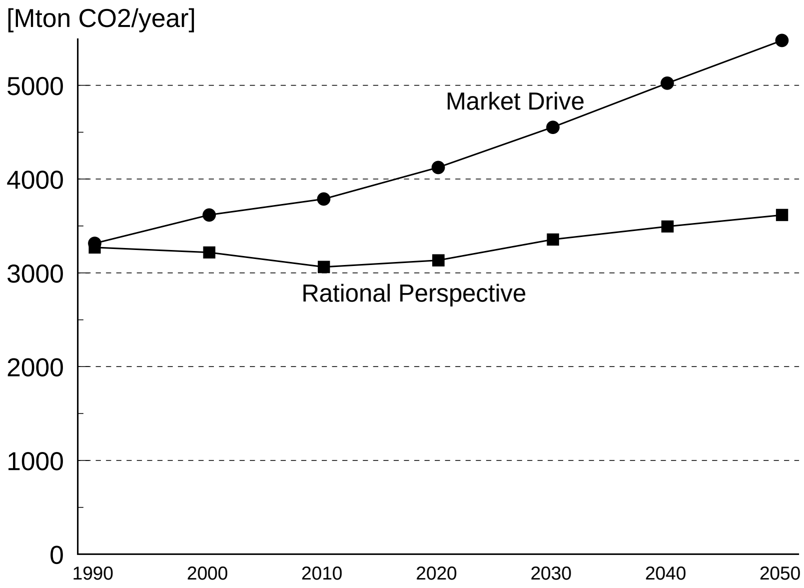
Both for nuclear power as well as for hydro, a pattern similar to the Market Drive scenario can be observed in Rational Perspective. Hydro supply remains almost constant in time, while the supply of nuclear power drops by the year 2030 to a level 50% below current nuclear production.

A large growth in the supply of biomass takes place in Rational Perspective between 2000 and 2010. This is sooner than in Market Drive, where the largest increase takes place between 2020 and 2030. The amount of biomass consumed for energy purposes by the year 2030, however, does not differ much between the two reference scenarios. Renewables such as wind turbines gain a much larger market share in Rational Perspectivethan in Market Drive. By the year 2030 the supply of renewables is 3 times higher in Rational Perspective. This is completely due to the difference in the assumed discount rates between the reference scenarios. As a result, investments in wind turbines onshore are cost-effective in Rational Perspective and not in Market Drive.

CO_2 emission levels in reference scenarios

The development of the CO_2 emissions between 1990 and 2050 is shown in Figure 4.3. As a result of the differences in the developments in the energy system, CO_2 emission levels differ also substantially. By the year 2010 CO_2 emissions have increased with almost 15% in Market Drive relative to the 1990 level, while they have dropped with 8% in Rational Perspective. In Rational Perspective the development of CO_2 emissions remains in line with the relatively constant historic CO_2 emission levels that occurred between 1970 and 1990. Emissions continue to increase in Market Drive. By the year 2040 CO_2 emissions in Market Drive amount to 5000 Mton CO_2.

Figure 4.3 CO_2 emissions in the reference scenarios between 1990 and 2050



4.3 Overview of sectoral results

This section gives general sectoral results. Detailed results for per sector can be found in three other reports: electricity generation [5], transport [6] and the building sector (residential and commercial) [7]. Results for the industry sector can be found in [11].

Market Drive

In the period 1990-2020 final energy consumption increases in Market Drive at an average rate of 1.1% per year (see Figure 4.4). After 2020 the rate of growth of final energy drops to 0.6% per year. Growth is relatively high in transport and in the commercial sector. The final energy consumption in these sectors more than doubles over the 60 years between 1990 and 2050. The share of the transport sector in total final energy use increases from 31% in 1990 to 40% in 2040. On the other hand, growth in agriculture and in the residential sector is relatively low and the relative shares of these sectors in final energy use drop. The share of industry in energy consumption decreases as well, from approximately 35% in 1990 to 30% by 2040/2050.

Figure 4.4 Final energy consumption per sector in the base case of the Market Drive scenario.

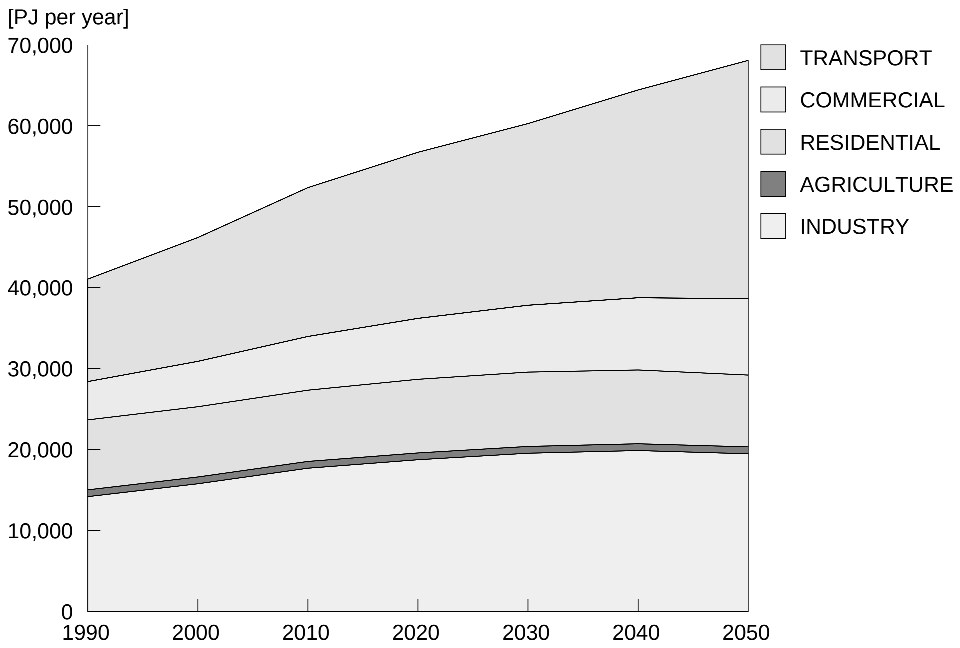
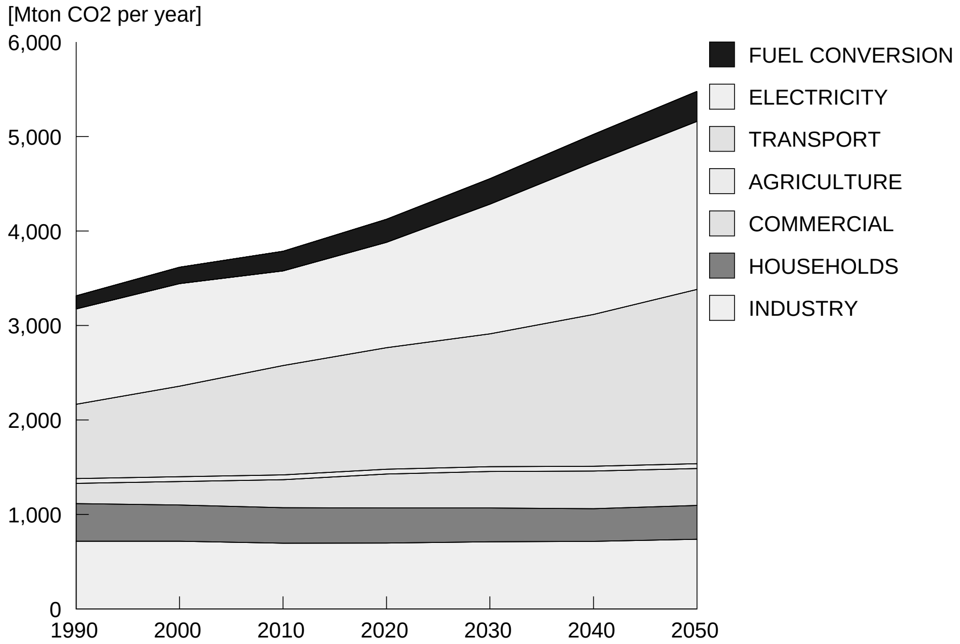


Figure 4.5 shows the emissions of CO_2 over time in the Market Drive scenario. Electricity generation and transport are the largest contributors to CO_2 emissions and these are also the sectors where the largest growth takes place. The growth in emissions from electricity generation occurs only after the year 2010. Before 2010 emissions from electricity generation decrease slightly. This is due to the expected decarbonization of electricity generation sources. Emissions from industry, households and agriculture remain constant. Emissions from the commercial sector and from fuel conversion (e.g. refineries) increase slightly.

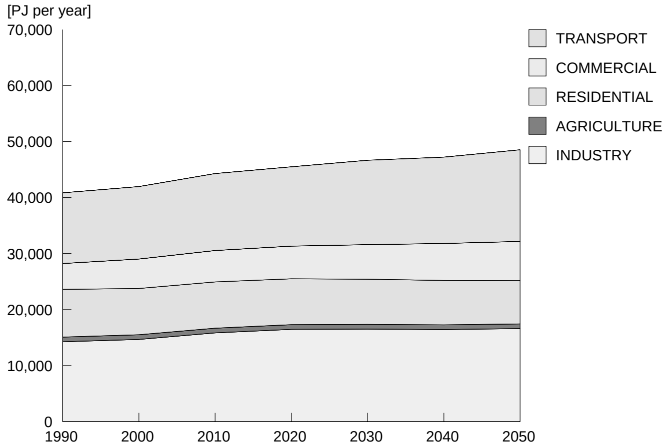
Figure 4.5 Sectoral CO_2 emissions per sector in the base case of the Market Drive scenario.



Rational Perspective

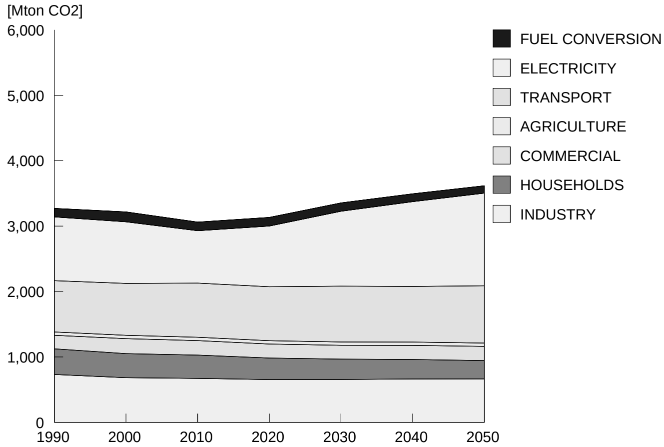
The growth in final energy use is much lower in the Rational Perspective scenario (see Figure 4.6). Final energy use in the year 2040 is only 16% higher than in 1990. The difference in growth with Market Drive is especially large for the transport sector with final energy use only increasing with 30% between 1990 and 2050. As a consequence, the share of transport in total energy consumption remains fairly stable with a level of 33% in 2040. The much smaller growth in final energy use for the transport sector results both from the lower demand projection and from the larger efficiency improvements in Rational Perspective. Growth in the commercial sector is in Rational Perspective also relatively high. The final energy consumption in 2050 is more than 50% higher than in 1990.

Figure 4.6 Final energy consumption per sector in the base case of the Rational Perspective scenario.



In the residential sector final energy consumption drops with 10% between 1990 and 2050 despite the projected growth in useful demand. The growth in demand for energy services in this sector is more than compensated by efficiency improvements. Energy conservation is especially large in space heating. Energy consumption in the industry sector increases slightly. The share of the industry in total energy consumption remains practically constant at 35%.

Figure 4.7 Sectoral CO_2 emissions per sector in the base case of the Rational Perspective scenario.

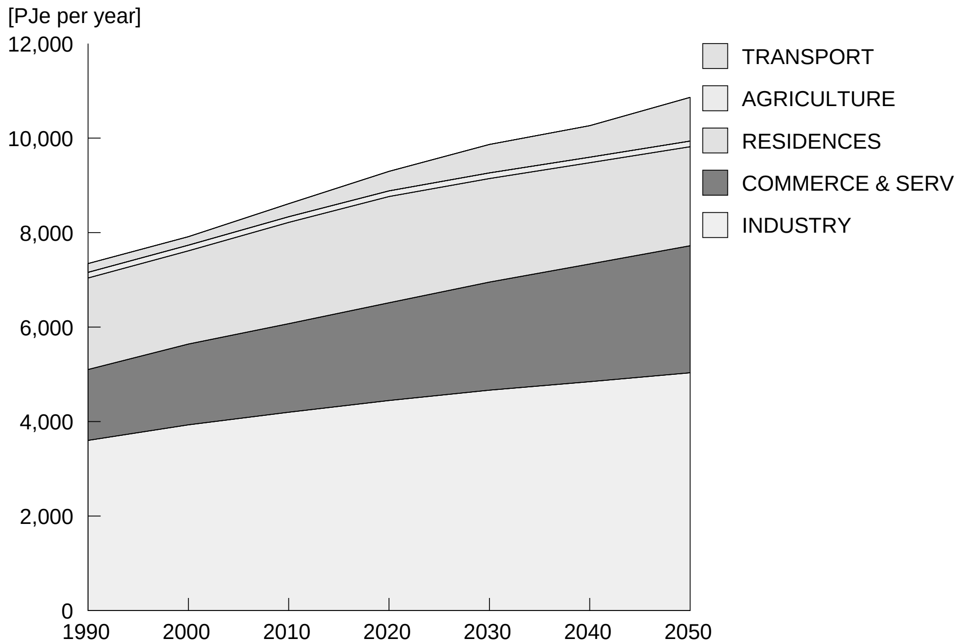


In general, the sectoral contribution to CO_2 emissions is similar for Market Drive and Rational Perspective except for the transport sector. The contribution of the transport sector to the growth in CO_2 emissions is much smaller in the Rational Perspective scenario than in Market Drive (see Figure 4.7 and compare with Figure 4.5). Other differences with Market Drive are the emissions from the commercial sector and from fuel conversion which remain constant in Rational Perspective while they increase slightly in Market Drive. Electricity generation is the largest source of CO_2 in the Rational Perspective scenario.

4.4 The role of electricity

Electricity consumption increases in both scenarios. Figure 4.8 shows electricity consumption per sector in the Rational Perspective scenario. Between 1990 and 2010 growth in electricity consumption is 0.8% per year. This is clearly below the growth that occurred over the last 10 years (2% per year). Between 2020 and 2050 growth in electricity consumption drops further to an average of 0.3% per year. This change in comparison with historic patterns is caused by saturation effects in energy demand and efficiency improvements. Substitution from fossil fuels to electricity or from electricity to fossil fuels plays a minor role. Some electric resistance heating is replaced by fossil fuels. Electric vehicles and electric heatpump have a very low penetration.
Growth in electricity demand occurs mainly in industry, the commercial sector and in the transport sector. Electricity consumption in Rational Perspective in the residential sector remains almost constant over time.

Figure 4.8 Electricity consumption by sector in the Rational Perspective scenario.



In Market Drive the early growth in electricity production is higher than in Rational Perspective. Electricity conservation options have a smaller penetration and demand levels for electric appliances are somewhat higher.

Important variables that determine the mix of power generation are the level of the interest rate and the fossil fuel price development. The interest rate is assumed to be low for Rational Perspective (5%) and high for Market Drive (15% for investments in power generation). A high interest rate is detrimental to capital intensive options. The increasing gas price (compared to the coal price) over time favours coal fired power, nuclear power, hydro power, and other renewables over gas fired power. However, in the medium term (until 2010/2020) the level of the gas price in both scenarios is low enough to favour gas fired power over competing options.

Figure 4.9 Electricity production by source in the Rational Perspective scenario.

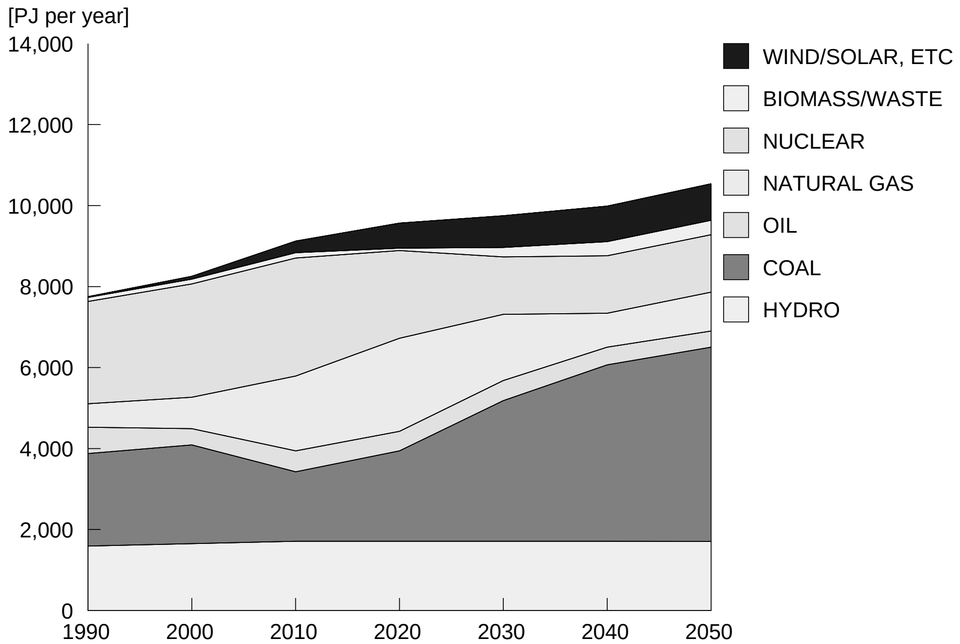


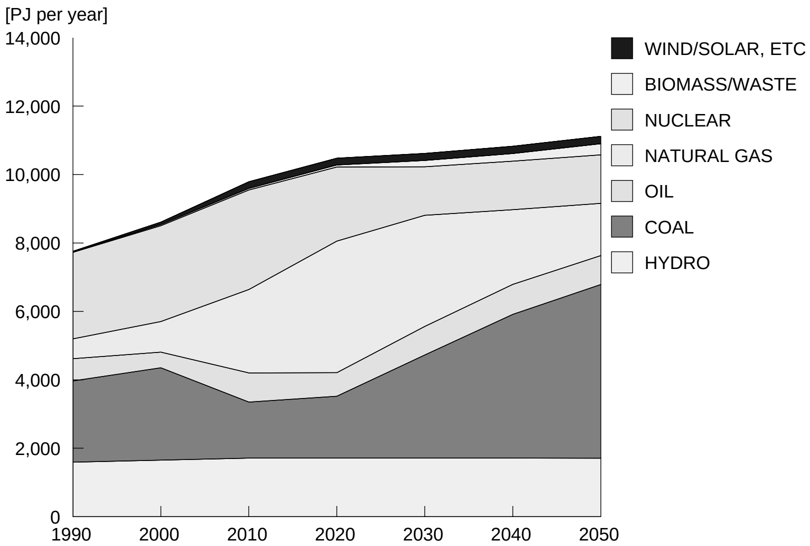
Figure 4.9 with electricity production by source clearly illustrates the trends that occur in the Rational Perspective scenario. The role of contribution of hydropower remains constant. Production of electricity from coal decreases between 2000 and 2010. At the same time electricity generation based on natural gas increases strongly. Power generation based on nuclear energy remains stable until 2010.

After 2010 nuclear based power generation starts to decrease. By the year 2030 nuclear generation has reached its assumed lower limit of 1400 PJ_e. After 2020 coal fired electricity generation increases strongly. This is caused by the occurring cost advantage of coal fired power generation over nuclear power and over gas based electricity. The largest role of natural gas in electricity generation is reached in the year 2020 (2300 PJ_e). As a result of the price competition with coal, electricity generation from natural gas decreases somewhat after 2020 but it keeps a substantial role which never drops below its 1990 share in power generation (8%).

Use of renewable energy other that hydro becomes significant around 2010, when onshore wind energy becomes competitive. The output of wind energy is substantial in 2050 (800 PJ_e). Biomass fuelled power is used to a somewhat smaller extent. The combined output of wind energy and biomass fuelled power is equivalent to 12% of total power production in 2050.

The high discount rate in the Market Drive scenario favours natural gas over coal. Indeed, the contribution of natural gas to power generation is substantially larger in the Market Drive scenario than in Rational Perspective. The maximum production of electricity from natural gas is reached in 2020 with 3800 PJ_e which is 65% higher than in the Rational Perspective scenario (see Figure 4.10).

Figure 4.10 Electricity production by source in the Market Drive scenario.



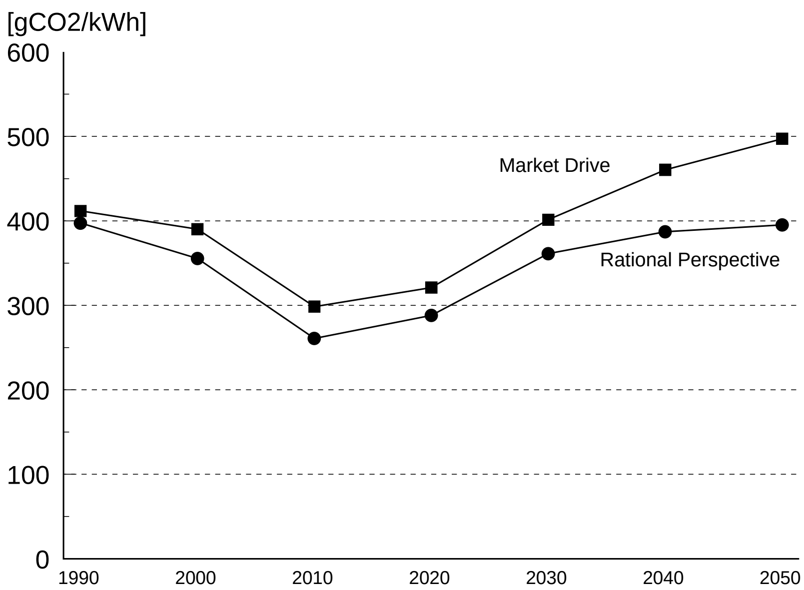
Coal fired power generation increases slightly more between 2020 and 2050 in Market Drive than in Rational Perspective.

Most renewables are not cost effective in the reference Market Drive scenario. Only biomass fuelled power shows about the same penetration as in scenario Rational Perspective; it becomes competitive in 2030, while in Rational Perspective penetration startes in 2010. Wind energy clearly suffers from the high interest rate of scenario Market Drive, as it is more capital intensive than biomass fuelled power. The share of renewables other than hydro in total power production is only 5% in 2050.

The role of electricity is becoming larger in both scenarios. The CO_2 intensity of electricity depends on the relative shares of the different sources for power generation and the efficiency of the power plants. Figure 4.11 shows how the CO_2 intensity, expressed as average CO_2 emissions per unit of electricity generation in Western Europe develops over time. The average CO_2 emissions per kilowatthour are higher in Market Drive than in Rational perspective. This is the net result of two counteracting effects. The electricity generation mix in Market Drive has an emphasis on low investment plants, thus, natural gas fired power plants (which have relatively low CO_2 emission levels for electricity generation) have a larger role than in Rational Perspective. On the other hand, the role for nuclear power, wind turbines and biomass (with virtually no CO_2 emissions) is smaller in Market Drive than in Rational Perspective. As a net effect, the CO_2 emissions per unit of electricity are higher in Market Drive than in Rational Perspective.

The two scenarios show a similar pattern over time. From 1990 to 2010 the CO_2 intensity drops with approximately 25%; this is mainly a result of the increasing role of natural gas but also a result of increasing efficiencies of power plants. However, after 2010 the CO_2 intensity of electricity increases again. By the year 2030 the CO_2 intensity of power generation is back at the 1990 level (400 gCO_2/kWh) in Market Drive and increases further to almost 500 gr/kWh in 2050. This is a result of the return of coal fired power generation. In Rational Perspective it takes 20 more years until the 1990 level is reached again.

Figure 4.11 Development of the average CO_2 emissions per kilowatthour (kWh) in the scenarios Rational Perspective and Market Drive.



4.5 Results for sectors and groups of technologies

This section gives some details on the scenario results of the main energy consuming sectors households, commercial and service sector, industry and transport. Results are also presented in this section about the contribution of renewables to the energy system. It is noted that further detailed technology results are not presented in this report; they can be found in the other MATTER study reports [5-7].

Residential sector

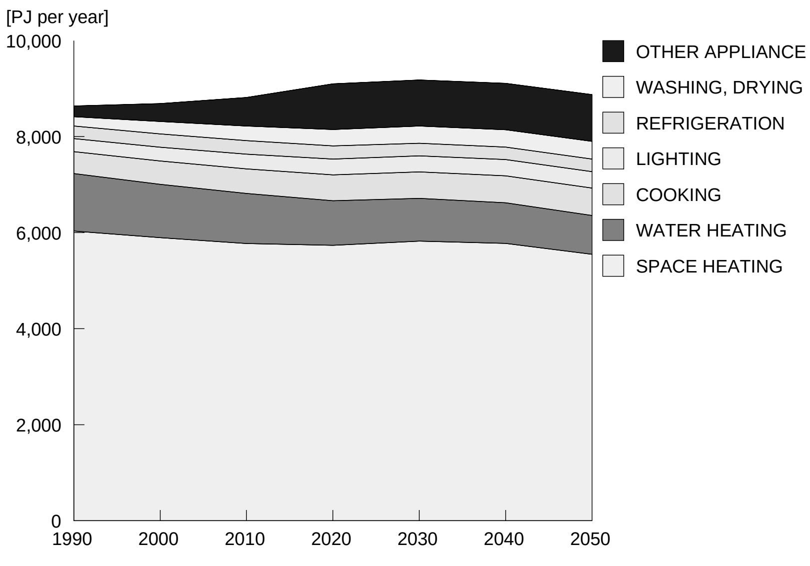
Figure 4.12 presents the development of final energy consumption per energy service in the residential sector in the Market Drive scenario. The almost constant total energy use in the residential energy will imply a change from historic development. It is noted that the resent historic growth of energy use (between 1970 and 1990) was slightly less than 1%.

Space heating accounts for three quarters of total energy consumption. Energy consumption for space heating remains almost constant in Market Drive. This is a net result of an increasing number of houses to be heated on one hand (volume effect) and on the other hand the shift towards new and thus better insulated houses (structure effect), increasing penetration of insulation of existing houses and more efficient boilers (energy savings effect).

Final energy demand for water heating drops considerably in Market Drive as a result of a shift toward more efficient water boilers, introduction of electric heatpump boilers and reduction of system losses of hot water production (e.g. losses from night storage of water and heat losses in hot water pipes inside the dwellings).

Total electricity consumption of the ‘traditional’ electric appliances such as refrigerators, washing machines, dish washers and wash dryers remains fairly constant as the growth in penetration of these appliances and efficiency improvements compensate each other. The energy demand for lighting remains constant as well. Compact fluorescent light bulbs (CFLs) penetrate but not for applications with low annual lighting hours. Energy consumption for other (not explicitly classified) electric appliances increases strongly until the year 2030 and then remains constant.

Figure 4.12 Development of final residential energy use per energy service in the household sector in scenario Market Drive.



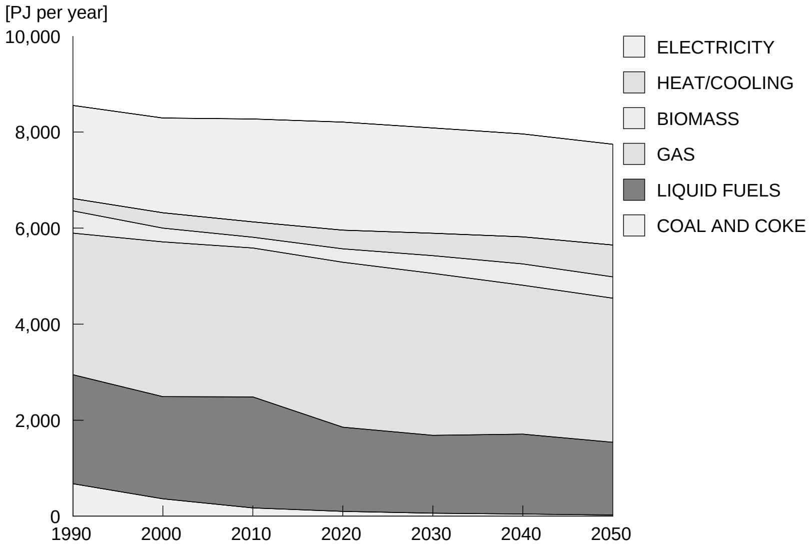
For Rational Perspective the development of energy consumption per residential energy service shows similarities with Market Drive. Two clear differences can be observed. Penetration of efficient electric appliances and CFLs is considerably higher than in Market Drive. This is a results of the lower discount rate for investment decisions about electric appliances in Rational Perspective. Total energy consumption for space heating in 2040 is about 10% less than in Market Drive as a result of a higher penetration of insulation and efficient (gas) boilers.

The net decrease in household consumption of fossil fuels can be seen from Figure 4.13. The reduction in fossil energy use mainly takes place for coal and oil products. This would imply a continuation of the recent historic developments (see also 2.4). The contribution of natural gas remains more or less constant. This implies that an increasing share of the dwellings is heated with natural gas. The reduction of fossil energy use mainly occurs in the middle part of Western Europe. North Europe has already a relatively high level of insulation. In South Europe insulation and efficient appliances are not so cost-effective.

Space heating and water heating based on heat from combined heat and power (CHP) production (both from large district heat systems and from small scale total energy heat systems) increase, although the contribution of CHP remains small.

Total electricity consumption of the residential sector remains constant in Rational Perspective. The growth in electricity use for new electric applications compensates the reduction of electricity consumption for space heating and water heating.

Figure 4.13 Development of final residential energy use per energy carrier in scenario Rational Perspective.

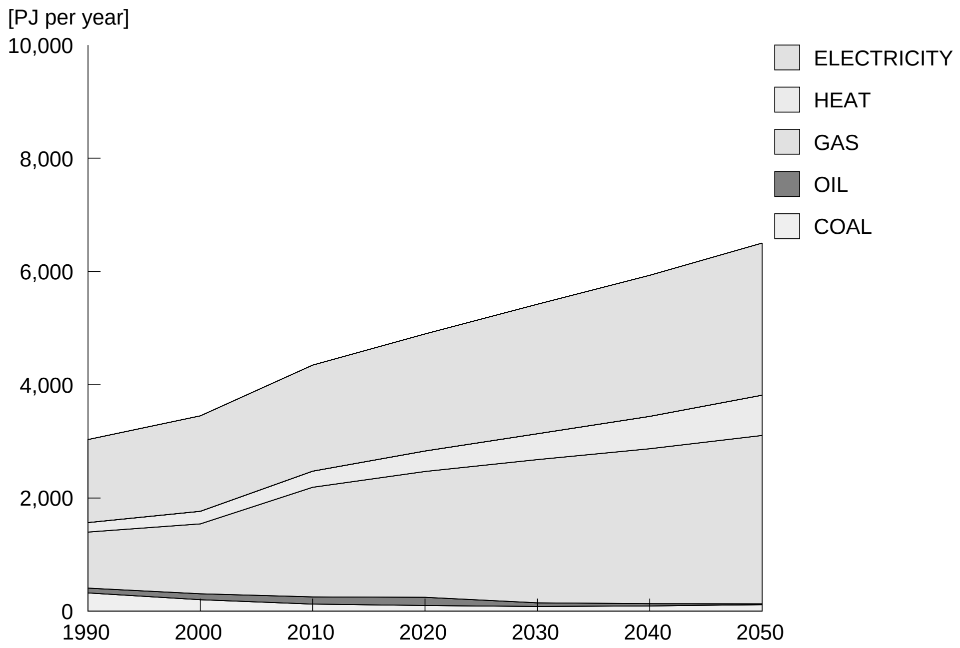


In contrast with Rational Perspective the consumption of fossil fuels remains almost constant in Market Drive. In Market Drive electricity consumption increases with 1.2% per year between 1990 and 2020. After 2020 electricity consumption remains constant.

Commercial and service sector

The development of energy use in the commercial sector differs substantially from the development of energy use in the residential sector. Total energy use increases significantly in the commercial sector both in Rational Perspective and in Market Drive while it remained almost constant in the residential sector. Figure 4.14 shows energy consumption per fuel in the commercial and service sector. Between 1990 and 2010 total energy use increases with 1.8% per year. After 2010 growth continues but at a lower rate. While the consumption of coal and oil products decreases, consumption of natural gas increases. Electricity consumption also increases significantly although electricity consumption for space heating purposes decreases over time.

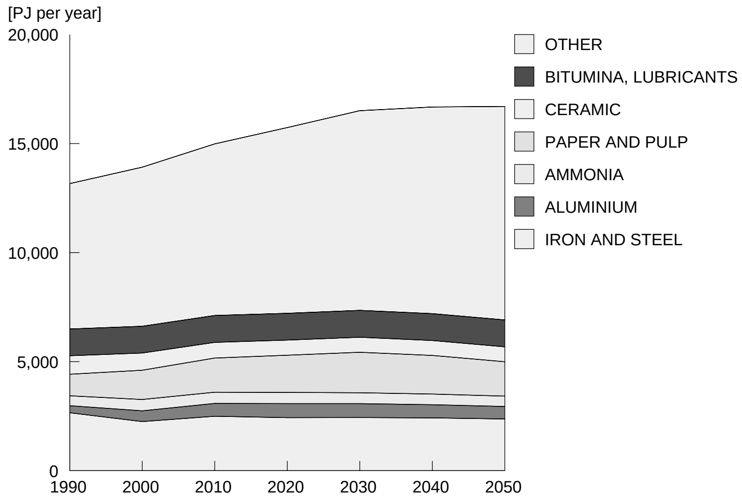
Figure 4.14 Development of final energy per energy carrier in the commercial and service sector in scenario Rational Perspective.



Industry sector

In the Market Drive scenario final energy use in the industrial sector shows a moderate increase until the year 2030 (see Figure 4.15) after which final energy use stabilises. The industrial sectors with a substantial growth are aluminium, paper production and other industries. Energy use remains fairly stable for iron and steel, ammonia and the ceramic industry.

Figure 4.15 Industrial energy demand per subsector in Market Drive.



Final energy use in the industrial remains even more constant in the Rational Perspective scenario (Figure 4.16) than in Market Drive. With the very modest growth of 0.2% per year the final energy use in Market Drive appears to be a continuation of historic trends (Figure 2.3).

Figure 4.16 Development of final energy consumption in industry in scenario Rational Perspective.

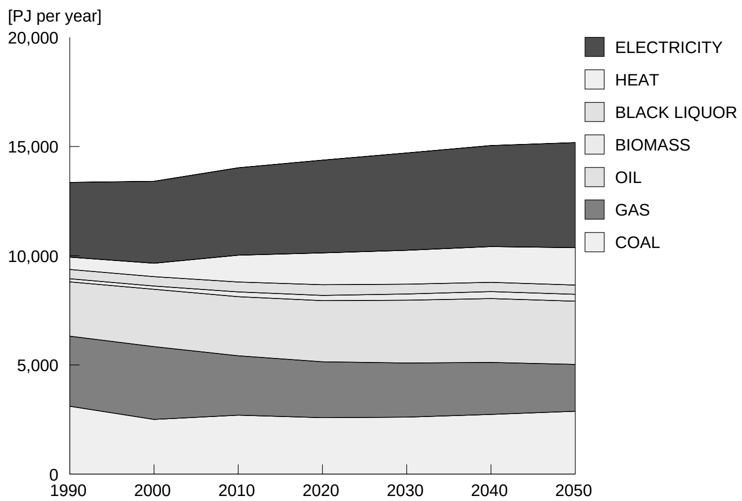


Figure 4.16 shows that the use of coal and natural gas will drop in Rational Perspective. Industrial oil consumptions remains constant. The use of electricity and (waste) heat will increase.

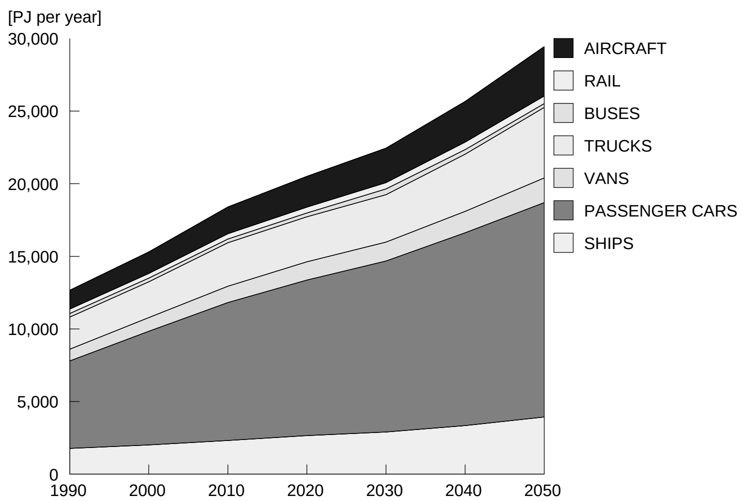
Transport sector

The largest difference between Rational Perspective and Market Drive occurs in the development of energy use in the transport sector. Growth in energy consumption for transport is very high in Market Drive. By the year 2050 it amounts to about 30 EJ which is twice as much as in Rational Perspective. This large difference is caused by two reasons:

- transport demand is assumed substantially higher in Market Drive;
- the penetration of efficient vehicles stagnates in Market Drive while the total car fleets moves to increasingly efficient vehicles in Rational Perspective.

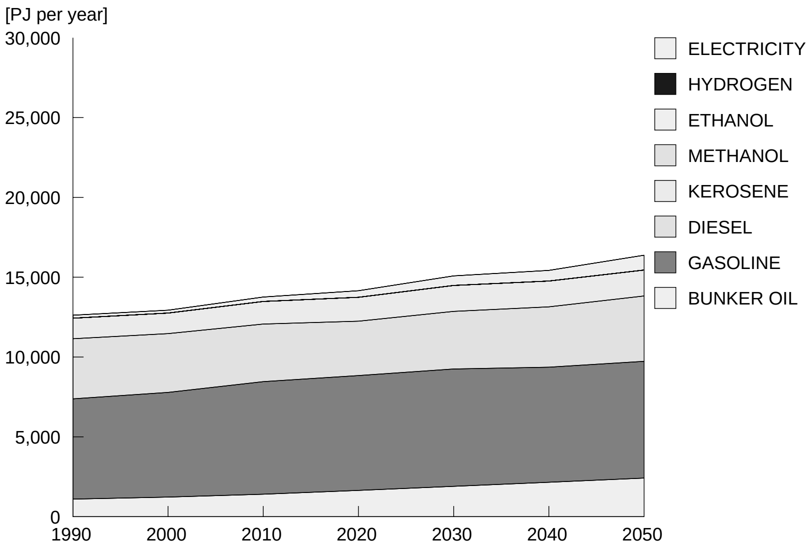
Figure 4.17 shows energy consumption per mode of transport in Market Drive. The increases in energy demand for passenger cars, trucks and aircraft are very large. Growth is moderate for internal navigation buses and rail.

4.17 Development of final energy consumption per mode of transport in Market Drive scenario.



Significant changes in the transport fuel mix occur neither in Market Drive nor in Rational Perspective. Figure 4.18 shows final energy consumption per mode of transport. Alternative transport fuels are too expensive in comparison with oil products. Electric vehicles are not introduced. Figure 4.18 also illustrates how much lower final energy consumption is for Rational Perspective than for Market Drive (compare the total with the total of figure 4.17).

Figure 4.18 Development of transport energy consumption per energy carrier in the Rational Perspective scenario.



Renewable sources

The growth in the role of renewables in the Market Drive scenario is limited (see Figure 4.19). Its share in total primary energy use amounts to 8% by the year 2050. Hydro power remains the most important renewable source. The production of biomass for energy purposes increases after the year 2020. The biomass is used for electricity production and for heating in industry and the residential and commercial sector. Wind turbines have a very small role. With the high energy pay back requirements in Market Drive wind turbines are not cost effective. The limited penetration of wind in Figure 4.19 represents the assumed lower bound for the penetration of wind turbines.

Figure 4.19 Energy from renewable sources in the Market Drive scenario.

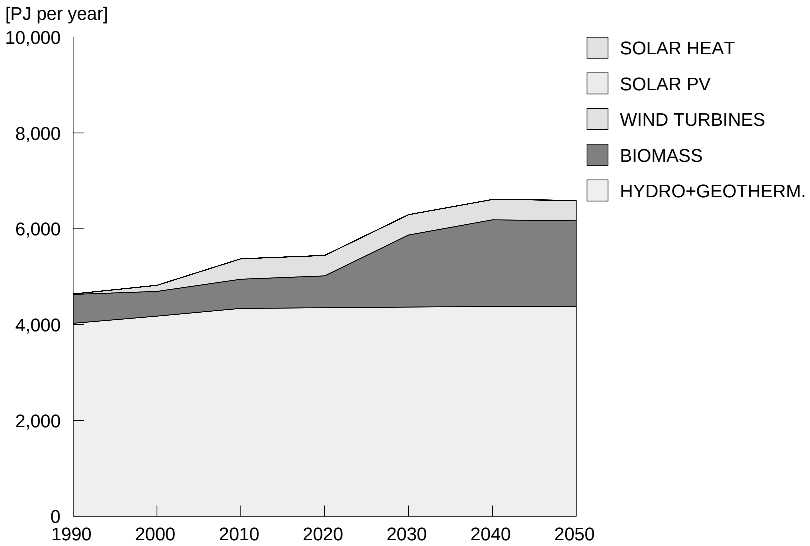
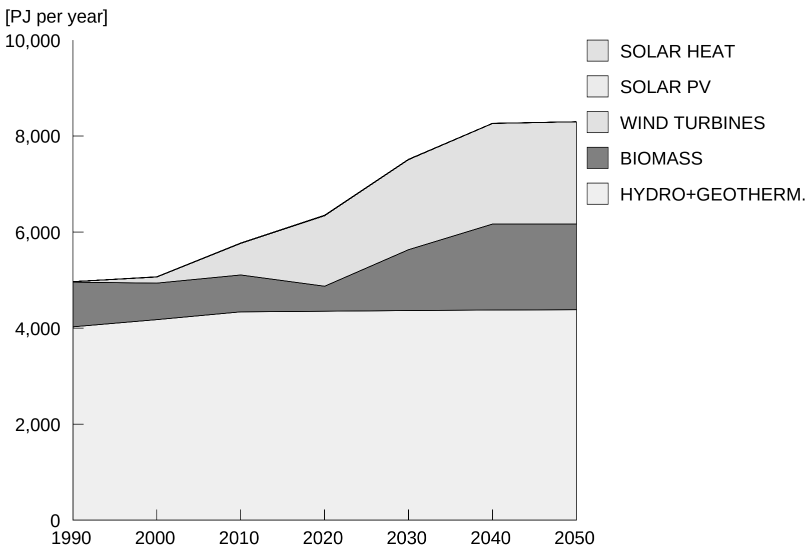


Figure 4.20 Energy from renewable sources in the Rational Perspective scenario.



In Rational Perspective the role of renewables is larger than in Market Drive. This is mainly due to the much higher penetration of wind turbines. Onshore wind turbines are a cost-effective energy technology in Rational Perspective and reach a substantial penetration level. The reason that wind turbines are cost effective in Rational Perspective and not in

Market Drive is the fact that a lower discount rate is applied in Rational Perspective. Due to the fact that total primary energy requirements are less in Rational Perspective than in Market Drive the share of renewables in TPER amounts to 15%.

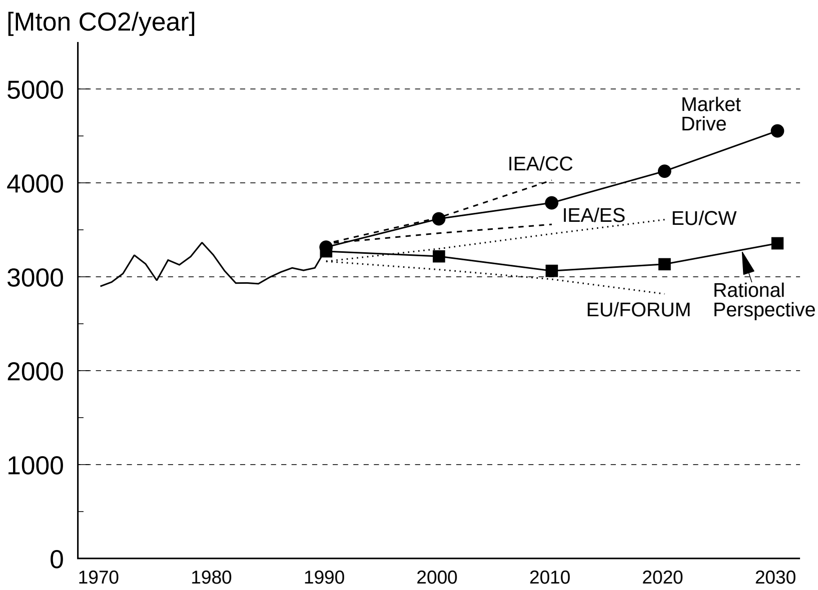
4.6 Comparison with results of other scenarios

Other recent energy scenarios for Western Europe or the European Union, although with a shorter time horizon than the one presented in this study, can be found in the World Energy Outlook [12] and in 'European energy to 2020' [4] for DGXVII. The World Energy Outlook has a time horizon until 2010; the time horizon of the DGXVII study is 2020. It is worthwhile to briefly compare the results of the scenarios to identify differences and similarities. It is noted that differences exist in modelling approach and in the exogenous scenario assumptions.

It is noted that the geographical scope of the present scenario also study differs slightly both from the World Energy Outlook and the study for DGXVII. The World Energy Outlook considers OECD Europe, thus also including Turkey. The DGXVII study contains the 15 Member States of the European Union and is therefore not including Norway and Switzerland.

Figure 4.21 shows the development of CO_2 emissions. The IEA scenario 'Capacity Constraints' has the highest level of CO_2 emissions. This is partly due to the different geographical scope and partly because final energy demand grows more than in the other scenarios due to relatively little efficiency improvements. The scenarios of the present study fall within the range of the other scenarios although the Market Drive scenario is found at the top end of the range and the Rational Perspective scenario at the bottom end. This is according to our expectations. The Rational Perspective scenario is a prescriptive least cost energy scenario. The models used for the World Energy Outlook and for 'European energy to 2020' are in general more descriptive than MARKAL with the final energy use projections not being optimized but being based on historic relationships. The Market Drive scenario is closer to the World Energy Outlook and 'European energy to 2020' due to the sectoral specific discount rates.

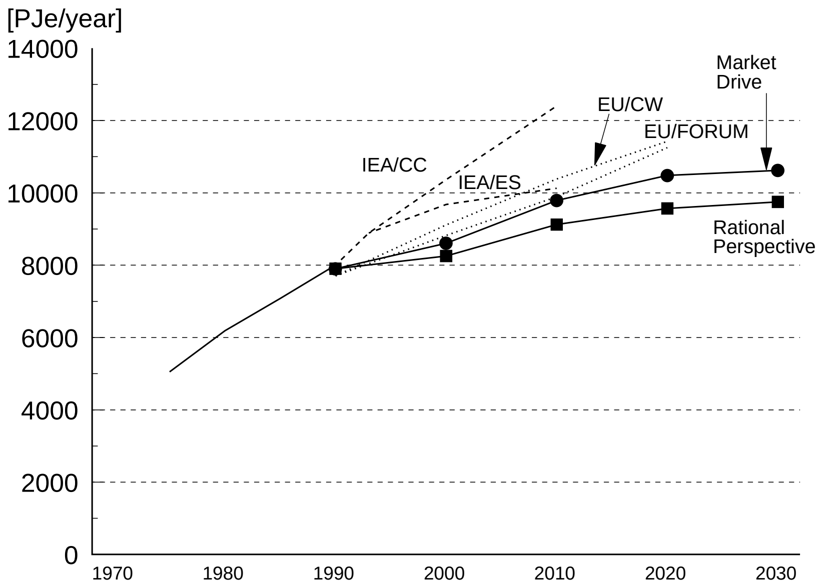
Figure 4.21 Development of CO_2 emissions in Western Europe according to various scenario studies.



The level of CO_2 emissions is a result of total energy requirements and the relative shares of the different fuels. It is noted that both Market Drive and Rational Perspective tend in the base case more towards a returning role for coal while such shifts are hardly observed in the scenarios of World Energy Outlook and 'European energy to 2020'.

A second and last comparative picture is Figure 4.22 which shows the level of electricity production in Western Europe according to various scenarios. The scenarios Market Drive and Rational Perspective project electricity production levels below the levels of electricity generation in the other scenario studies. Although most of the scenarios in World Energy Outlook and 'European energy to 2020' also project the growth in electricity consumption to decrease, this occurs sooner and more obvious in the scenarios of the present study. Since the total level of energy use of the scenarios is similar the explanation must be that the present study expects electrification to saturate sooner than the other studies assume. It is difficult to judge which projection is more correct. The main cause is probably in the approach of demand estimation. The World Energy Outlook and 'European energy to 2020' forecast energy demand from econometric relationships. The present study explicitly considers all end-uses identifying limits to penetration as a result of saturation effects. It is noted that with increasing limits for the emissions of CO_2, the consumption of electricity will increase in Market Drive and in Rational Perspective (see Section 5.4).

Figure 4.22 Development of total electricity production in Western Europe according to various scenario studies.



5. RESULTS OF CASES WITH CO_2 REDUCTION

5.1 Main results

The future CO_2 emissions from the energy system have been forced downward by including taxes on the CO_2 emissions in the MARKAL model. Including CO_2 emission penalties results in changes in the energy system relative to the baseline scenarios to limit the CO_2 emissions. The changes in the energy system imply different investment choices for energy technologies and different operational choices for the utilisation of energy technologies.

Four different levels of CO_2 taxes have been considered. In all cases the taxes start by the year 2010 and reach the ultimate level in the year 2020. The tax levels are shown in Table 5.1.

Table 5.1 Taxes on emissions of CO_2 in various CO_2 abatement cases.

	CO_2 Tax level [ECU/tCO_2]	
	2010	2020-2050
A	10	20
B	25	50
C	50	100
D	100	200

The 20 ECU per ton tax on CO_2 emissions is equivalent to an increase in the oil price with 10.5 ECU per barrel (1.5 ECU per GJ). The corresponding increase in the coal price is larger (1.9 ECU per GJ) and it is less for natural gas (1.1 GJ per GJ). The relative shares of coal and natural gas change as a result of the change in the price ratio. Natural gas becomes more competitive in comparison with coal. It is noted that the high tax levels are outside the range of cost levels that are currently considered by CO_2 mitigation policy. However, it is not impossible that such cost levels will be required to meet environmental objectives.

The CO_2 reduction scenarios differ substantially from the two base case scenarios. Some main messages that emerge from the results are listed below. Detailed results of the calculation are given in the successive sections. Main messages from the CO_2 abatement calculations are:

- The emissions of CO_2 can be significantly abated in comparison with both base cases.
- The level of emission reduction relative to the 1990 emission level depends strongly on the scenario background and the availability of supply technologies which have low CO_2 emission levels.
- The Market Drive scenario needs a 100 ECU/tCO_2 emission tax to keep the emissions at the 1990 emission level.
- In the Rational Perspective scenario the emissions can be reduced significantly in comparison with historic emissions (40% reduction with a tax of 100 ECU/tCO_2 and 60% with a tax of 200 ECU/tCO_2).
- Abatement of CO_2 emissions implies significant changes in the supply mix of Western Europe.
- Emission reduction is most difficult in the transport sector.
- Oil consumption decreases slightly under CO_2 emission reduction, however, oil remains the most important fossil fuel
- The role of coal diminishes with drastic emission reduction targets.
- Natural gas becomes more important with medium emission reduction levels. With more drastic CO_2 emission reduction the contribution of natural gas decreases again.
- Energy efficiency improvements, substitution between fossil fuel, nuclear energy and renewables contribute to long term emission reduction.
- In general, energy efficiency improvements have the largest contribution to the reduction of CO_2 emissions, especially in Market Drive. The contribution of this option continuously increases with time and with increasing tax levels.
- Substitution between fossil fuels is cost-effective at low CO_2 taxes (20 ECU/tCO_2) and has a significant contribution to long term CO_2 reduction. The potential of this option becomes already largely utilized at low tax levels.

- Nuclear power becomes cost-effective at low CO_2 tax levels (around 20 ECU/tCO_2). As a result of the assumed limitations for the potential, the contribution to CO_2 reduction is limited to 200 Mton CO_2.
- Renewables contribute little to CO_2 reduction at low CO_2 tax levels. However, with high CO_2 tax levels, renewables have a large share in emission reduction.
- With CO_2 abatement, the electricity sector becomes much less CO_2 intensive.
- With a 50 ECU/tCO_2 emission tax in the Rational Perspective scenario, 75% of electricity generation is non-fossil. Half of the electricity generation is based on renewables, one quarter is nuclear energy.
- The average CO_2 emission intensity of electricity generation drops with 70 to 80% compared to the baseline.
- Electricity replaces fossil fuels in several end-uses under CO_2 abatement.
- The cost of CO_2 emission abatement increase non-linearly with increasing CO_2 emission reduction levels.
- The direct cost of emission reduction involve the cost of technologies, interest, operation and maintenance and fuel cost. The direct annual cost dependd very much on the baseline scenario.
- To stabilize the CO_2 emissions in 2040 relative to the Market Drive scenario the cost amounts to 80 billion ECU. To stabilize CO_2 emissions relative to the Rational Perspective scenario, the cost is 4 billion ECU in 2040.

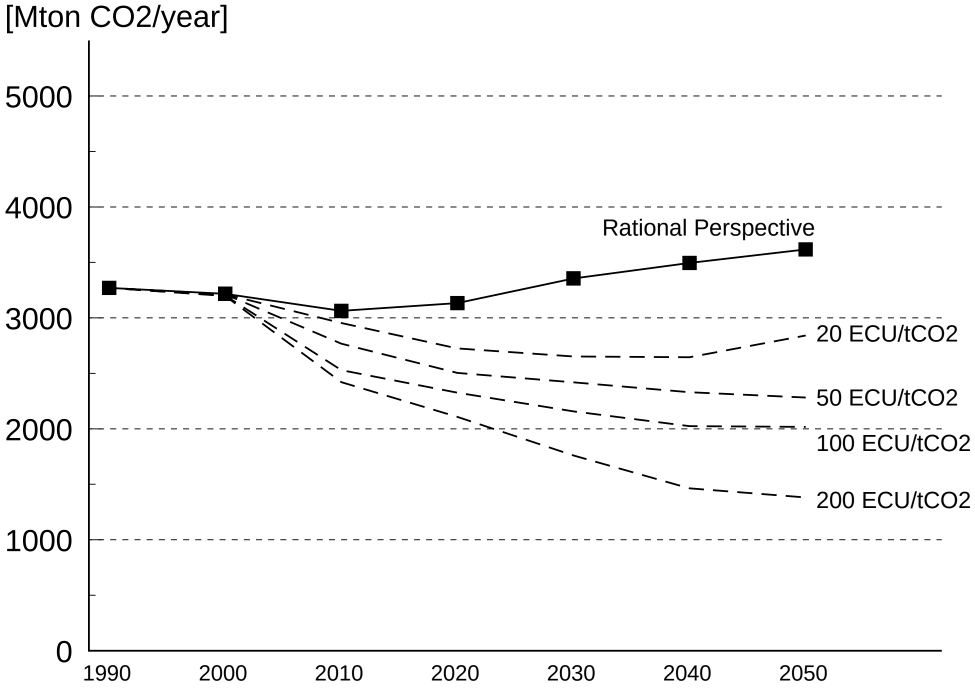
5.2 Primary energy mix and CO_2 emissions

CO_2 emissions

As one could expect, the emissions of CO_2 decrease with increasing levels of CO_2 penalties. Figure 5.1 shows the CO_2 emissions with the various tax levels relative to the Rational Perspective scenario.

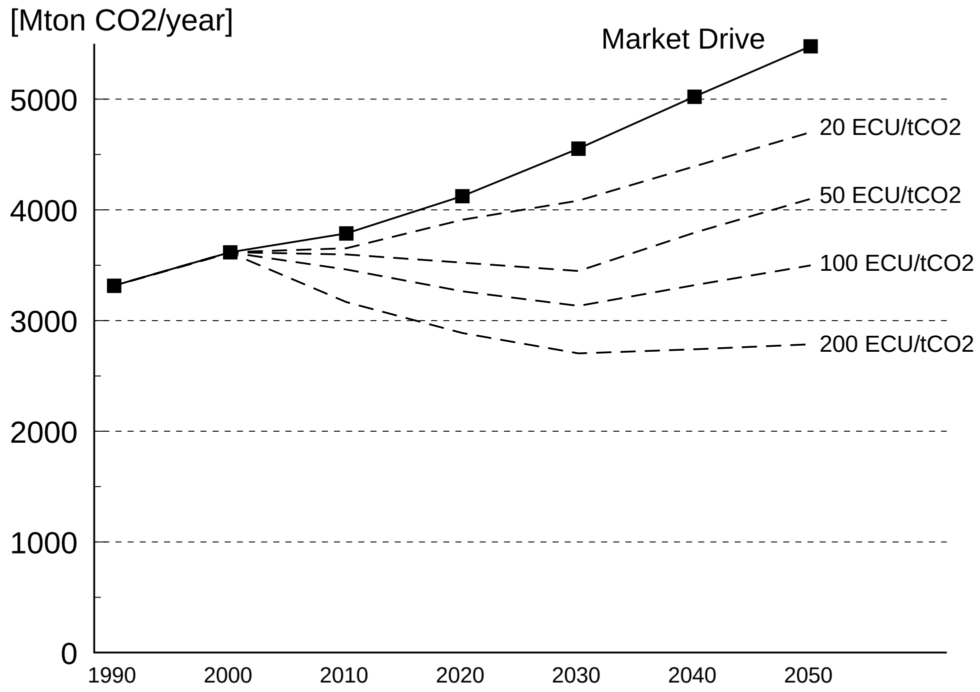
The 20 ECU per ton CO_2 tax is already sufficient to keep the CO_2 emissions below the 1990 emission level. In 2010 the CO_2 emissions are precisely 10% lower than the emissions in 1990. By the year 2040 the CO_2 emissions amount to 2650 Mton CO_2. This is 19% less than the 1990 emission level.

Figure 5.1 CO_2 emissions in the Rational Perspective scenario.



With the 50 ECU per ton CO_2 tax the CO_2 emissions are reduced to slightly over 2300 Mton CO_2. With a 100 ECU/tCO_2 tax the CO_2 emissions amount to slightly over 2000 MTon CO_2. This is equivalent to an emission reduction of almost 40% in 2040 and 2050 in comparison with the 1990 emission level. With the highest CO_2 tax (200 ECU/tCO_2) the emission are reduced to about 1460 Mton in 2040 (55% emission reduction).

Figure 5.2 CO_2 emissions in the Market Drive scenario.

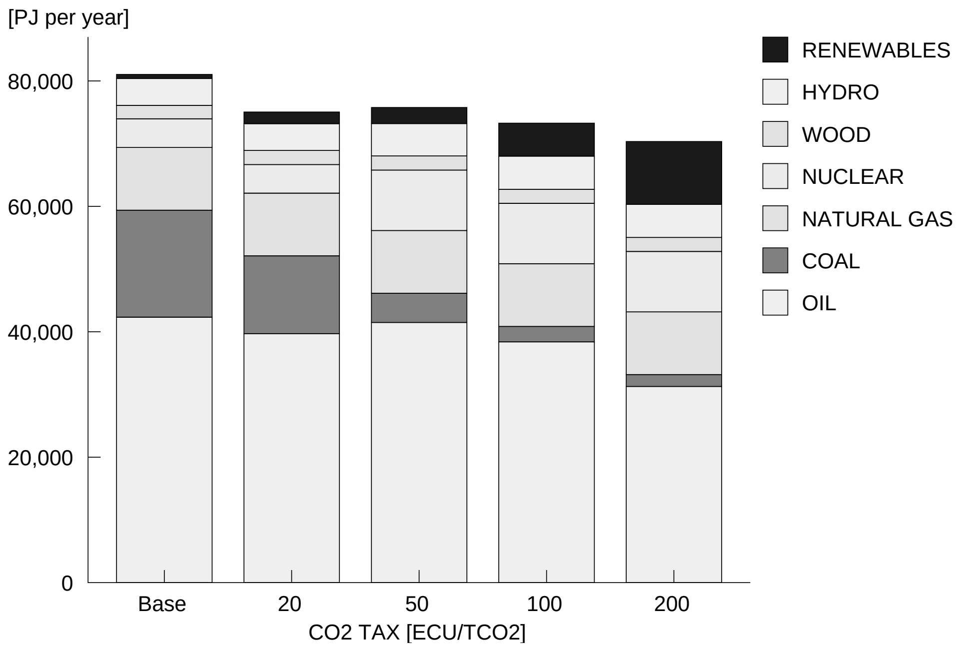


The emission reduction that is achieved in Market Drive in comparison with the base case is similar to Rational Perspective (see Figure 5.2). The emission reduction compared to the 1990 emission level is much less. A 100 ECU/tCO_2 tax is required to stabilize the CO_2 emission at the 1990 emission level. With the highest emission tax the CO_2 emissions are reduced with only 14% compared to the 1990 emission level.

Primary energy mix

Figure 5.3 shows the primary energy demand in the year 2040. Each stacked bar shows the primary energy mix at a different CO_2 tax level. In the Market Drive scenario the primary energy mix changes gradually with increasing CO_2 taxes. With a carbon tax of 20 ECU/tCO_2 total primary energy drops with 8% compared to the base case. Coal consumption is already significantly reduced at this tax level. The contribution of natural gas remains the same as in the base case as the total use of natural gas is constrained in Market Drive. The contribution of renewables increases slightly.

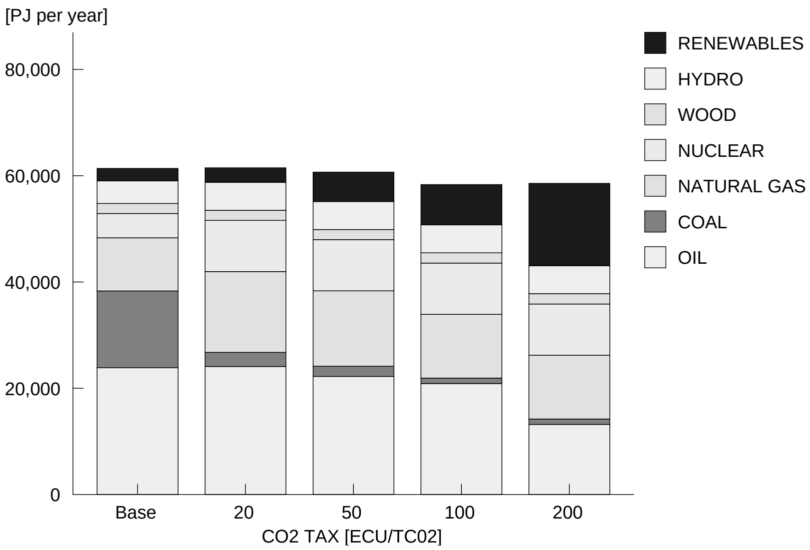
Figure 5.3 Primary energy demand in the Market Drive scenario in 2040 with increasing CO_2 tax levels.



With a 50 ECU/tCO_2 tax the role of coal decreases much further and it becomes substituted for by nuclear power, hydro and renewables. Nuclear power generation reaches its upper bound at this tax level. Total primary energy requirements increase with the step from a 20 ECU/tCO_2 tax towards a 50 ECU/tCO_2 tax. This is mainly a result of the shift towards nuclear power. The primary energy equivalent of nuclear power is calculated with a generation efficiency of 40%. This is lower than the efficiency of the coal fired power plants in 2040 that are substituted for which causes an *increase* of total primary energy requirements.

With further increasing CO_2 taxes, total primary energy requirements decrease and fossil fuels are further substituted for by renewables. Renewables amount to 30% of total primary energy requirements at a tax level of 200 ECU/tCO_2. The role of coal in the energy mix is very small at the high tax levels. Oil consumption decreases substantially with a tax of 200 ECU/tCO_2. The role of natural gas remains constant.

Figure 5.4 Primary energy demand in the Rational Perspective scenario in 2040 with increasing CO_2 tax levels.



In the Rational Perspective scenario larger changes in the primary energy mix occur at a 20 ECU/tCO_2 tax than in Market Drive with this tax (see Figure 5.4). More than 80% of coal consumption in the base case is replaced by natural gas and nuclear power. The changes for the other primary energy sources are less significant. Hydro supply and renewables increase slightly. Oil consumption remains constant.

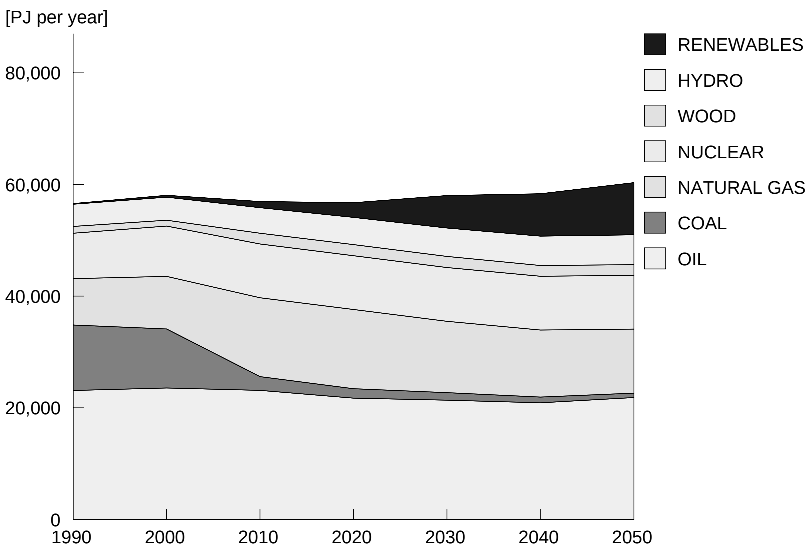
With a 50 ECU/tCO_2 tax, the role of new renewables increases substantially. Further, natural gas consumption and oil consumption decrease somewhat.

Total primary energy use is 6% lower at a 100 ECU/tCO_2 tax . Oil and gas consumption have dropped a little further and renewables have become more important.

The contribution of renewables is again significantly higher with a 200 ECU/tCO_2 tax. Renewables replace oil products at this tax level.

For one of the CO_2 abatement scenarios (Rational Perspective with a 100 ECU/tCO_2 tax) the development of primary energy over time is shown in Figure 5.5. The figure shows that the large changes within the fossil fuel mix already occur between 2000 and 2010. Coal is then replaced by natural gas. Nuclear power maintains a contribution equivalent to the contribution in 1990. It is noted that in the baseline the role of nuclear would drop between 2010 and 2030. The large introduction of new renewables, however, only starts after the year 2020. Thus, three phases in the CO_2 reduction strategy can be distinguished. In the first phase natural gas and energy conservation are the two main CO_2 reduction options. In the second phase (after 2010) nuclear power is responsible for most CO_2 emission limitation. In the third phase (after 2020) new renewables are the main CO_2 reduction option.

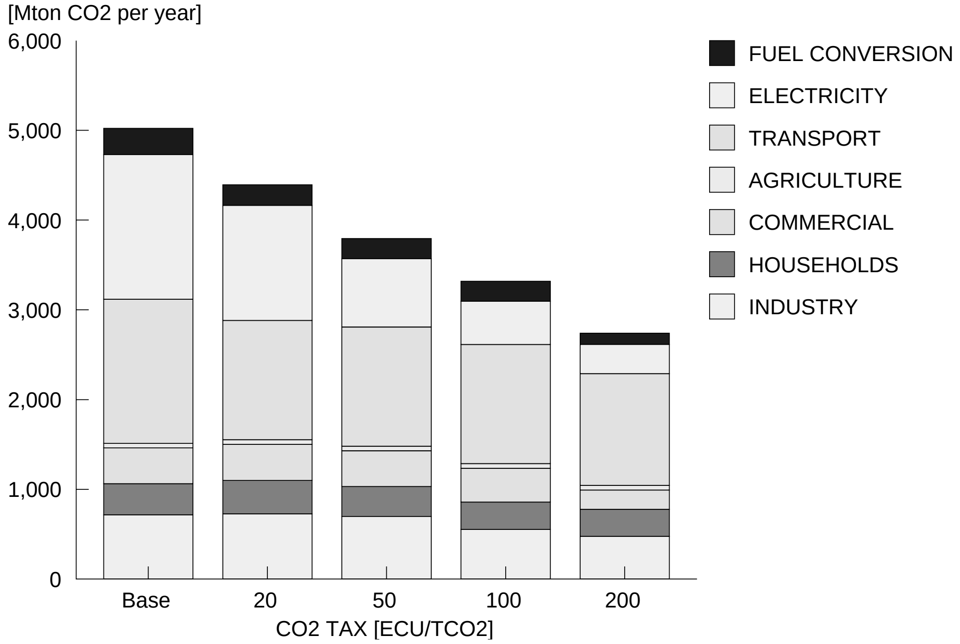
Figure 5.5 Development of primary energy demand over time in the Rational Perspective scenario with a CO_2 tax of 100 ECU/tCO_2.

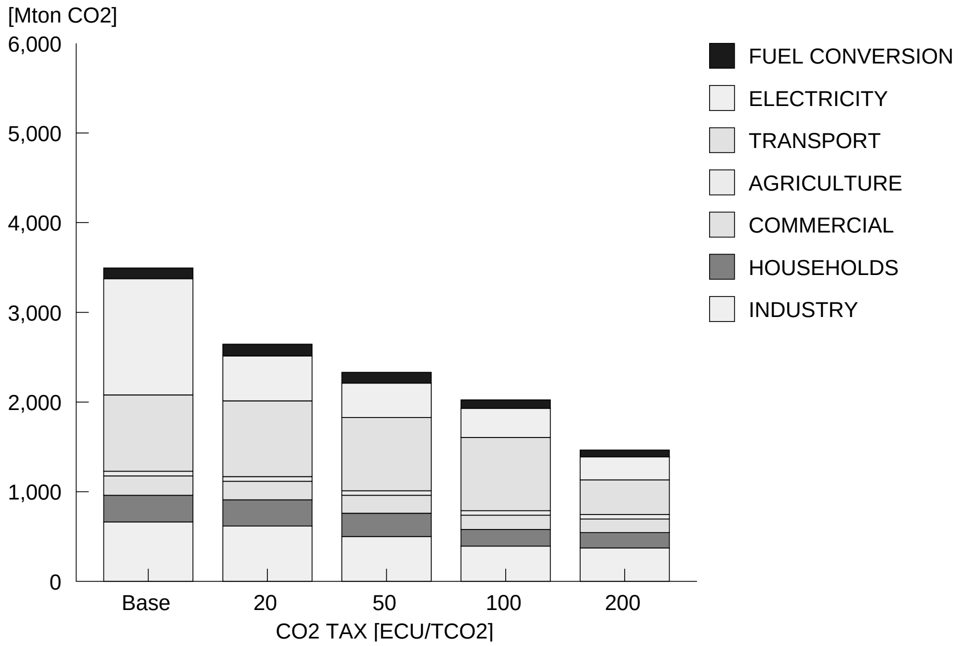


5.3 Overview of sectoral results

The energy consuming sectors respond differently to a tax on the CO_2 emissions. The CO_2 emissions from electricity generation are substantially reduced (more than 75% compared to the baseline) both in Market Drive and in Rational Perspective with increasing CO_2 taxes, as can be seen from Figure 5.6. In the electricity generation sector there are many different alternatives for power generation and by the year 2040 it is possible to drastically change the mix of electricity technologies at limited cost. In the Rational Perspective scenario CO_2 emissions from the industry sector, fuel conversion (refineries), households and the commercial and service sector can be reduced with typically 40% in comparison with the baseline CO_2 emissions. In Market Drive, however, the CO_2 reduction relative to the baseline is around 50% for the commercial sector and for fuel conversion, while it is 35% for industry and only 15% for the residential sector. For the residential sector, this difference between the scenarios mainly results from the higher energy pay back requirements assumed for Market Drive. The CO_2 emissions from fuel conversion were substantially higher in the baseline of Market Drive than in Rational Perspective. Therefore, more emission reduction can be achieved in Market Drive under CO_2 emission taxes.

Figure 5.6 Sectoral CO_2 emissions per sector in 2040 in the Market Drive scenario (top) and in the Rational Perspective scenario (bottom) with increasing CO_2 tax levels.





In the transport sector the situation is quite different. CO_2 emissions appear difficult to abate. In the Market Drive scenario part of the technical potential for efficiency improvements (20% reduction) is utilized with a 20 ECU/tCO_2 tax. With increasing CO_2

taxes the CO_2 emission from transport are not further reduced. In the Rational Perspective scenario CO_2 emissions are only reduced by 5% with a tax of 100 ECU/tCO_2 as the potential for efficiency improvements was already largely taken up in the base case. Drastic reduction of CO_2 emissions from the transport sector is expensive. A 200 ECU/tCO_2 tax is required to substitute gasoline and diesel by alternative fuels such as electricity.

The emissions in individual sectors are not only reduced further in Rational Perspective than in Market Drive, CO_2 emission reduction occurs also at lower CO_2 taxes than in Market Drive. A substantial emission reduction can be observed in industry in Rational Perspective at a 50 ECU/tCO_2 tax. In Market Drive a 100 ECU/tCO_2 tax is required before this stepwise emission reduction occurs in industry.

5.4 The role of electricity

The results for the electricity sector are briefly discussed here. A more extensive discussion of the results for electricity generation can be found in [5].

Electricity consumption *increases* with higher levels of carbon taxes in both scenarios. The carbon taxes induce changes at the demand side of the energy system where fuels are replaced by electricity e.g. for electric heatpumps, industrial processes and electric cars. The extra introduction of electricity conservation options in comparison with the baseline is only marginal in Rational Perspective.

Figure 5.7 Electricity production by source in the Market Drive scenario in 2040 with increasing CO_2 tax levels.

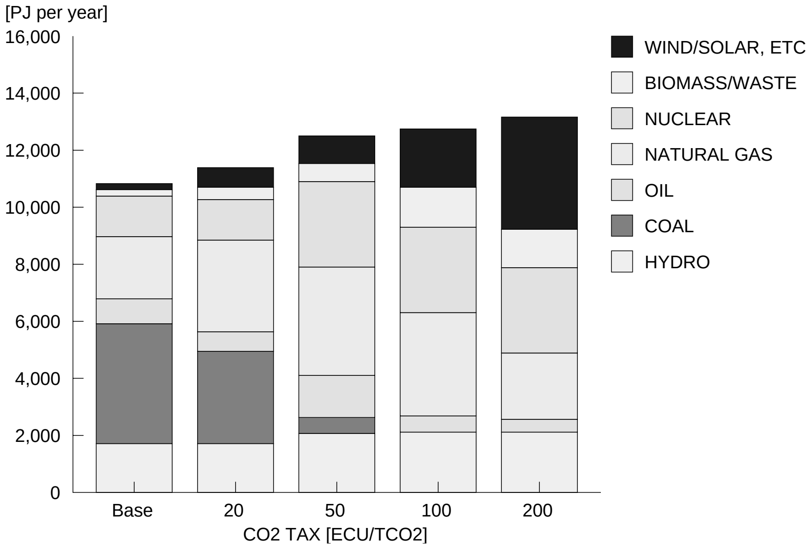
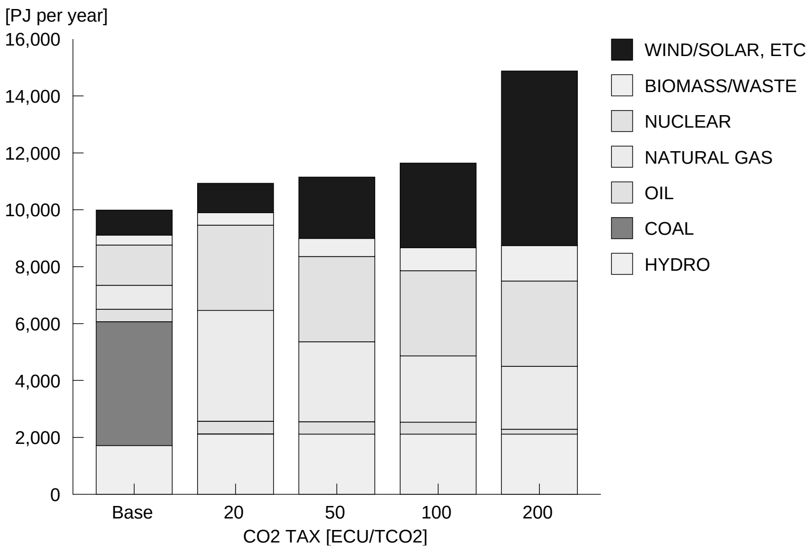


Figure 5.7 shows electricity production in the year 2040 for increasing CO_2 tax levels. The contribution of the different power generation technologies are discussed subsequently. Electricity generation from hydro power increases up to its maximum level at a CO_2 tax of 50 ECU/tCO_2. Coal fired electricity generation drops drastically with increasing CO_2 taxes. At a 50 ECU/tCO_2 tax electricity generation from coal is only 20% of the base case level and at a 100 ECU/tCO_2 tax coal fired electricity has completely disappeared. At a 50 ECU/tCO_2 tax level electricity production from oil has doubled in comparison with the baseline generation level. With further increasing CO_2 taxes the production of electricity from oil products decrease again to levels below the base case electricity generation level. With modest CO_2 taxes electricity generation from natural gas is considerable higher than in the base case. Electricity generation from natural gas is the highest at a 50 ECU/tCO_2 tax. With further increasing CO_2 taxes the use of natural gas fired electricity technologies decreases again. The natural gas is then used for other applications, e.g. in industry. Nuclear power becomes cost-effective at a CO_2 tax of 50 ECU/tCO_2 and reaches its assumed maximum level. Electricity generation from biomass increases significantly with a 100 ECU/tCO_2 tax and contributes to 6% of total electricity generation. Renewables, such

as wind turbines and solar PV, become exponentially more important with increasing CO_2 taxes. More than 15% of total power generation is based on these renewables at a 100 ECU/tCO_2 tax.

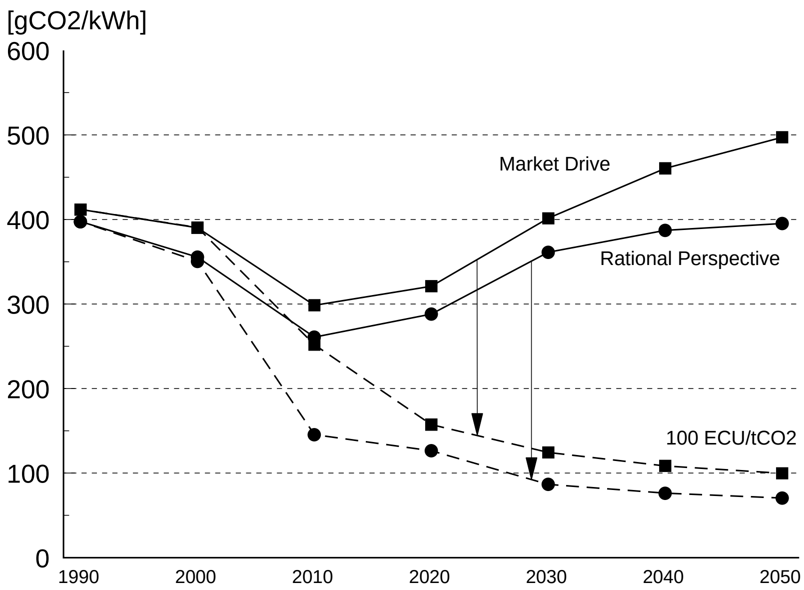
Figure 5.8 Electricity production by source in the Rational Perspective scenario in 2040 with increasing CO_2 tax levels.



The changes in electricity generation with modest CO_2 taxes are more pronounced in Rational Perspective than in Market Drive (see Figure 5.8 and compare with Figure 5.7). Coal fired electricity generation disappears entirely with a 20 ECU/tCO_2 tax. Oil fired electricity generation remains very small in Rational Perspective. This is a difference with Market Drive where the electricity generation sector is an important destination for residual fuel. As the transport sector is much larger in Market Drive than in Rational Perspective, more residual oil is produced from the refineries. Natural gas plays a dominant role for electricity generation at a 20 ECU/tCO_2 tax level. With further increasing CO_2 taxes the role of natural gas drops again but it remains substantially higher than in the base case also with the highest CO_2 tax level. In Rational Perspective nuclear power is cost-effective with CO_2 tax of 20 ECU/tCO_2. The contribution of biomass to electricity generation is somewhat smaller in Rational Perspective than in Market Drive. Electricity generation from wind turbines and solar PV, however, is significantly higher in the Rational Perspective than in Market Drive. 40% of total electricity generation is based on wind and solar power with the 200 ECU/tCO_2 tax level. Only 16% of total electricity generation is based on fossil fuels at this tax level.

With a 200 ECU/tCO_2 tax the level of electricity generation is *higher* in Rational Perspective than in Market Drive while the level was *less* in all other tax cases. This results from the penetration of electric vehicles in Rational Perspective which starts in 2020. Electric vehicles do not penetrate in Market Drive.

Figure 5.9 Development of the average CO_2 emissions per kilowatthour (kWh) in the scenarios Rational Perspective and Market Drive, base cases and cases with 100 ECU/tCO_2 tax.



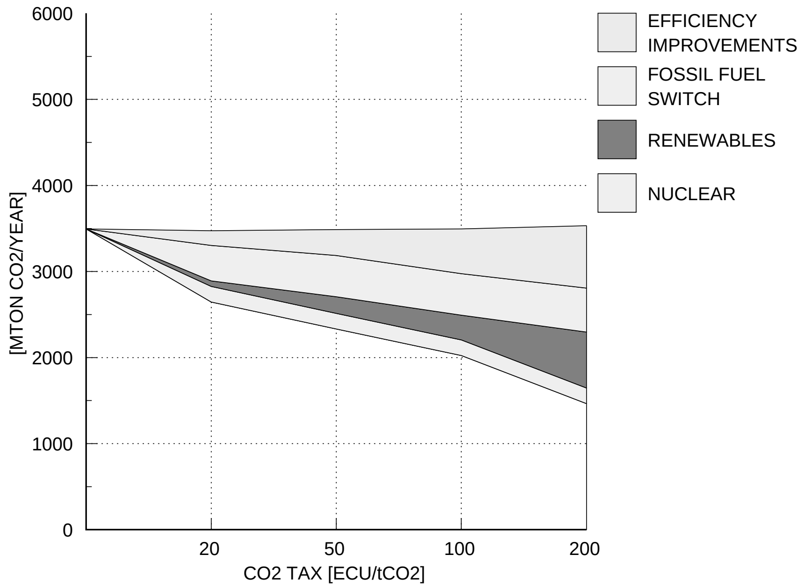
The CO_2 emission intensity of electricity drops considerably as a result of the changes in technologies and fuels for power generation. Figure 5.9 shows that the average CO_2 emissions per kWh drop already by the year 2010 to a level of 150 g CO_2/kWh in Rational Perspective and to 250 g CO_2/kWh in Market Drive. Further in time CO_2 emissions continue to drop. The CO_2 emission intensity of electricity generation of Rational Perspective remains below the CO_2 intensity of Market Drive. Therefore, switching towards electricity based end-uses is also more effective in Rational Perspective than in Market Drive. The low levels of CO_2 emissions per kWh make electric heatpumps and other fossil fuels substituting technologies more attractive with CO_2 taxes.

5.5 Contribution of options to CO_2 reduction

Technologies compete for a role in the energy system. In this section the contributions of groups of technologies to CO_2 reduction are reported. The individual role of technologies is not presented in detail. The sectoral reports are referred to for more detailed information per technology [5-7].

Four groups of options are distinguished: efficiency improvements, fossil fuel switch, renewables and nuclear. Figure 5.10 shows the contribution of groups of options to the reduction of CO_2 emissions in the Rational Perspective scenario in the year 2040 with different CO_2 taxes. It appears that the emission reduction with a tax of 20 ECU/tCO_2 largely takes place through substitution of coal and oil by natural gas (410 Mton or 50% of emission reduction). Efficiency improvement (170 Mton or 21%) and nuclear power (180 Mton or 22%) have also significant contributions. Additional deployment of renewables contributes to a reduction of 64 Mton or 8% of the total emission reduction. With higher CO_2 taxes the emission reduction resulting from fossil fuel switching and nuclear power increases only marginally as the (assumed) potential of these options are exhausted. On the other hand, the limits to efficiency improvements and renewables are not yet reached. The emission reduction resulting from efficiency improvements and renewables increases strongly to 300 Mton and 195 Mton respectively with a CO_2 tax of 100 ECU/ton CO_2. With a tax of 200 ECU/tCO_2 efficiency improvements and renewables have the largest contributions to reduction of CO_2 emissions amounting to 725 and 650 Mton CO_2 respectively.

Figure 5.10 Contribution of groups of options to the reduction of CO_2 emissions compared to Rational Perspective in the year 2040 with various CO_2 taxes.



The contribution of options in Market Drive (see Figure 5.11) differs considerably from Rational Perspective. At first glance one can see that the contribution from efficiency improvement to CO_2 reduction is larger in Market Drive while the contributions from fossil fuel switch and renewables are smaller.

With the low CO_2 tax of 20 ECU/tCO_2 efficiency improvements are the dominant options to reduce CO_2 emissions. The contribution in 2040 is 470 Mton or almost 75% of the emission reduction. This is since the less efficient baseline developments in Market Drive allow for more efficiency improvements than in Rational Perspective. Nuclear power is not yet contributing to CO_2 emission reduction at this tax level. At a tax of 50 ECU/tCO_2 the contribution of options becomes somewhat more balanced. Then, efficiency improvement gives an emission reduction of 620 Mton. This is equivalent to 51% of the emission reduction. Fossil fuel switching gives a comparatively small contribution to emission reduction. The limited contribution of fossil fuel switching to emission reduction in comparison with Rational Perspective results from the larger role of natural gas in the baseline of Market Drive and the limit to the assumed limit for imports of natural gas.

With the two highest emission reduction targets, efficiency improvements account for 50% or more of the CO_2 emission reduction. The contributions of nuclear and fossil fuel switching are fully used. The contribution of renewables increases slightly. Renewables have their largest contribution (480 Mton) with the highest CO_2 tax considered.

Figure 5.11 Contribution of groups of options to the reduction of CO_2 emissions compared to Market Drive in the year 2040 with various CO_2 taxes.

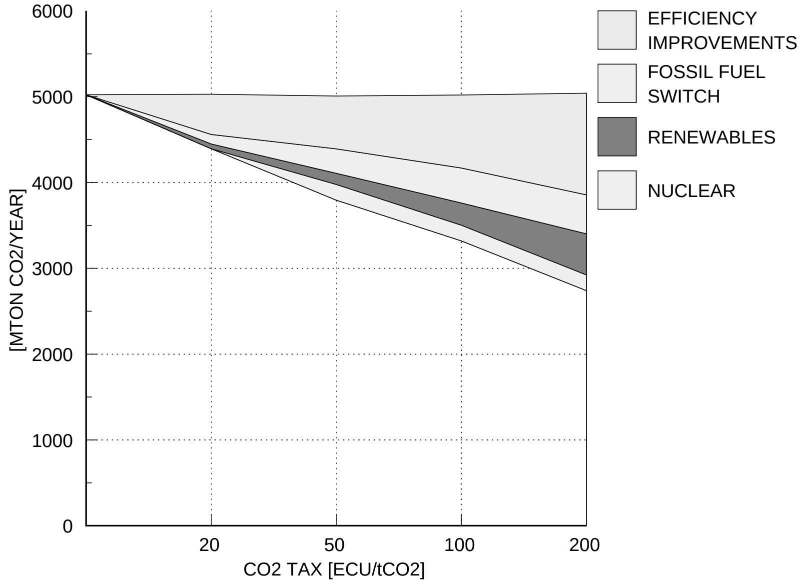
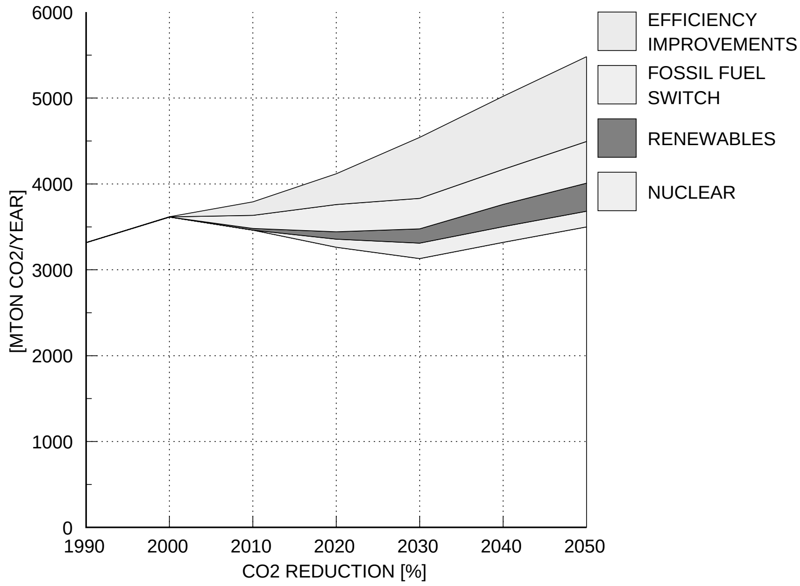


Figure 5.12 shows for the 100 ECU/tCO_2 tax in the Market Drive scenario the contribution of options over time. Three phases can be distinguished. First, the emission reduction has to come from efficiency improvements and fossil fuel switch. Then by 2020, renewables and nuclear also increasingly contribute to emission reduction. And finally after 2030, additional reduction is based on more efficiency improvements and renewables, while the contribution of nuclear and fossil fuel switch remains almost constant.

By the year 2010 both efficiency improvements and fossil fuel switching contribute for 47% to the emission reduction. Renewables account for the remaining 6% of the emission reduction. The contribution of nuclear starts by the year 2020 and amounts by 2030 180 Mton CO_2.

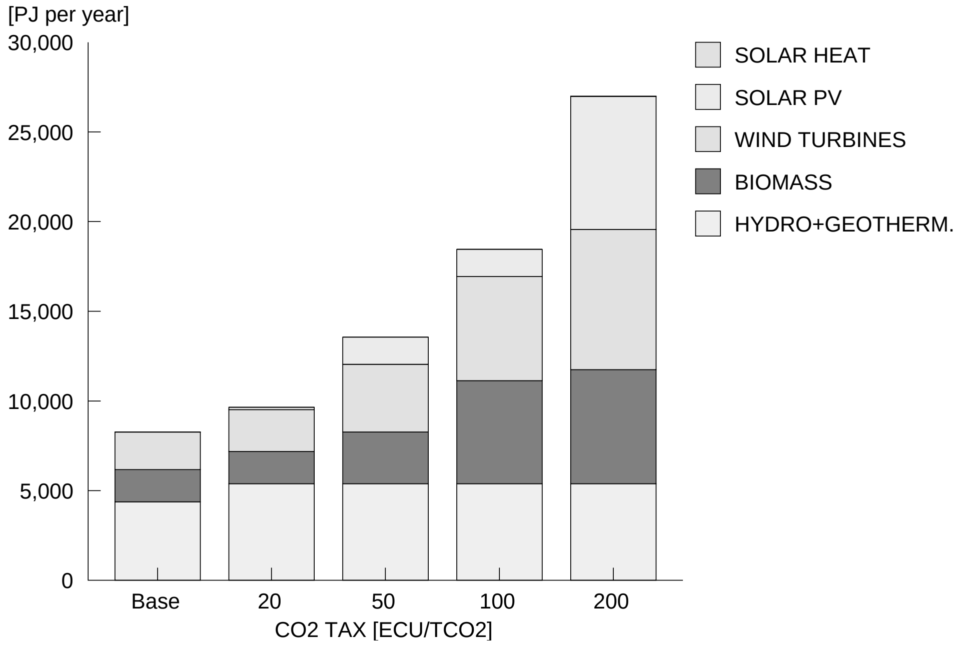
The emission reduction by efficiency improvements increases continuously over time. This is a result of the fact that an increasing share of the energy system is replaced over this time frame and since end-use technologies become increasingly efficient. It is noted that timely action in the field of energy improvements and infrastructural changes is required to fully exploit such conservation potentials.

Figure 5.12 Contribution of groups of options to the reduction of CO_2 emissions compared to Market Drive with a tax level of 100 ECU per ton CO_2.



The increasing role of renewables under CO_2 reduction taxes is shown in more detail for the Rational Perspective scenario in Figure 5.13. Power production with hydro power and wind turbines will increase slightly with a CO_2 tax of 20 ECU/tCO_2. Hydro power already reaches its maximum potential at this tax level. Solar PV systems are also introduced at this tax level but only to a very limited extent. With a CO_2 tax of 50 ECU/tCO_2 the contribution of biomass, wind turbines and solar PV systems are significantly higher. At a 100 ECU/tCO_2 tax biomass, wind turbines and hydro power are equally important energy producers, each accounting for approximately 5600 $PJ_{primary}$. With the highest CO_2 tax (200 ECU/tCO_2) solar PV systems are applied on a large scale and become one of the two largest renewable sources. Wind turbines are the other largest renewable source. Biomass and hydro power contribute slightly less. The contribution of solar heat is very small in all CO_2 tax cases.

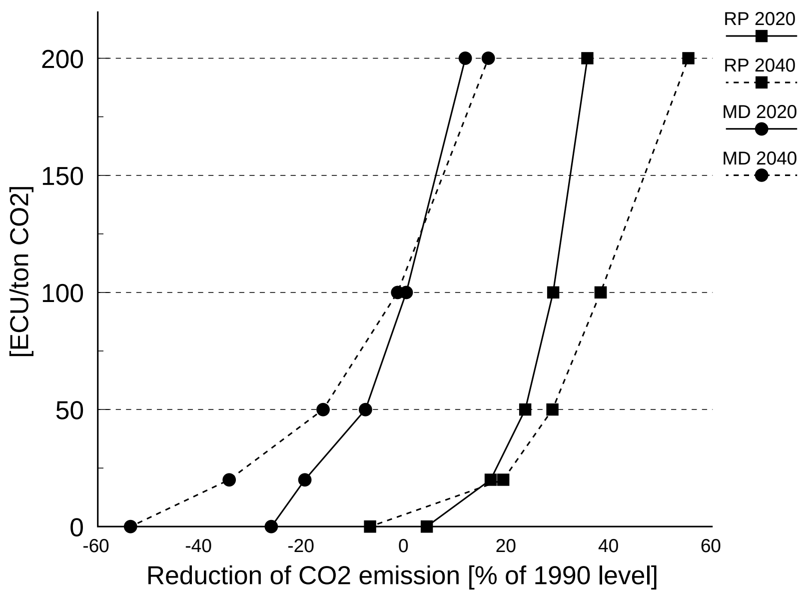
Figure 5.13 Primary renewable energy supply in the Rational Perspective scenario in 2040 with increasing CO_2 taxes. Heat pumps are not included in this graph.



5.6 Cost of CO_2 emission reduction

The additional emission reduction that results from increasingly higher taxes becomes less and less. This suggests that the marginal cost curve for the reduction of CO_2 emissions is non-linear. Figure 5.14, that depicts the marginal CO_2 reduction cost as a function of the emission reduction, shows that this is indeed the case.

Figure 5.14 Marginal cost of CO_2 emission reduction in 2020 and 2040 in the Market Drive scenario and the Rational Perspective scenario.

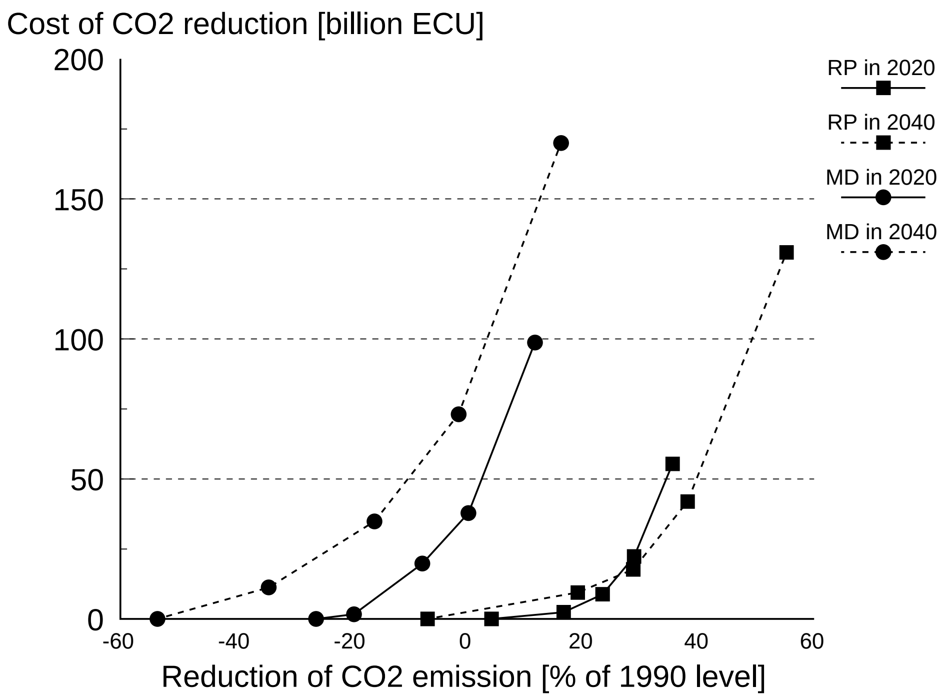


The solid lines show the marginal CO_2 abatement cost for the year 2020. The dashed lines show the marginal cost for the year 2040. The marginal cost are lower in Rational Perspective than in Market Drive. Below 18% CO_2 emission reduction relative to 1990 emissions, the marginal cost in Rational Perspective are lower in 2040 than in 2020. This implies that drastic emission reduction will become cheaper in the long term than in the medium long term. This is a result of the wider availability of energy technologies and the larger flexibility in the energy system over a long time frame (as the larger part of the energy technologies will be replaced between now and 2040). In Market Drive the situation is different since the emissions in the base case of Market Drive continue to increase and the emission reduction to be achieved is much larger for the year 2040 than for the year 2020. Therefore, cost for emission reduction are higher in 2040 than in 2020.

It is noted that most countries do not seriously consider energy technologies that have cost which are higher than 50 ECU/tCO_2. Stabilization of CO_2 emissions is not yet possible for Market Drive with this tax level. In Rational Perspective an emission reduction of about 25% can be achieved.

The MARKAL model calculates the *direct cost* of the energy system. The direct cost for CO_2 emission reduction involve investment costs, interest, operation and maintenance cost and (saved) fuel cost. Cost of policy instruments and from macro-economic effects are not quantified.

Figure 5.15 Direct cost of CO_2 emission reduction in 2020 and 2040 in the Market Drive scenario and the Rational Perspective scenario (ECU).



The direct cost for CO_2 emission reduction in Western Europe are shown in Figure 5.15 as a function of CO_2 emission reduction. The first part of the cost curves for Market Drive are noticeably steeper than for Rational Perspective, indicating a smaller low cost potential in Market Drive than in Rational Perspective. The cost for emission stabilisation amount to 40 and 80 billion ECU in Market Drive for respectively 2020 and 2040. The cost for stabilisation of CO_2 emission in Rational Perspective amount only to 4 Billion ECU in 2040. The cost to achieve more drastic reduction targets is also substantial in Rational Perspective. They amount to 100 billion ECU to achieve 50% emission reduction in 2040. With this amount of money, only 10% reduction of CO_2 emissions can be obtained in

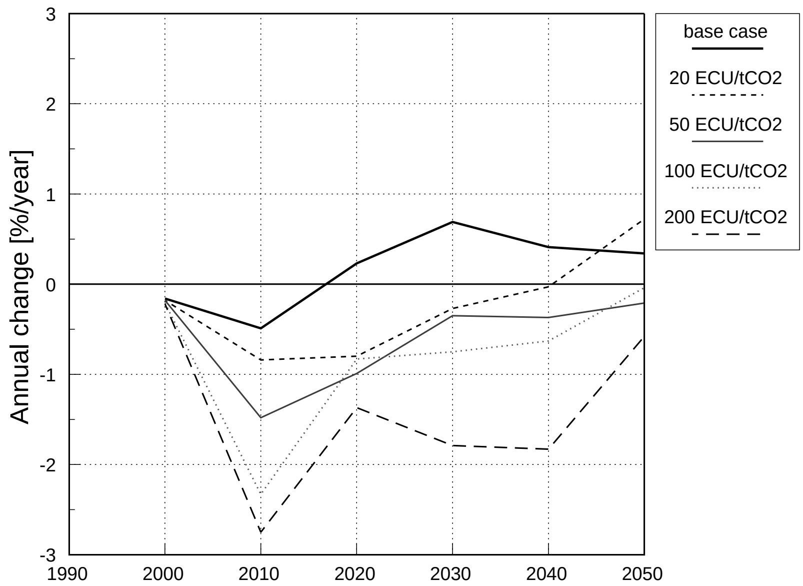
Market Drive. To allow for comparison it is noted that the assumed GDP of Western Europe amounts in both scenarios to 12 trillion ECU in 2020 and 20 trillion ECU in 2040.

5.7 Maximum rate of change in level of CO_2 emissions

Some integrated assessment models on climate change use the concept of *annual changes in the level of CO_2 emissions*. This is e.g. done by the IMAGE team of the National Institute of Public Health and the Environment (RIVM) in the Netherlands. RIVM calculates safe corridors for regional and global CO_2 emissions in a future year [13]. To remain on the safe side for climate change in the long run, the emissions of CO_2 in the near term should remain below the upper level of the emission corridor. Due to inertia in the energy system the level of CO_2 emissions can not change with more than a certain percentage per year. It is assumed by RIVM that the maximum rate of change for a region is 2% per year. The maximum rate of change is an important assumption to calculate the safe emission corridor.

The maximum rate of change for the Western European energy system can be calculated from the results of the present scenarios. Figure 5.16 shows the annual rate of change in the CO_2 emissions for the Rational Perspective scenario and the tax variants. In the Rational Perspective base case the long term rate of change (period 2000-2050) is +0.2%/year. With the highest tax level considered, the rate of change for the period 2000-2050 is on average -1.7%/year. In Market Drive the maximum rate of is only -0.3%/year.

Figure 5.16 Annual rate of change in the level of CO_2 emissions in the Rational Perspective scenario



This study has limitations in exploring the possibilities for CO_2 reduction should be noted (see Section 7.2). On the other hand it is optimistic with respect to barriers to introduction of new technologies. Therefore, it can be concluded that the maximum rate of change of CO_2 emissions that is assumed by the IMAGE team (-2%/year), is very optimistic. The present scenario study only achieves an equivalent rate of change in emissions if a shift towards a less energy intensive economy is assumed and if barriers for efficiency improvements are removed and if a very high CO_2 tax level is assumed. Only if additional technical options are assumed a -2% rate of change over a long time path is feasible.

6. SCENARIO VARIANTS WITH EXTENDED ENERGY SUPPLY OPTIONS

6.1 Description of scenario variants

Several energy supply options can play a large role in the future energy system but have an uncertain future potential. The potential is uncertain for different reasons, e.g:

- the technology is currently not generally accepted by the public ;
- the technological development path is relatively uncertain;
- the supply to Western Europe depends developments in other regions (e.g. Russian natural gas);

Technologies and energy sources with especially uncertain potentials for Western Europe are nuclear power, natural gas, CO_2 removal, solar PV systems and import by Western Europe of renewable fuels. The potentials for energy technologies in the scenarios presented in Chapter 4 and 5 can be considered as realistic. In addition, a scenario variant has been developed with extended potentials for these energy sources and groups of technologies.

The technologies are allowed to penetrate to a larger extent in this variant than in the base case and the CO_2 reduction cases that were discussed in Chapters 4 and 5. The extended assumptions about the potentials of the technologies and sources are summarized in Table 6.1. It is noted that the cost data of technologies have not been adjusted compared to the scenarios presented Chapters 4 and 5.

Table 6.1 Potentials for energy technologies in the variants with extended supply options.

	Rational Perspective	Rational Perspective variant	Market Drive	Market Drive variant
Annual supply of natural gas period 2030-2050	price tranches	price tranches	10 EJ	unlimited
Nuclear power potential in 2040	127 GW_e	220 GW_e	127 GW_e	220 GW_e
CO_2 removal options:	not allowed		not allowed	
- IGCC		1900 PJ		1900 PJ
- gas fired STAG		1900 PJ		1900 PJ
- hydrogen production		3800 PJ		3800 PJ
- iron industry		50%-80%		50%-80%
- ammonia industry		50%-80%		50%-80%
Solar PV potential in South Europe in 2040	100 GW	400 GW	100 GW	400 GW

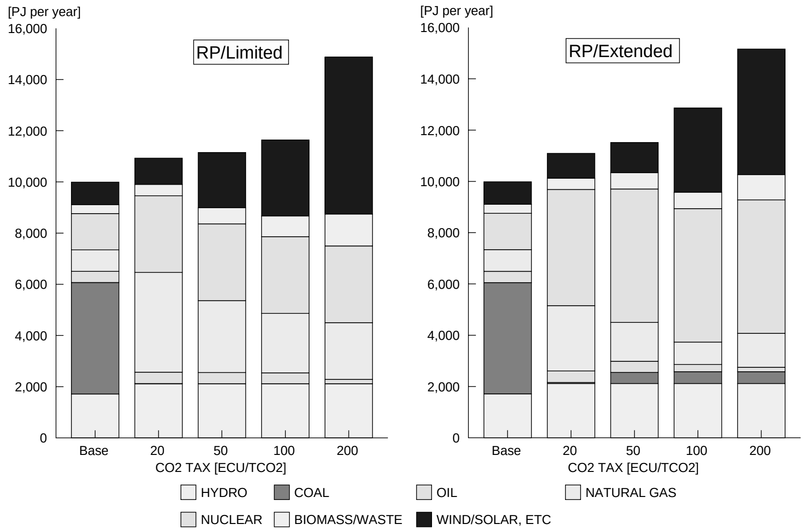
In the next sections part of the results of the scenario variants are discussed. The results of the calculations without CO_2 constraints are equal to the baseline results presented in Chapter 4. However, the results differed increasingly with increasing CO_2 tax levels.
The results for electricity generation, CO_2 removal processes, contributions of groups of options to emission reduction and reduction cost are discussed in the following sections.

6.2 Electricity production

The wider choice for low carbon electricity supply options results in significant differences in the results. Electricity production with nuclear power is significantly increased in the scenario variants (see Figures 6.1 and 6.2). Coal fired power generation (with CO_2 removal) also plays a role from 50 ECU/tCO_2 while coal fired power was phased out in the scenario with limited CO_2 reduction options. On the other hand the role of natural gas, biomass and solar PV in power generation is smaller. Th roles of hydro power and oil are not affected by the extended supply potentials.
Nuclear power does not reach its maximum allowed share in either of the scenarios until a 50 ECU/tCO_2 tax. The role of nuclear is already significantly higher in Rational

Perspective at 20 ECU/tCO_2, but not in Market Drive. Nuclear power appears more cost effective than CO_2 removal regarding the result that nuclear power is already introduced at a lower emission tax than CO_2 removal from coal fired power generation.

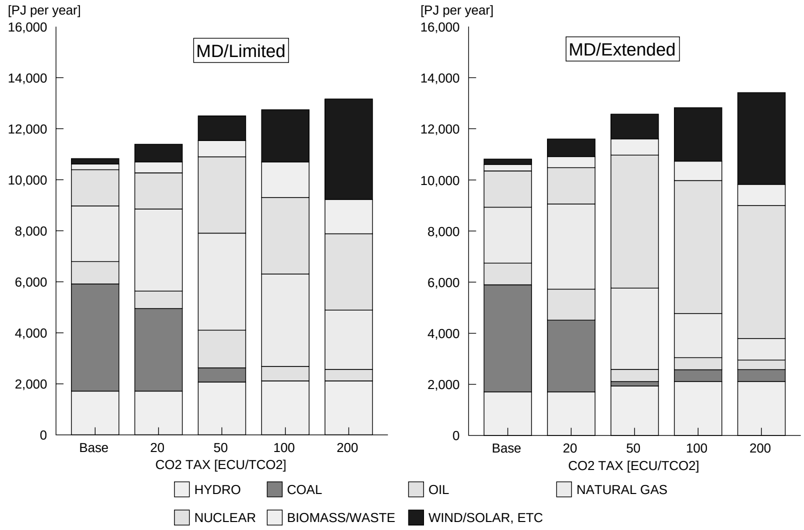
Figure 6.1 Electricity production by source in the Rational Perspective scenario in 2040 with increasing CO_2 tax levels. Left: limited supply options and right: variant with extended supply options.



In Rational Perspective natural gas has a much smaller role in the 20 ECU/tCO_2 tax case with extended supply option than in the case with limited supply options. In Market Drive this is not the case at 20 ECU/tCO_2. In Market Drive nuclear power is not yet substituting natural gas at this tax level.

The extension of the allowed penetration of supply options allows electricity to become even more CO_2 free than in the base CO_2 reduction cases and at lower cost. As a result, total consumption of electricity is slightly higher in the variants with extended supply options. In most cases electricity consumption is only a few percent higher than in the normal CO_2 reduction cases. However, in Rational Perspective with a 100 ECU/tCO_2 tax electricity consumption is more than 8% higher in the variant with extended supply options. Electric heatpumps and electric vehicles have a higher penetration in this variant than in the normal CO_2 reduction cases.

Figure 6.2 Electricity production by source in the Market Drive scenario in 2040 with increasing CO_2 tax levels. Left: limited supply options and right: variant with extended supply options.



6.3 CO_2 removal options

The fertilizer industry is the application where CO_2 removal is most cost-effective. CO_2 removal at ammonia production plants is attractive at 20 ECU/tCO_2 in both scenarios (see Figures 6.3 and 6.4). CO_2 removal in the iron industry is introduced at 20 ECu/tCO_2 in Rational Perspective, but in Market Drive only at a tax level of 100 ECU/tCO_2. The higher discount rate in Market Drive reduces the attractiveness of this option in Market Drive.
CO_2 separation at IGCC power plants is introduced at 50 ECU/tCO_2 both in Rational Perspective as well as in Market Drive. In Rational Perspective CO_2 separation is also attractive at gas based plants at a tax of 50 ECU/tCO_2. The gas based plants refer both to STAG power plants and hydrogen production. These options are cost-effective in Market Drive at a tax of 100 ECU/tCO_2.

Figure 6.3 CO_2 removal technologies and their contribution to CO_2 removal in the Market Drive scenario variant with extended supply options in the year 2040 and with increasing CO_2 tax levels.

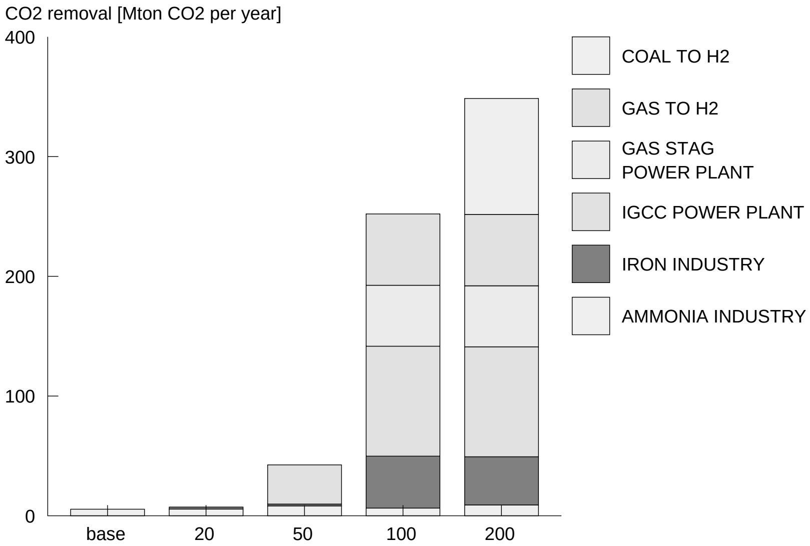
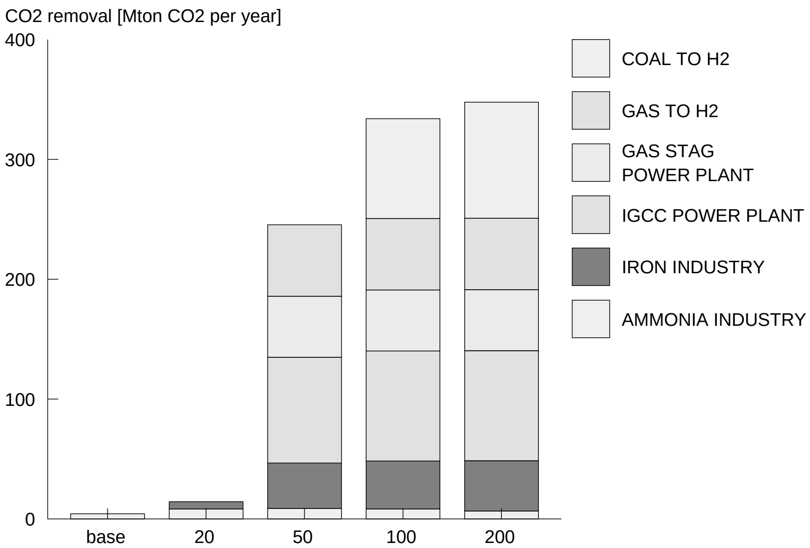


Figure 6.4 CO_2 removal technologies and their contribution to CO_2 removal in the Rational Perspective scenario variant with extended supply options in the year 2040 and with increasing CO_2 tax levels.

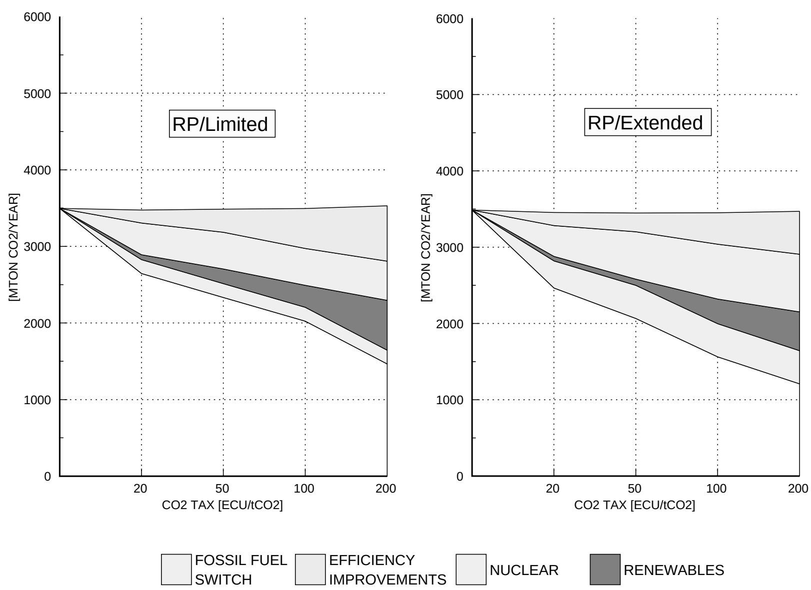


6.4 Contribution of options to CO_2 reduction

As expected, the contribution of groups of options to the reduction of CO_2 emissions differs in the "base" reduction case and the cases with extended supply options. In Rational Perspective with extended options the contribution of nuclear and fossil fuel switch (this includes CO_2 removal) is higher, while at CO_2 taxes of 50 ECU/tCO_2 and above the contribution of renewables and efficiency improvement is smaller (see Figure 6.5). It must be noted that efficiency *losses* are a consequence of CO_2 removal, Thus, the reduced contribution of efficiency improvements is largely related to the introduction of CO_2 removal technologies.

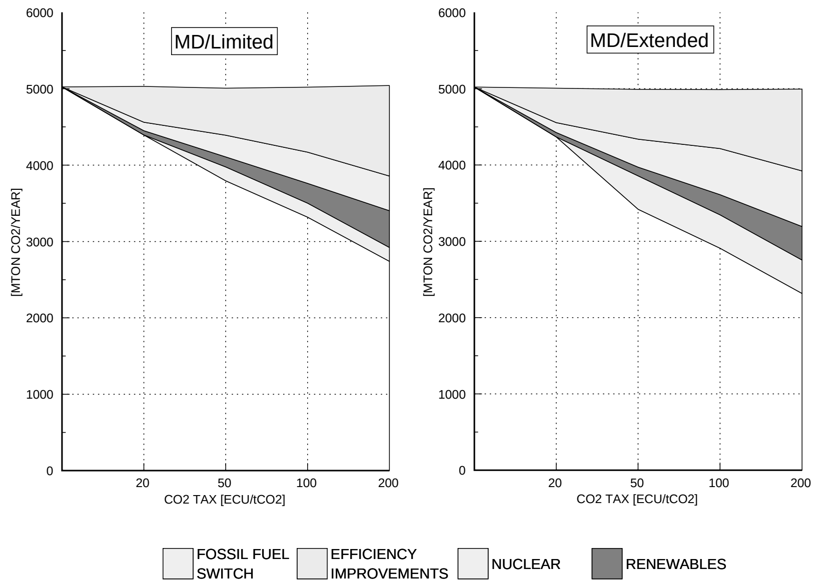
The graphs with the contribution of options illustrate the competition for emission reduction between different technologies. The assumed ample availability of nuclear power reduces the contribution of renewables.

Figure 6.5 Contribution of groups of options to the reduction of CO_2 emissions compared to Rational Perspective in the year 2040 with various CO_2 taxes. Left: limited supply options and right: variant with extended supply options.



The extended supply options lead to a deeper reduction of CO_2 emissions in Rational Perspective at all CO_2 tax levels. With a 20 ECU/tCO_2 tax the CO_2 emissions in Market Drive are not further reduced than in the "base" reduction case with a 20 ECU/tCO_2 tax (see Figure 6.6). At higher tax levels the extended options result also in a deeper reduction of CO_2 emissions.

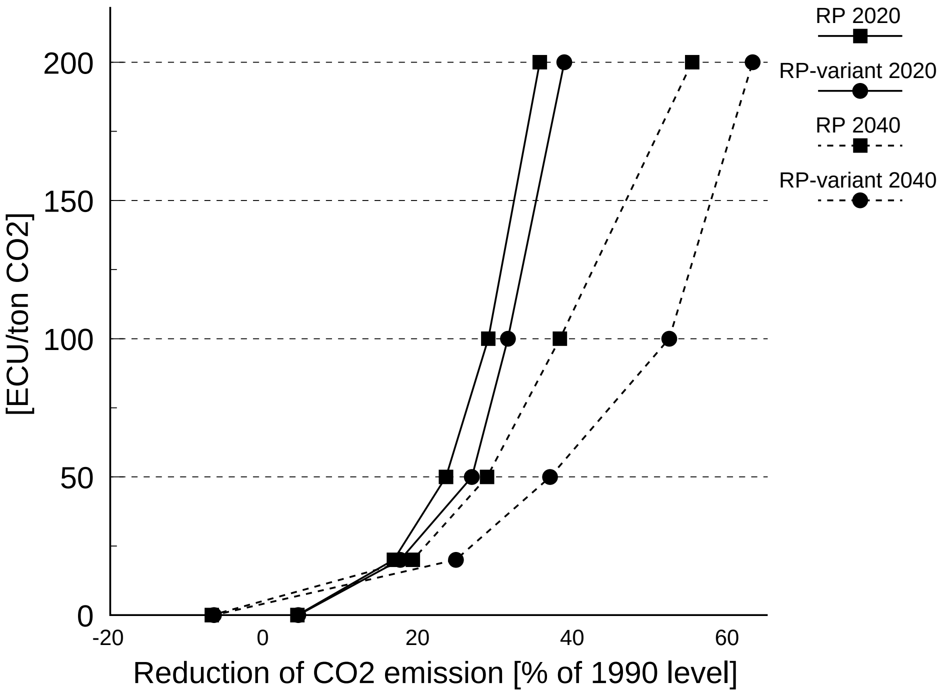
Figure 6.6 Contribution of groups of options to the reduction of CO_2 emissions compared to Market Drive in the year 2040 with various CO_2 taxes. Left: limited supply options and right: variant with extended supply options.

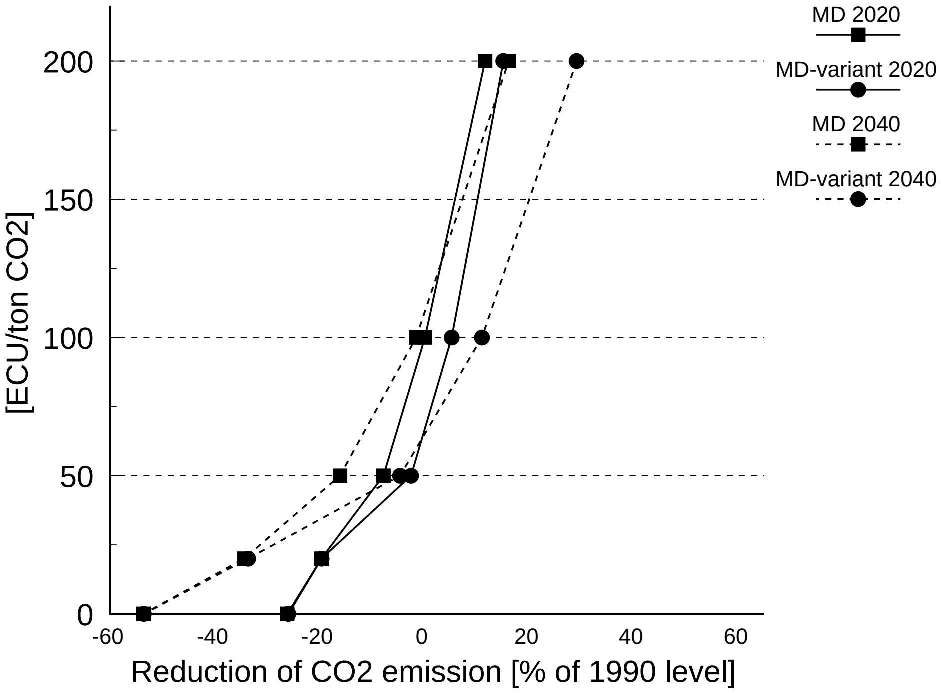


6.5 Cost of CO_2 emission reduction

The cost of CO_2 emission limitation are lower in the variants with extended energy supply options as can be seen from Figure 6.7. Figure 6.7 shows the direct cost for CO_2 reduction from Western Europe for the normal CO_2 reduction cases and the variant with extended energy supply options. The top parts of the cost curves have moved to the right in comparison with the normal CO_2 reduction cases. This implies that the more drastic emission reduction targets become substantially cheaper with extended supply options. The move to the right is larger for 2040 than for 2020. This is since a wider availability of technologies is assumed for 2040 than for the year 2020.

Figure 6.7 Marginal cost of CO_2 emission reduction in 2020 and 2040 in the Rational Perspective scenario and the Rational Perspective variant with extended supply options (top) and the Market Drive scenario and the Market Drive variant with extended supply options (bottom).





7. DISCUSSION OF RESULTS

7.1 Insights of the study

The present study gives an impression of the *technical* possibilities to reduce the emissions of CO_2 from the future energy system of Western Europe. Two base case scenarios and several CO_2 abatement scenarios aiming at different levels of emission reduction have been calculated. The main insights from these scenarios are reported below.

Base case scenarios

The results of the two base case scenarios suggest that we are close to a crossroad with two different development paths of the energy system being possible. In one of these development paths (Rational Perspective scenario), Western Europe is capable to utilize the cost-effective potentials of energy conservation, to limit the growth in demand in the transport sector and to introduce new renewable sources to a significant extent. The autonomous development of the energy system in this scenario indicates that energy demand only grows slightly and CO_2 emissions remain near to the 1990 emission level. This would imply a continuation of the almost constant CO_2 emission levels between 1970 and 1990. In the other scenario (Market Drive) the positive developments mentioned above do not occur or they occur at a much lower level. As a result energy demand in road transport increases continuously, efficiency measures are only implemented to a limited extent as barriers persist in investment behaviour for energy efficiency measures. Energy demand increases significantly in this scenario and the emissions of CO_2 in 2040 will have increased with more than 50% compared to the 1990 emission level.

In the base case scenarios fossil fuels maintain their dominant role in the energy system. The contribution of new renewables is projected to grow but it remains small compared to total energy use. In both base scenarios oil remains the most important energy source as the transport sector will continue to rely on oil products. The scenarios project somewhere between 2020 and 2030 an important change in the relative competitiveness of natural gas versus coal due to the increasing natural gas prices. Until 2030 the contribution of natural gas to the primary energy mix is projected to grow. While the base case scenarios indicate that the contribution of coal will drop until 2020, it is expected that after 2020 the share of coal will grow again limiting the role for natural gas. The projected change will have important impacts on the CO_2 emission level.

CO_2 reduction scenarios

The two scenarios also differ substantially with respect to the possibilities to abate the future CO_2 emissions. Reduction of CO_2 emission below the 1990 emission level appears much more difficult in the Market Drive scenario than in Rational Perspective. This results primarily from the higher level of baseline CO_2 emissions but also from the different sectoral distribution of CO_2 emissions. The transport sector is the sector with the highest emissions in Market Drive and it appears most difficult to reduce CO_2 emissions from this sector. In Rational Perspective, on the other hand, the lower base level of CO_2 emissions and the smaller share of transport in total CO_2 emissions allows for much further CO_2 emission reductions. In Rational Perspective electricity generation is the sector which has the highest CO_2 emission and it is the sector where limiting the CO_2 emissions is most cost-effective.

Limits are identified in the maximum rate to reduce the emissions of CO_2 with technical measures. In the low energy demand scenario and with optimistic assumptions for the market penetration of efficient and low carbon energy technologies, technical measures allow a maximum reduction between 1.5% and 2.0% per year over a period of 50 years. In the scenario with rapid growth in demand, the maximum rate of emission reduction is only 0.5% per year over a such a period of time.

The reduction of future CO_2 emissions can be achieved most optimally by the deployment of a mix of technologies. Four groups of technologies can be distinguished which compete to contribute to emission reduction:

- energy efficiency improvement;
- switching towards fossil fuels with lower carbon content, this options can be subdivided in:
  - switching from coal or oil to natural gas;

- carbon dioxide removal from large plants and storage of CO_2 in depleted gas field or aquifers;

- renewable energy;
- nuclear energy.

The contributions of the groups of technologies to CO_2 reduction are summarized in Table 7.1 and discussed below.

Table 7.1 Contribution of groups of technologies to CO_2 reduction, cost and barriers.

	contribution to CO_2 reduction [Mton][1]			
	2020	2040	cost	main barriers
Efficiency improvements	250-350	600-1200	varying	implementation
Fossil fuel switch	± 300	400-500	low	supply security
CO_2 removal	± 100	200-300	medium	acceptance
Renewables	70-90	250-650	high, decreasing	cost
Nuclear	90-100	200-400	low	acceptance, waste

[1] The size of the contributions of options differ per scenario. The table figures can not be summed.

Energy efficiency improvement in demand and supply sector is a prominent contributor to the reduction of CO_2 emissions at each of the emission tax levels considered and in both scenarios. Efficiency improvements technologies range from insulation of buildings to more efficient industrial processes and from increased application of CHP generation technologies to lighter passenger vehicles. In the scenarios, the potential for efficiency improvements appears to increase with time. This is caused by two effects. First, it results from the ongoing replacement of old equipment that allows for an increasingly larger potential for efficiency improvements. Secondly, it is resulting from the expectation that various technologies become increasingly efficient over time.

Implementation problems will be the main barrier for efficiency improvements in practice. Efficiency improvements require action from many individual decision makers. To achieve the desired penetration of efficient technologies asks for well designed combinations of policy instruments.

It appears from the model calculations that to guarantee a large potential for efficiency improvement in the long term that early action is required in many instances. Two kinds of situations can be distinguished where this is most relevant:

- Various efficiency improvements need to be implemented "now" or "never". There are many "now or never" opportunities for energy conservation. This is the case with technologies that have long lifetimes and where the decision is practically irreversible. Examples are applying a thick package of insulation materials in buildings and solar orientation of houses which determines energy demand for a long time period or spatial planning decisions which determine the potential for e.g. district heat or other uses of waste heat for a long time period.
- The implementation of many new and efficient technologies requires that the proper technical conditions are met. "Anticipating" measures are referred to if conditions need to be early satisfied for certain technologies. This is e.g. the case with electric heatpumps. These require the possibility to connect to a heat source and a low temperature central heating system to allow for a high seasonal performance factor (SPF). In houses that are to be built, these conditions need to be met to allow electric heatpumps to reach a significant market penetration.

Switching towards fossil fuels with lower carbon content appears to involve relatively low cost measures to reduce emissions of CO_2. In practice it implies mainly the replacement of coal by natural gas in power generation and replacement of oil by natural gas for space heating and industrial applications. With modest CO_2 reduction targets fuel switching has already a sizeable contribution to emission reduction. However, the contribution hardly increases with more ambitious reduction targets as the potential is already exploited at modest targets. The main barrier of this option will be the reduction of supply security. With an increasing role for natural gas, Western Europe will increasingly have to rely on imports of natural gas from elsewhere as Western Europe itself has fairly moderate resources of natural gas. By 2030 Russia will be the principal supplier of natural gas for Western Europe. Natural gas will replace coal that will also mainly be imported. With coal, however, supply security is hardly an issue. As coal is a solid material it can easily be transported by ship and coal supplies can be selected from many suppliers in the world. Switching from coal to natural gas will increase the price of natural gas. In the model calculations this feedback mechanism has been included to a limited extent as additional tranches of natural gas are only available at higher cost (see Section 3.3). It is noted that a precise forecast of the price response to the extra demand for natural gas is difficult.

If *carbon dioxide removal* technologies are applied, fossil fuels can maintain a large role in the energy system while CO_2 emissions can be reduced. CO_2 removal technologies have only been included in the sensitivity analyses reported in Chapter 6. It appears that CO_2 removal can make a significant contribution to the reduction of CO_2 emissions from Western Europe. CO_2 removal is not a very cheap way to mitigate CO_2 emissions but it is neither very costly. An advantage is that CO_2 removal does not require large changes in the energy infrastructure as the size of plants remains similar as in the current situation and as fossil fired plants can be operated in a flexible way. Demonstration of CO_2 storage projects is just starting. Investigations about the underground storage capacity and about environmental and safety risks still indicate uncertainties in the possibilities of this option. Security of supply will not improve when carbon dioxide removal is applied as extra energy is required for the separation and storage of CO_2.

An optimal location of *renewables* in Western Europe is assumed in this study with each renewable in first instance located at the most favourable sites. Renewable energy contains a diverse group of energy technologies with different levels of maturity, ranging from hydro power to solar PV. As a result of this diversity, renewables show a specific role in CO_2 emission reduction under different CO_2 tax levels. In the base case the contribution of hydro power slightly increases and the roles of biomass and wind turbines increase marginally. CO_2 tax levels of 50 ECU/tCO_2 are at least required to launch offshore wind turbines and solar PV but the contribution of these options to CO_2 reduction is still limited. With drastic CO_2 taxes renewables have a large contribution to CO_2 emission reduction. It is interesting to note that in a scenario with an ambitious CO_2 reduction policy that for the Western European situation the shares of four the four primary renewable energy sources become similar in size.

Extra *nuclear power* belongs to the relatively more cost-effective ways to reduce CO_2 emissions. Nuclear power plays a large role in current Western European power production. In the base case scenarios the role of nuclear drops. Under a CO_2 tax regime, the share of nuclear power can grow again. In many European countries nuclear power faces large acceptance barriers related to insufficiently solved safety, waste and proliferation issues. Depending on the assumptions with respect to the accepted potential for nuclear in Western Europe, the contribution to CO_2 reduction will range between small and modest.

7.2 Limitations and characteristics of the study

For a proper perception of the results of the present study it is important that the limitations and characteristics of the present study are taken into consideration. The description of the methodology in Chapter 3 already gave some information on limitations, but it recognized valuable to also discuss here the possible impacts of the limitations on the scenario results:

- The present study does not include a *feedback of energy demand to increased energy prices*. In the MARKAL model the demand level of energy services is exogenous to the energy prices. With increasing levels of CO_2 taxes, the cost of energy increases. In real life, this will both have an impact on the economic structure resulting in a shift towards less energy intensive activities and to a reduction in the demand for energy services via changes in budget spendings and behaviour adaptations. If such feedbacks would have been included, energy demand would be reduced and the CO_2 emissions would be smaller. Analysis with the MARKAL-MICRO model or the MARKAL-MACRO model allow to incorporate such feedback relations. Studies with these models indicate that the economic feedback mentioned can contribute up to 20% of the reduction in CO_2 emissions, but 80% or more of the emission reduction is due to technical changes [14].

- *Import prices of fossil energy are not endogenized*. The primary energy mix changes when CO_2 taxes are applied. As a result the prices of coal, oil and natural gas will also change. The prices of coal and oil will become less and the natural gas price may increase. Forecasting the response of fossil energy prices requires also information on energy demand and supply developments in other parts of the world than Western Europe. Therefore, this feedback was implemented only to a limited extent. In the Rational Perspective scenario a step curve in the price of natural gas was built in with additional tranches of natural gas having a higher price. If this feedback mechanism would have been included in a more advanced way, the main result would be that the contribution of fossil fuel switch to CO_2 reduction would have been reduced.
- *Not all possible abatement options have been considered*. We believe that the most important groups of technologies have been considered. However, several technologies are missing or allowed with limited potentials:
  - For some end-uses the substitution options have not been investigated. This is the case with end-uses which are small in terms of absolute energy consumption such as coffee machines, micro waves motorbikes, etc. In total these end-uses are not insignificant.
  - Technologies with large uncertainties about their further development with respect to the technical concept and costs have not been considered in the analysis. This is the case for e.g. breeder reactors, fusion power, super conductors, fuel cells and wave power. In reality innovations will continue and this will widen the range of options to reduce CO_2 emissions.
  - Changes in the transport infrastructure have only been considered as different points of departure for the two scenarios, not as technological choices. Rational Perspective assumes a shift towards a larger role for electricity driven passenger transport. In Market Drive the modal split remains constant.

- Import of renewables from other continents, e.g. import of electricity from PV system located in North Africa has not been considered as an option.
- The scenarios take optimistic but still realistic potentials for technologies as point of departure. However, it is not impossible that potentials of some technologies will appear larger than assumed here.

If the above mentioned limitations in energy technologies would be removed, CO_2 emissions can be reduced further than in the scenario calculations.

- The model does *not yet include the material system*. Including the material system will allow other CO_2 reduction options such as material substitution in products, recycling, material efficiency improvements and waste management.
- The different *market actors* in the real world have not been distinguished. This study follows a macro perspective in which the costs of the energy system are minimized from a national viewpoint. Interest of individual actors may not always be in line with the national interests.
- *Implementation of technologies* has not been considered in detail. Some of the technologies may be easier to implement than others. Barriers to the implementation of technologies or incentives to increase the implementation of technologies are difficult to be assessed for a study with a long timespan, as the study under consideration.
- It is assumed that Western Europe will have *one electricity grid* by the year 2010 which allows electricity transport over large distances within Western Europe. This electricity grid allows renewable energy to be produced at the locations with the most favourable circumstances and electricity storage capacity to be optimally utilised. The contribution of renewables to reduce CO_2 emissions would decrease if the interconnections between national electricity grids remain limited.
- The model calculations *assume certainty* in technology development and scenario conditions. Reduction strategies are chosen assuming this perfect foresight. This is too an optimistic assumption. In reality future targets and circumstances are not known with certainty and an optimal strategy with a long time horizon cannot yet be decided. A stochastic version of MARKAL has recently been developed which allows to calculate so-called "least regret" strategies to reduce CO_2 emissions based on multiple CO_2

reduction targets. Results of such analyses for the Netherlands indicate that early action to reduce CO_2 emissions is recommended [15].

- *Technological learning* has not been endogenized. The cost of new technologies will not only reduce as a result of research and development but also as a result of scale effects. The effect of economies of scale on the cost of technologies is not endogenized in the present model. The main reasons that this was omitted is that:
  - Western Europe is only a small part of the world market for energy technologies. Learning effects through scaling can only be included properly in energy models of the world [16].
  - The scale parameters are too uncertain.

  It is difficult to predict the changes in model results that would result from endogenized technological development. Optimization models with learning endogenized appear very sensitive as they include "snowball effects". The more a technology is used, the lower the cost and the more it is used. The technology that becomes the fastest learner, may gain a very large market share.
- *Emissions of NO_x and SO_2 and local pollutants are excluded*. Energy use leads also to other emissions than CO_2. If emissions of acidifying compounds, carbon monoxide and organic compounds and technologies to abate these emissions would have been included, the results would have changed somewhat, especially in the transport sector. It is assumed for this study that the cost of current standard end-of-pipe equipment to clean flue gases is included in the cost of the equipment.
- *Non-CO_2 greenhouse gases and indirect CO_2 emissions are excluded*. Coal mining, gas production and gas distribution cause emissions of methane. The energy use needed for the transport of coal and crude oil by ship and for the transmission of natural gas by pipeline can amount up to 10% of the energy content of the transported fuels. In many cases these emissions occur outside Western Europe. Therefore, such emissions have not been considered in the present study as the system boundaries are assumed to be the borders of Western Europe. Methane emissions and indirect energy use are relatively large for coal. The indirect CO_2 emissions and the methane emissions are not so large

that they would alter the contributions of options to CO_2 emission reduction much but it will have some effects [17].

It is difficult to predict the effects on the scenario results of including all the above mentioned issues. In Table 7.2 the effect of including the individual issues on the CO_2 reduction results of Rational Perspective cases with higher CO_2 taxes (100 or 200 ECU/tCO_2) has roughly been estimated.

Table 7.2 Estimated impacts on the CO_2 emission level in 2040 in Rational Perspective cases with high CO_2 tax level.

	Estimated change in CO_2 emission
Include feedback of energy demand to energy	-20%
prices	+10%
Endogenize energy prices	-20%
Extend abatement options	-10%
Include changes in material system	+20%
Distinguish between different market actors	+20%
Include implementation problems of technologies	+5%
Assume multiple electricity grids	+10%
Assume uncertainty in scenario conditions	-10%
Include technological learning	-5%
Include emissions of NO_x and SO_2	0%
Include emissions of non-CO_2 greenhouse gases	
Total	0%

It is expected that the net effect of including all the above mentioned issues will not change the results very much.

8. CONCLUSIONS

Base case scenarios

The first objective of this study is to forecast possible autonomous trends in CO_2 emissions from Western Europe. Two scenarios have been constructed which project different possible developments in the energy system until the year 2050 without restrictions imposed on the emissions of CO_2. The results of the two scenario show differences and similarities. The following conclusions can be drawn from the *similarities* in the results of the two base case scenarios:

- Western Europe will increasingly become dependent on imports of energy carriers.
- Oil remains the most important energy carrier for the Western European energy system.
- The role of natural gas will increase. Imports of natural gas by Western Europe will increase.
- The role of nuclear power will decrease.
- Gas fired power and coal fired power are the main power options. Gas fired power is favoured by the relatively low gas prices in the first decades of the next century. Coal fired power becomes more competitive in the last decades until 2050, at the expense of gas fired power.
- Total final energy consumption in industry and the household sector will not change much.
- The rate of growth in electricity consumption will decrease compared to historic rate of growth as a result of demand saturation, efficiency improvements and substitution by natural gas.
- Offshore wind energy and solar power are not competitive.

The following conclusions are based upon the *differences* in the results of the base case scenarios:

- There is substantial uncertainty about the autonomous development of the CO_2 emissions from Western Europe. One scenario projects a 1% annual growth in CO_2 emissions while the other scenarios has almost constant CO_2 emissions.
- The uncertainty in projected CO_2 emissions is mainly due to:

1) uncertainty in demand projections for the transport sector and
2) uncertainty in market penetration of efficient end-use technologies.

- Some renewables other than hydro (e.g. biomass fuelled power and wind turbines) could become competitive but this depends on the discount rate.

CO_2 reduction scenarios

The second and equally important objective of this study is to assess the potential role of energy technologies in the future energy system of Western Europe to limit future CO_2 emissions. To analyze this, various scenario cases have been considered with different levels of CO_2 reduction policy. The following conclusions can be drawn from the *similarities* in the results of the set of CO_2 reduction scenarios:

- There are larger possibilities to reduce CO_2 emissions in the long term than in the short term. However, it appears that to realise the implementation of this large efficiency improvement potential in the long term that early action is required in many instances. In many situations with long lifetime equipment "no action" implies a lost opportunity for low cost emission reduction.
- A mix which consists of different groups of energy technologies is required to limit the future emissions of CO_2.
- Near term reduction of CO_2 emissions will mainly have to result from energy efficiency improvements and fossil fuel switch.
- Also in the longer term energy efficiency improvements will continue to give the largest contribution to emission reduction compared to other groups of options.
- Additional emission reduction will have to come from renewables and, depending on the social acceptance, from CO_2 removal technologies or nuclear power.
- The absolute role of electricity in the energy system will increase with a CO_2 reduction policy. This is the result of substitution of fuels by electricity e.g. in the case of space heating, water heating and passenger cars.
- Reduction of CO_2 emissions is most cost-effective in the electricity sector.
- The transport sector is the sector where drastic emission reduction is most difficult.

- With stringent emission reduction the contributions from hydro power, biomass and wind turbines to the Western European energy system are similar in size.
- A CO_2 reduction policy can increase the fuel import dependency of Western Europe.

These conclusions are based upon the *differences* in the results of the CO_2 reduction scenarios:

- Reducing emissions in the high demand scenarios is more difficult. This is primarily caused by the higher level of baseline CO_2 emissions (transport sector) but also by the higher sectoral discount rates.
- The high demand scenario has a larger potential to reduce CO_2 emissions by efficiency improvements.
- Renewable energy technologies remain comparatively less cost-effective in the scenario with high discount rates.
- The cost to reduce CO_2 emissions depend on the baseline projection and the level of emission reduction. Compared to a base case scenario with modest growth in CO_2 emissions, the annual cost in 2040 amount to 100 billion ECU to achieve 50% emission reduction in 2040. With this amount of money, only 10% reduction of CO_2 emissions can be obtained in a high energy demand scenario.

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