Hydrogen or methanol in the transportation sector?

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Abstract

Governmental policies and international treaties that aim at curbing the emissions of greenhouse gases and local pollutants can be expected. These regulations will increase the competitiveness of CO_2-neutral energy sources, i.e., renewables, nuclear or fossil fuels with CO_2-sequestration. The purpose of this paper is to assess the relative competitiveness of methanol and hydrogen as fuels in the transportation sector. This is done using a global energy systems model, with a transportation module, where vehicle costs (fuel cell, reformer and storage tank), infrastructure, flexibility in fuel supply and biomass availability are treated explicitly. The model is then run under the assumption that atmospheric concentrations of CO_2 should be stabilised at 400 ppm. Two main results emerge: (i) despite the stringent CO_2 constraints, oil-based fuels remain dominant in the transportation sector over the next 50 years, and (ii) once a transition towards alternative fuels takes place, the preferred choice of fuel is hydrogen, even if we assume that hydrogen fuel cell vehicles are substantially more costly than methanol fuel cell vehicles. Detailed sensitivity analyses with respect to a number of important parameters are carried out.

TABLE OF CONTENTS

Abbreviations/Acronyms used in this study

NAM	North America
WEU	Western European Union
PAO	OECD countries in the Pacific Ocean
FSU	Former Soviet Union
EEU	Eastern Europe
LAM	Latin America
MEA	Middle East
AFR	Africa
CPA	Centrally Planned Asia
PAS	Other Pacific Asia
SAS	South Asia

PEM	Polymer electrolyte membrane, Proton Exchange Membrane
FC	Fuel Cell
IC	Internal Combustion
EJ	10^{18} J
H2	Hydrogen
MeOH	Methanol
FRG+	Freight, buses, ships
NG	Natural Gas

1. Introduction

The transportation sector has a poor environmental record: it impoverishes local air quality, causes acidification and is a major emitter of CO_2. In 1990, the transportation sector was responsible for some 25% of the world's energy use, and 22% of the global CO_2 emissions (IPCC, 1996). The enhanced greenhouse effect is by many considered as one of the most serious environmental problems. Calls for policies to reduce CO_2 emissions are growing stronger, and there is a widespread demand for viable CO_2 neutral primary energy sources. Although technological changes have reduced emissions of local pollutants, these emissions remain a serious problem in most countries of the world. Further technological development is needed to bring down these emissions to acceptable levels.

Fuel cell vehicles are by many seen as a promising option or even solution to these problems. Emissions of local pollutants are reduced to zero or near-zero levels, and CO_2 emissions are lower (because of the higher efficiency of fuel cells) or zero if renewable primary energy sources are used. However, it is still being discussed which fuel should be used in the long run, when there are stronger restrictions on CO_2 emissions. The two main candidates are methanol and hydrogen. Methanol and hydrogen can be produced from all fossil fuels, but if CO_2 emissions are to be kept at very low levels, renewable energy sources or fossil fuels with CO_2 sequestration are required.

It is in this context that bioenergy receives a steadily growing interest (see e.g., Hall *et al.*, 1993; Larson, 1993). Bioenergy, both residues and energy crops, can be converted into modern energy carriers such as hydrogen, methanol, ethanol or electricity (see Larson (1993) for a survey of bioenergy conversion technologies). Whether bioenergy should be used directly for heat or power generation, or converted into biodiesel, ethanol, methanol or hydrogen is still a debated issue. An emerging consensus, however, suggests that bioenergy should initially be used for heat generation, and/or co-generation, rather than in the transportation sector (Gustavsson *et al* 1995; Sterner, 1997). The main reason for this is the larger energy losses that are involved when converting biomass into liquid or gaseous forms. This means that you get more CO_2 reductions when using one GJ of biomass for heating than if converted into, say methanol, and used in the transportation sector.

Although the studies mentioned above are convincing, they only look into short-term issues. There are fewer studies available looking into the question on how to deal with the transportation sector once emission reductions are required in that sector as well. One option would of course be to use hydrogen derived from CO_2 free or neutral technologies. Hydrogen as a fuel in the transportation sector has several advantages (e.g., zero emissions and high efficiency when used in fuel cells and the fact that it can be generated from all primary energy sources in combination with water). Its major disadvantage is the additional costs associated with building a hydrogen infrastructure and the cost and volume requirement of hydrogen storage in vehicles. If these difficulties prove impossible to overcome, biomass derived liquid fuels may turn out to be the only option for the transportation sector. If so, one could expect biomass to be used for heat and power generation initially (the next couple of decades), and then used in the transportation sector (when deeper cuts in global emissions are required).

Thus, several studies suggest that methanol (or liquid biofuels in general) possibly in combination with hydrogen has an important role to play in the transportation sector under stringent CO_2 constraints (see e.g., IPCC Working Group II (Johansson & Ishitani, 1996), IIASA/WEC (1995), de Vries et al, 1999, Steen m fl, 1997).

Some recent studies which have specifically looked at the question of hydrogen or methanol in the transportation sector include, for example, Ogden *et al.* (1999), Adamson & Pearson (1999) and Jung (1999). Ogden et al. report values that suggest that hydrogen is the preferable option. Jung finds that the cost of hydrogen storage is comparable to the cost of the methanol reformer, and the development of these costs largely determines which technology is less costly. These papers neither look at the overall primary energy availability under stringent CO_2 constraints nor the demand for energy from other sectors (electricity and process heat).

In this study, we only look at three alternative fuels to gasoline/diesel in the transportation sector, hydrogen, methanol and natural gas. Methanol is used as a proxy for all liquid biofuels, and we have not analysed the relative advantages of methanol versus ethanol.

The purpose of this paper is to analyse the transition towards lower CO_2 emissions on a global scale. In particular we analyse

– the transition towards CO_2 neutral energy technologies in the transportation sector,

– the relative competitiveness of hydrogen and methanol in the transportation sector,

– the potential for bioenergy, in the form of hydrogen or methanol, in the transportation sector.

These issues are studied using a global energy model developed specifically for this project. It is a linear programming model that is globally aggregated and has three end-use sectors. It is set up to meet exogenously given energy demands while meeting a specific atmospheric concentration target at the lowest energy system cost. Obviously, the choice of atmospheric stabilisation target is a prime driver of the development in the energy system. We choose a stabilisation target of atmospheric CO_2 concentrations of 400 ppm, following Azar and Rodhe (1997). The impact of other stabilisation targets are also discussed.

In section 2, we present the model in some more detail. In section 3, we present the global energy scenarios disaggregated into three sectors. In section 4, we present our major assumptions regarding primary energy supply potentials and the development of future energy technologies (costs and conversion efficiencies), and in section 5 we discuss our assumptions about parameters more specifically related to the transportation sector, including vehicle costs, energy efficiencies, distribution and refuelling infrastructure. Our results are presented in section 6, and some conclusions and directions for further research are given in section 7.

2. Model description

The global energy systems model that we have developed focuses on the transportation sector, while the use of electricity and heat (which includes fuel use for both households and industry) is treated in a more aggregated way. The model is composed of three different parts: the primary energy supply, the final energy demand, and the energy conversion system (which includes technologies used in the transportation sector), see Figure 2.1.

Energy supply potentials, maximum expansions rates, the CO_2-emission limit and the demand side are exogenously given. Under these constraints choices are made between primary energy sources, conversion technologies, energy carriers and propulsion technologies. An optimisation algorithm is applied to the model in order to generate the solution that meets the energy demands with the lowest total costs.

The demand for electricity and heat is taken from a published study, see section 3.1. We have used a separate model to generate transportation scenarios, which in turn is used to generate the energy demands for personal and goods transportation, see section 3.2.

The supply side is characterised by limited annual energy supply from biomass, hydropower, wind power, solar electricity and solar heat, while the fossil fuels (natural gas, oil, and coal) are limited by a maximum total extraction over the time period 1990-2130, see section 4.1.

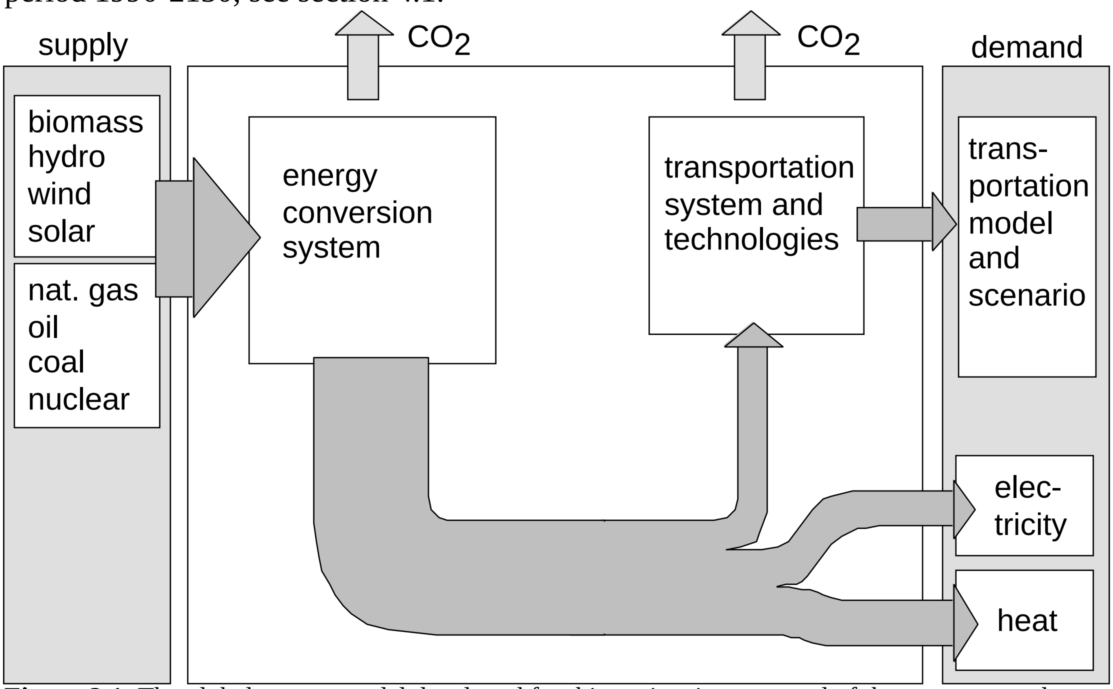

Figure 2.1. The global energy model developed for this project is composed of three parts: supply, demand, and the energy conversion system. The supply is characterised by annual or total extraction limits on the different available energy sources. The demand is exogenously given by a number of scenarios for transportation, electricity, and heat (including fuels for households and the industry). The technology system is characterised by a large number of technologies available both for conversion between different energy carriers as well as for vehicle propulsion. A cost minimisation algorithm with restriction on emissions of fossil carbon is then applied to generate scenarios.

The energy technology system has two components: technologies for production of energy carriers and technologies for distribution and use of transportation fuels. All technologies have their own characteristics in terms of investment costs, lifetime, efficiency and load factor, see sections 4 and 5. The model allows carbon sequestration to be applied to most fossil fuel conversion technologies.

3. Energy demand scenarios

Below we present the end-use energy demand scenarios that we used for this study. Future levels of GDP, electricity and heat (which includes fuels for all sectors except transportation) are assumed to follow the C1 scenario developed by IIASA/WEC [Nakicenovic *et al*., 1995]. This is one of their "ecologically driven" scenarios in which they assume that technological development leads to efficiency improvements, so that per capita energy demands in developed countries is reduced. A special scenario is developed for the transportation sector.

3.1 Per capita income

All IIASA/WEC scenarios provide for a substantial increase in economic. The assumed development of per capita GDP for the 11 regions used in the IIASA/WEC C1 scenario is shown in Figure 3.1.

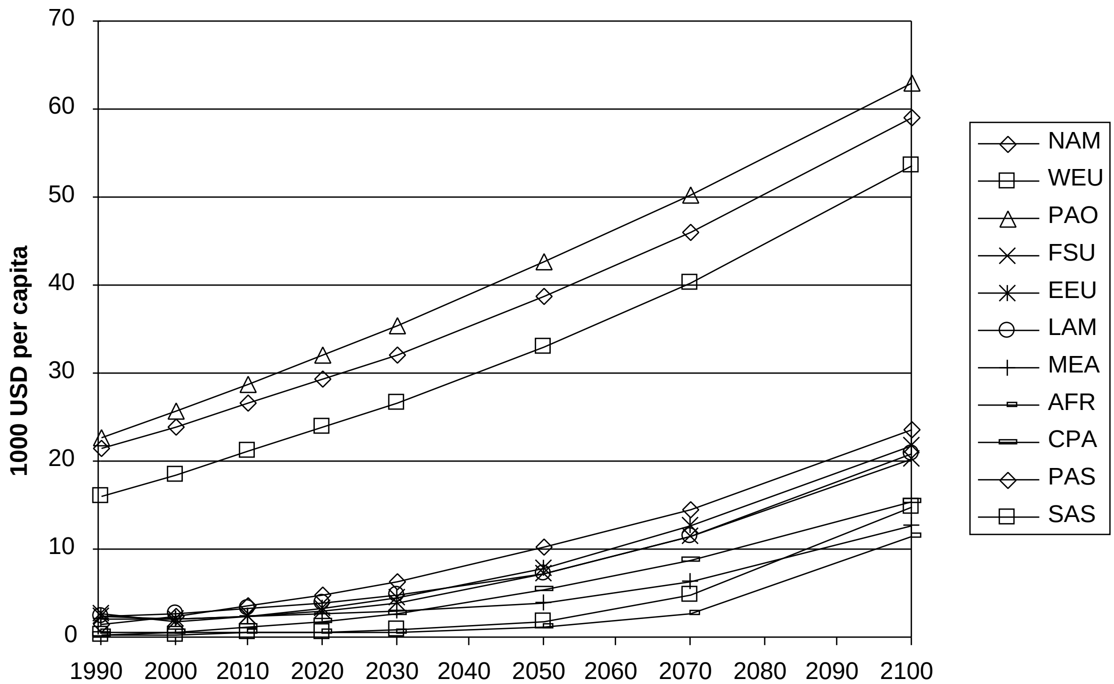

Figure 3.1 Development of per capita income in the IIASA/WEC scenario C1. This scenario is used as an input to this study. Key to the text box: NAM=North America, WEU=Western European Union, PAO= OECD countries in the Pacific Ocean, FSU=Former Soviet Union, EEU=Eastern Europe, LAM= Latin America, MEA=Middle East, AFR=Africa, CPA=Centrally Planned Asia, PAS=Other Pacific Asia, SAS=South Asia.

3.2 Transportation scenarios

We have developed separate scenarios for personal transportation and goods transportation (freight). The energy requirement is derived from *activity* measured as personkm (pkm) and tonnekm (tkm) and *energy intensity* measured as MJ/pkm and MJ/tkm. This results in four independent scenarios: personal transportation activity, personal transportation energy intensity, freight transportation activity and freight transportation energy intensity. In addition, scenarios for the number of cars and trucks in use are developed from the activity scenarios. The scenarios are made on a regional basis (eleven regions) and then aggregated to the world level. The developments of GDP_{PPP} per capita and population in the eleven regions that drive changes in activity are taken from IIASA/WEC scenario C1.

3.2.1 Personal transportation activity scenario

The scenario for personal transportation activity is based on a model developed by Schafer and Victor (Schafer 1998, Schafer and Victor 1999, Schafer and Victor 2000). In comparison to their original scenario, we have used other figures on economic growth and extended the scenario range from 1990-2050 to 1990-2100. The model parameterisation is derived from transportation data for the eleven regions for the time period 1960 to 1990. A precise mathematical description can be found in Schafer and Victor (2000). The model is based on two major assumptions, derived from two “anthropological constants” suggested by Zahavi (1981).

I *Total transportation activity per capita grows linearly with GDP_{PPP} per capita.*[1]
II *The average citizen in every society travels about one hour per day.*[2]

With a growing GDP per capita the two assumptions drive a change in modal split towards faster modes of transport. To fully determine the modal split between rail, bus, car and high-speed (mainly air but including high-speed trains) two additional assumptions are necessary.

III *The rail transport share decreases slowly in all regions.*
IV *The decreasing share of low-speed modes (bus and rail) in less industrialised regions with high population density (Asia) follow the trajectory of Japan and regions with medium density follow the trajectory of Western Europe.*

Schafer and Victor (2000) do not differentiate between different high-speed modes. Since high-speed modes grasp a growing share of total transportation during the modelled time-period such a differentiation needs to be made. Currently the share of

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[1] The mathematical formulation is somewhat more complex but results roughly in a linear relation.
[2] More specifically, Schafer and Victor use 1.1 hour.

high-speed trains is only significant in Japan were they account for 30% of high-speed personal transportation. On the global level we have assumed that:

V *Among high-speed modes, high-speed train increases its share from 4% in 1990 to 30% in 2100.*

The model version presented in this report use data aggregated to the world level (one region). The development of total transportation activity is presented in Figure 3.2. From 1990 to 2100 total transportation work increases ten times. Population growth accounts for half the increase. Personal mobility increases five-fold. Among modes, rail increases by a factor three, bus by a factor five, car by a factor eight and high-speed travel by a factor 40.

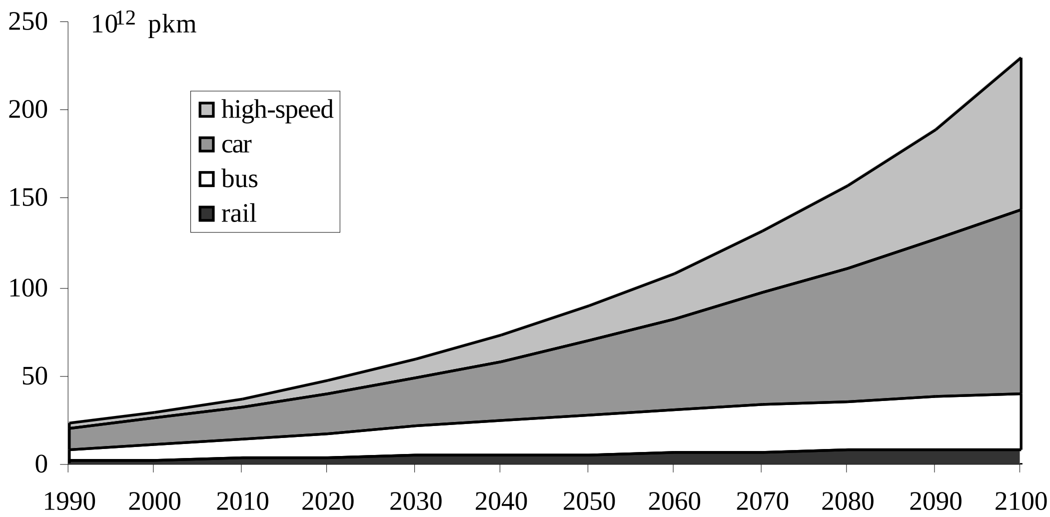

Figure 3.2 The future mobility of world population. High-speed modes include air and high-speed rail travel.

The aggregated scenario actually used in the model could correspond to a number of different scenarios at the regional level. However, as evident from the scenario architecture given above, the aggregated scenario was derived from particular regional scenarios.

The modal split for one industrialised and one less industrialised region, Western Europe (WEU) and Centrally Planned Asia (CPA), is shown in Figure 3.3 and 3.4. In CPA, cars become the largest mode of transportation around 2050, and in WEU, the share of car transportation declines continuously to be replaced by high-speed modes. As can been seen from Figure 3.5, the per capita distance travelled by car reaches a maximum between 2040 and 2070 in the three most wealthy regions of the world. In accordance with the above given assumptions I and II, people do not have time to sit in slow moving cars any longer. As a consequence car travel is equalised among regions at the end of the 21st century.

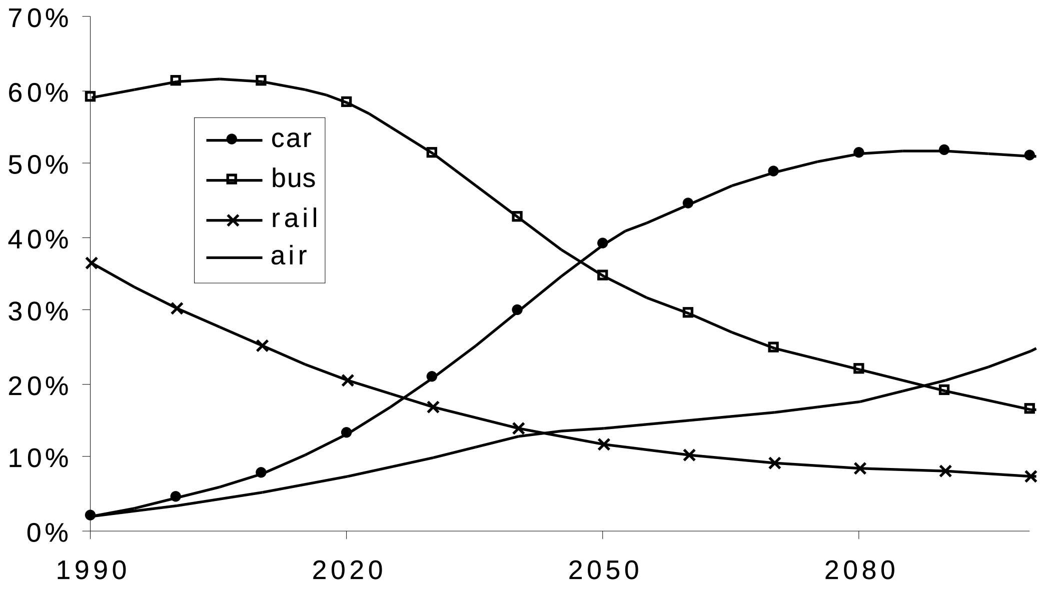

Figure 3.3 Modal split in CPA.

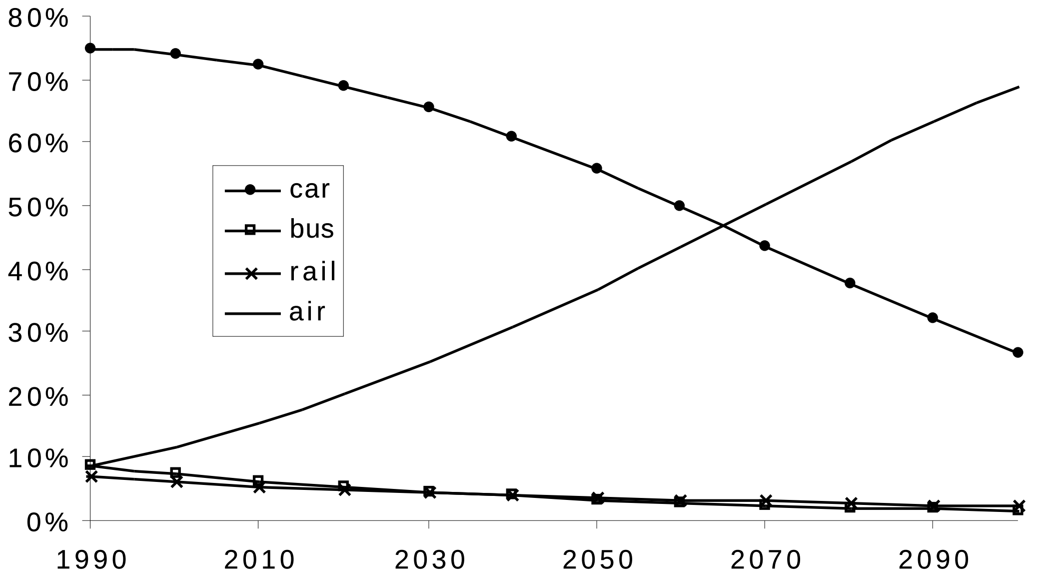

Figure 3.4 Modal split in WEU.

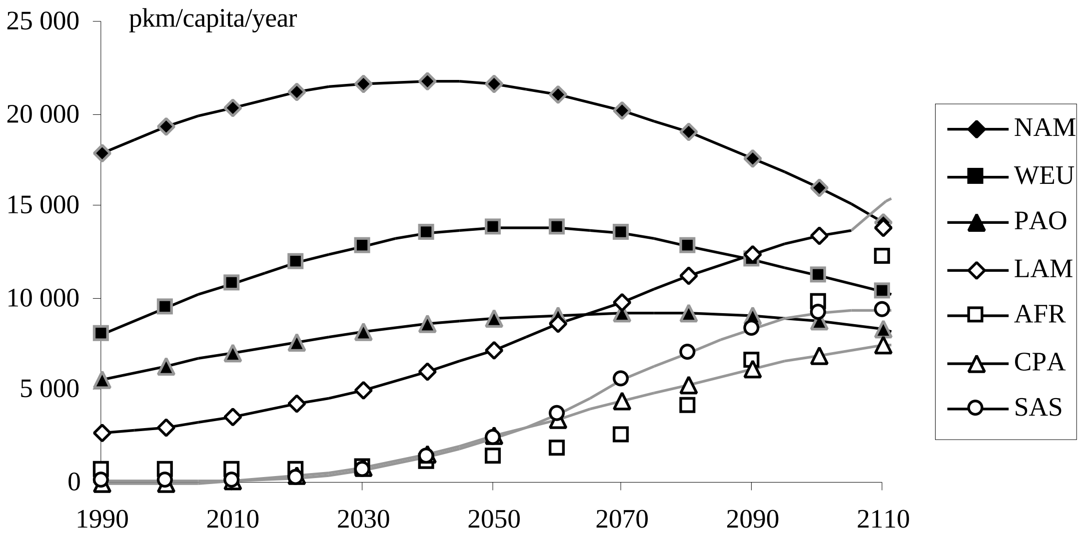

Figure 3.5 Per capita travel by car in seven regions. Initial values from Schafer (1999).

The most conspicuous feature of the scenario is the enormous growth of high-speed (primarily air) travel. The average European citizen increases her high-speed travel distance by a factor 30 and in North America, where people have the highest level of high-speed travel, the average citizen travel 41,000 km/year at high-speed in the year 2100. This may seem an awful lot, but in a world where companies are multinational and where social networks stretch out over the globe it might be realistic. In Europe the corresponding distance is 29,000 km/year. On the world level the growth rate for high-speed travel is 3.8%/year in the period 1990-2050 and 3.1%/year between 2050 and 2100. As a comparison, the growth in air travel was on average 9.7%/year between 1960 and 1990. In IPCC's special report on aviation, several different scenarios for air traffic growth 2100 are used, ranging from growth rates as low as 2.2%/year to 4.7%/year (IPCC, 1999). In the high growth rate scenario, CO_2 emissions reaches 1.5 Gton C/year by the end of the century.

We also developed an alternative scenario, in which personal high-speed travel saturates between 3000 and 9000 km/year in the different regions of the world. This is about 1 to 3 times the current level in North America. The two high-speed scenarios are illustrated in Figure 3.6. We have chosen to use the low-level scenario as the base case in the model, but results from both runs are presented in section 6.

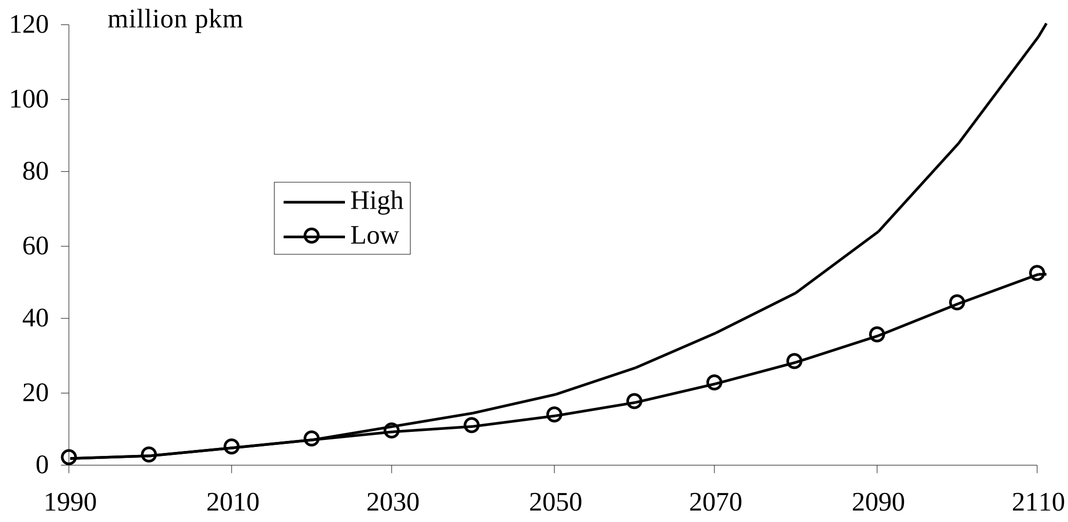

Figure 3.6 High and low high-speed personal transport scenarios. The low-level scenario is used as the base case in the model.

3.2.2 The number of cars

The number of cars (light-duty vehicles that transport people) in use was calculated by assuming that the annual driving distance per vehicle remains at about 22,000 km in North America, remains at or approach 12,000 km in densely populated regions (Asia) and 15,000 km in all other regions. The growth of world car population is shown in Figure 3.7. The global car density saturates at about 0.5 cars per capita around 2100, about the density in Sweden and Germany in the 1990s.

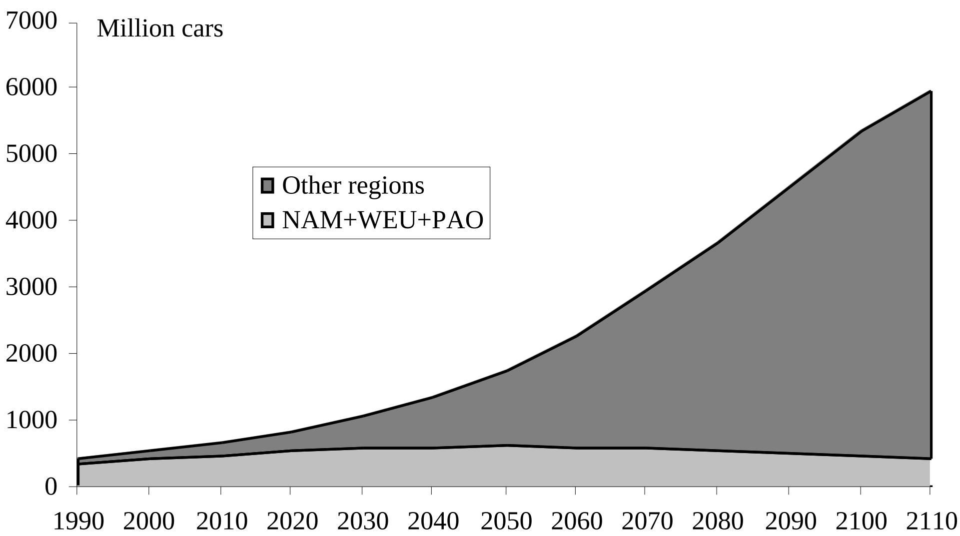

Figure 3.7 The future of world car fleet.

3.2.3 Personal transportation energy intensity scenario

We assume that the energy intensity decreases continuously for all modes of transport in all regions with the exception of high-speed rail. The world average for each mode is also affected by the varying development of transport activity among regions (Figure 3.8). The world average for personal transportation in total is in addition affected by the modal shift. The shift towards more energy intensive modes causes the average to decrease less in relative terms than each mode taken by itself (with the exception of high-speed rail[3]).

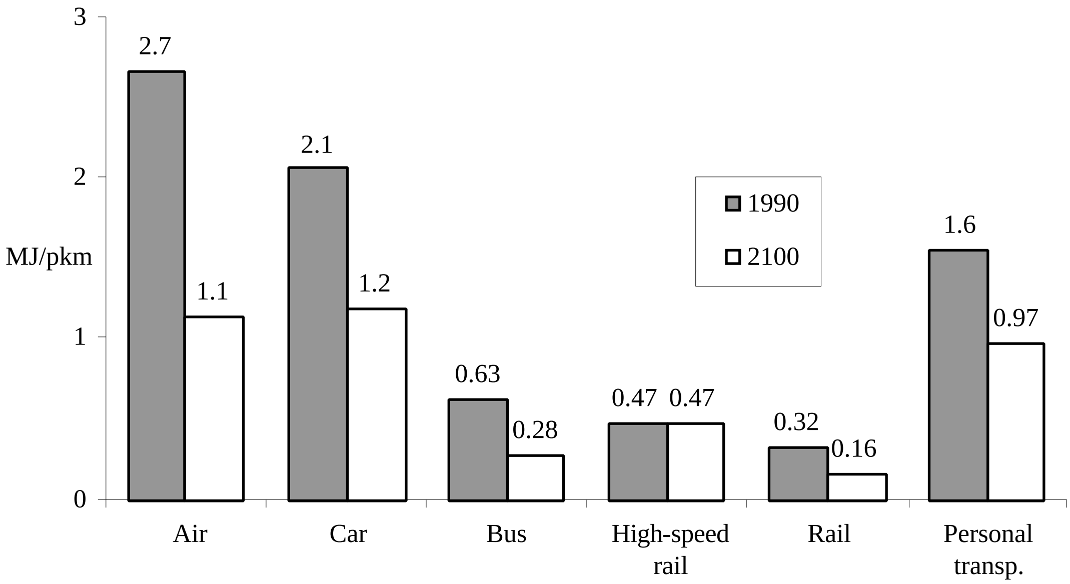

Figure 3.8 The assumed energy intensities of personal transport in 1990 and 2100. Values for 1990 are calculated from data given by IEA 1997, Schafer and Victor 1999 and Råde 1997.

These efficiency developments refer to today’s types of technology, for example gasoline internal combustion engine cars. These technology types do not have to be produced in 2100 but serve as reference technologies. An introduction of fuel cells would for example lead to additional efficiency gains.

Air transport is assumed to become 1-2% more efficient per year in terms of MJ/pkm in the period 1990 to 2020 based on assessment made by the World Energy Council (WEC 1998). Thereafter the energy intensity is assumed to decrease by 0.7% per year. As a result the intensity in 2100 is 1.1 MJ/pkm or 43% of the intensity in 1990. As a comparison, Green (1992) estimates energy use for future air crafts to fall in the range 0.9-1.2 MJ/pkm (60% load factor).

High-speed rail is assumed to develop towards faster speeds. We assume that the increased energy use due to speed increase evens out efficiency gains from technological progress. The intensity in 1990 represent values for Japanese high-speed

[3] High-speed rail affects the total average marginally since it only uses 0.1% of personal transportation energy in 1990 and less than 6% in 2100.

trains (Shinkansen, 60% load factor) with a top speed of 240 km/h (Hirota & Nehashi 1989). Energy intensities for future maglevs with top speeds in the range 400-500 km/h are estimated to fall in the range 0.3-0.7 MJ/pkm (Råde 1997).

Cars are assumed to become 0.7% more efficient per year in terms of MJ/vkm in each region. As a result the energy efficiency about doubles between 1990 and 2100. The reference gasoline internal combustion engine car in 2100 consumes 5.7 litres of gasoline per 100 km. In addition the load factor in all regions are assumed to follow the economic development and converge towards 1.5 pkm/vkm from initial values ranging from 1.5 in NAM to 2.5 in AFR, MEA, CPA and SAS (IEA 1997, Schafer 1998). As a consequence the intensity in terms of MJ/pkm does not decrease by more than 43% from 1990 to 2100. For comparison, between 1970 and 1994 the energy intensity (MJ/pkm) increased in Europe (average for eight countries) and Japan by 0.2% and 0.5% per year respectively, and decreased in the US by 0.9% per year (IEA 1997).

Buses are assumed to become 0.7% more energy efficient per year in terms of MJ/pkm in each region. This implies a reversal of the historic trend in OECD countries where intensities have increased by about 1% from 1973 to 1994 (IEA 1997). Raskin and Margolis (1995) assume a 1% annual decrease in intensity until 2050.

Rail is assumed to show constant efficiency in terms of MJ/pkm in each region. Technological progress is assumed to just about compensate for decreasing load factors. The initial energy intensities are lower in Japan and less developed regions than in Europe and North America. The decrease of the world average comes from a faster growth of rail travel in less developed regions. In the period 1973-1993 the energy intensity of rail travel fell by 1% annually in Europe, remained constant in Japan and increased by 0.8% per year in the US (IEA 1997). Raskin and Margolis (1995) assume 0.5% decrease per year until 2050, while Schafer and Victor (1999) assume that the intensity in less industrialised regions will have caught up with the intensity in industrialised regions in 2050, implying a 1.2% increase per year.

3.2.4 Freight transport activity scenario

The scenario for continental freight transport in each region and for intercontinental ocean freight is derived from freight *activity intensities* (tkm/GDP_{ppp}) and economic growth (GDP_{ppp}). The activity intensities for 1990 given in Figure 3.9 are calculated from values for 1995 (WEC 1998). These initial freight activity intensities reflect differences in demographic patterns as well as industrial structure and income level. One assumption determines the change of activity intensities.

I The income elasticity for freight transport is set to –0.5.

The income elasticity (e) is defined as

$$e = \frac{\Delta I / I}{\Delta y / y} \tag{1}$$

where I is the freight activity intensity (tkm/GDPppp), $\Delta I/I$ the annual rate of freight activity intensity change, y the GDPppp per capita, and $\Delta y/y$ annual rate of GDPppp per capita change. If the income elasticity is –0.5 and the per capita GDPppp grows by 2%, the freight activity intensity decreases by 1%, and, if the size of the population does not change, freight activity increases by 1%.

Raskin and Margolis (1995) use an income elasticity of –0.53 derived from country-level data for one year. An analysis of figures for 1973 and 1989 given by Schipper (1997) indicates elasticities in the range –0.40 to –0.55 for the US and the Scandinavian countries while the elasticity was higher in Japan (–0.89) and lower in an aggregate of the four largest European countries. One could argue that it is likely that e should be less negative or even positive for economies in an early phase of industrialisation and approaching or even fall below –1 for economies that become dominated by services. Such a pattern of dematerialization of economies has not yet been rigorously shown (see for example Cleveland and Ruth (1999) and de Bruyn and Opschoor (1997) for a general discussion of the existence of dematerialization on the macro level). In lack of a well-founded theory we will simply set e to –0.5 for all regions and all time periods. The resulting freight transport intensities for 2100 are given in Figure 3.9.

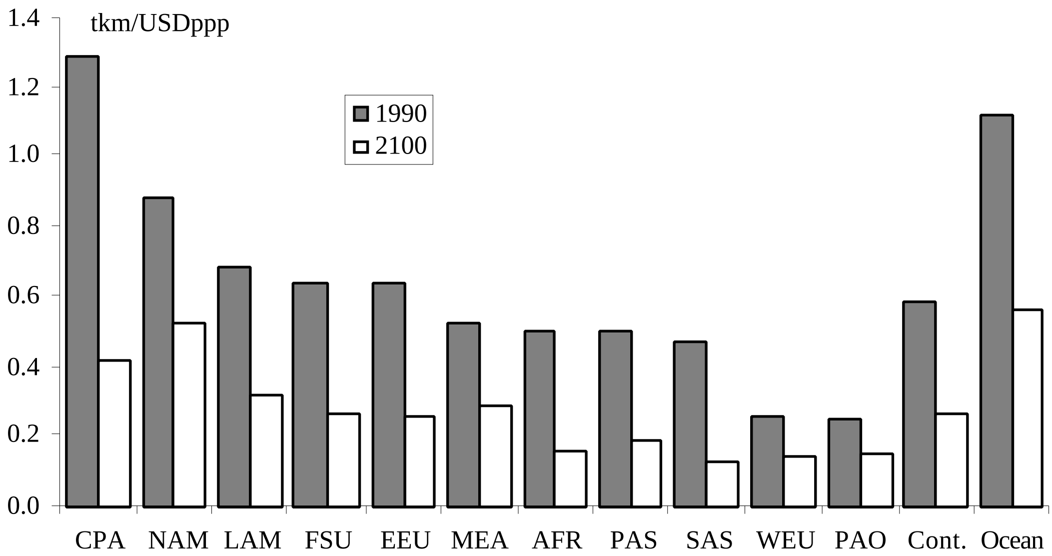

Figure 3.9 Freight transport intensity in 1990 and 2100 for the eleven regions, for world continental freight on average (Cont.) and for ocean freight. Values for 1990 from WEC (1998).

The modal split of continental freight is determined by the assumption that road and air transportation will continue to grow faster than rail and water transportation (WEC 1998, Raskin and Margolis 1995, US Department of Transportation 1998).

II The shares of rail and water transport decrease by 0.5% per year in all regions. Road and air transport shares increase proportionally to their initial values.

The resulting scenario for freight transport activity is given in Figure 3.10. Freight transport per capita increases about two times while the average income grows by a factor four. Intercontinental ocean transport dominates but road transport has the highest relative growth rate. Road transport grows by a factor six, air and ocean transport by a factor four and continental water and rail about doubles.

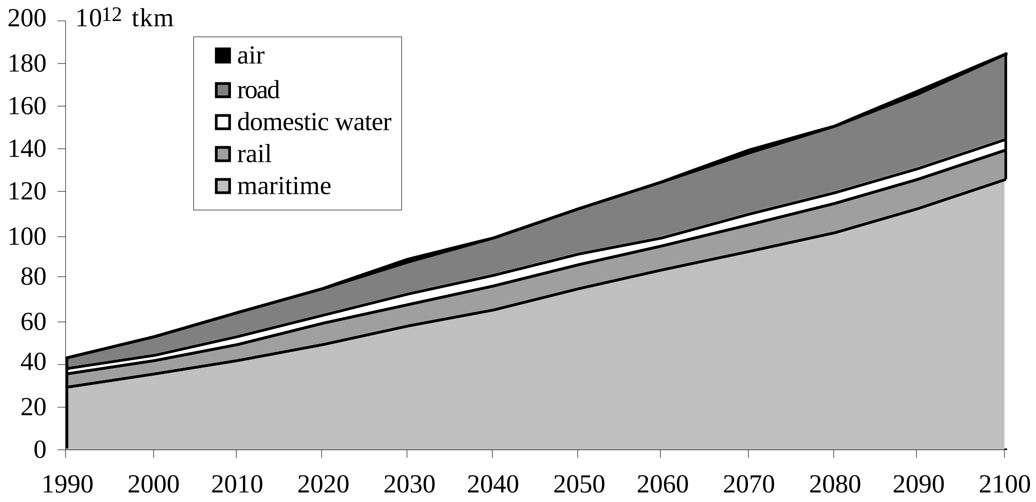

Figure 3.10. Scenario for the development of global freight

3.2.5 The number of trucks

The number of trucks that carry goods[4] was calculated by assuming an average transport work of 80,000 tkm/year per truck. The average in USA, Sweden and China in the 1990s was about 90,000 tkm per truck used for freight transportation (US Department of Commerce 1999, SCB 1998, SCB 1992, Yun 1996).[5] According to truck statistics (Davis 1999) the world average transport work per truck appears to be lower.

[4] There is a large number of light trucks in the USA that are used for personal transport, these are accounted for in the car category of personal transport.

[5] The major part (>95%) of the transport work is done by medium and heavy-duty trucks that only make up a minor part of the truck population (20% in the USA and Sweden) (US Department of Commerce 1999, SCB 1992, SCB 1998)

3.2.6 Freight transportation energy intensity scenario

The figures for energy intensity in 1990 are calculated from figures given for 1995 by WEC (1998). The energy intensity of rail and continental water transport is assumed to decrease by 0.4% per year in all regions (Raskin and Margolis 1995). WEC (1998) estimate values between 0 and 1% per year between 1995 and 2020 for the eleven regions. We have assumed the same efficiency gains (0.4%/year) for ocean transport. Air-freight transport is assumed to follow air personal transport and become 1-2% more efficient per year in 1990 to 2020 (WEC 1998) and 0.7% more efficient per year thereafter. Raskin and Margolis (1995) use 1.2% per year until 2050. We assume that the energy intensity for road freight transport decreases by 0.7% per year in all regions and all time periods. WEC (1998) use figures between 0.5% and 1.8% between 1995 and 2020 while Raskin and Margolis (1995) use 0.4% for all regions until 2050. The resulting efficiency gains from 1990 to 2100 are illustrated in Figure 3.11. The relatively low decrease in energy intensity for the average of all continental freight transport modes depends on the shift towards the more energy intensive modes road and air. Ocean freight that dominates transport activity (Figure 3.10) is comparatively energy efficient and in terms of total energy use road transport dominates the freight transport sector.

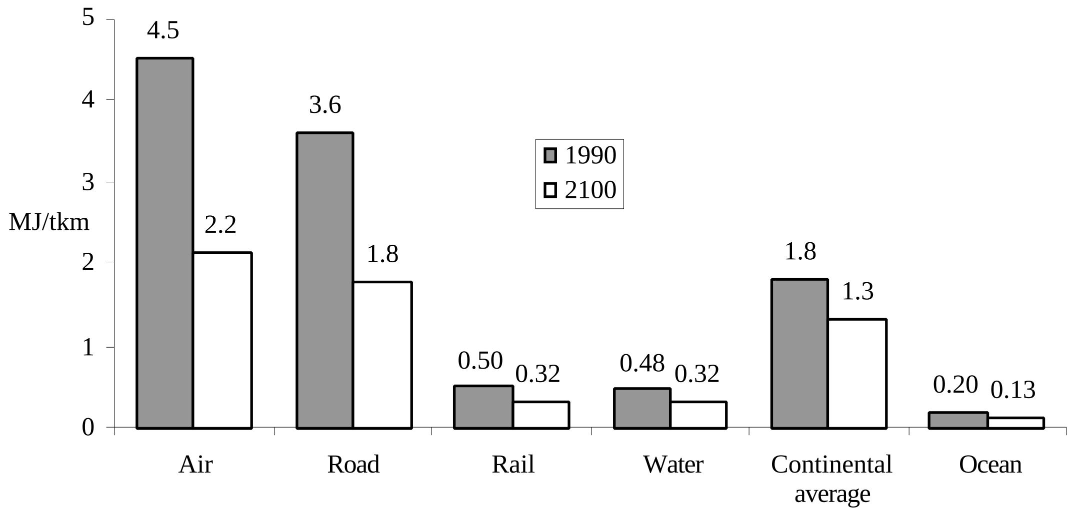

Figure 3.11. Energy intensities in freight transportation

3.3 Electricity and heat demand

The per capita demand of electricity and heat, for the 11 regions of the C1 scenario, is shown in Fig 3.12 and 3.13, respectively. It is assumed that technological development trigger large improvements in energy efficiency, clearly visible in the figures for North America (NAM) where there is a strong decrease in per capita demand, both for electricity and heat. In other regions strong economic development may increase the per capita demand even if efficiency improvements are taken into account. It is also assumed that electricity will replace parts of the heat demand, and, therefore, there are only insignificant changes in the per capita heat demand for the developing countries.

Despite the increased energy efficiency, this results in an aggregated (global) demand for electricity in the C1 scenario that increases from 40 EJ_{el}/year (by year 2000) to 130 EJ_{el}/year by 2100 — an increase that to a large extent is driven by the assumed improved economies in developing countries. The aggregated heat demand increases more slowly, from 175 EJ/year to 220 EJ/year by 2050 from where it remains throughout the century.

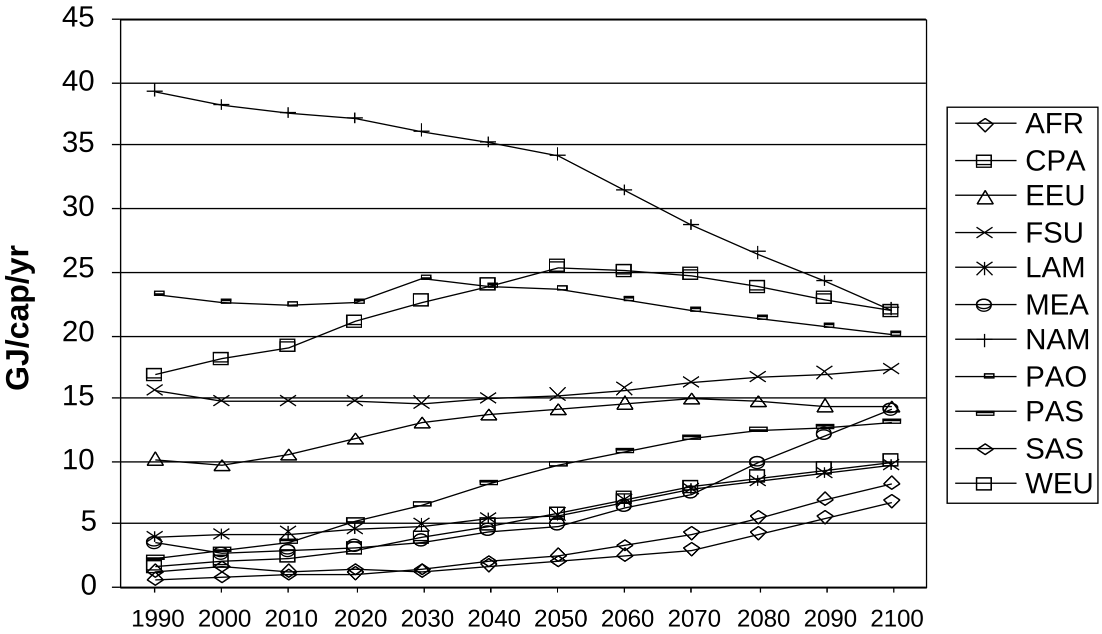

Figure 3.12. Per capita electricity demand.
Source IIASA/WEC (1995)

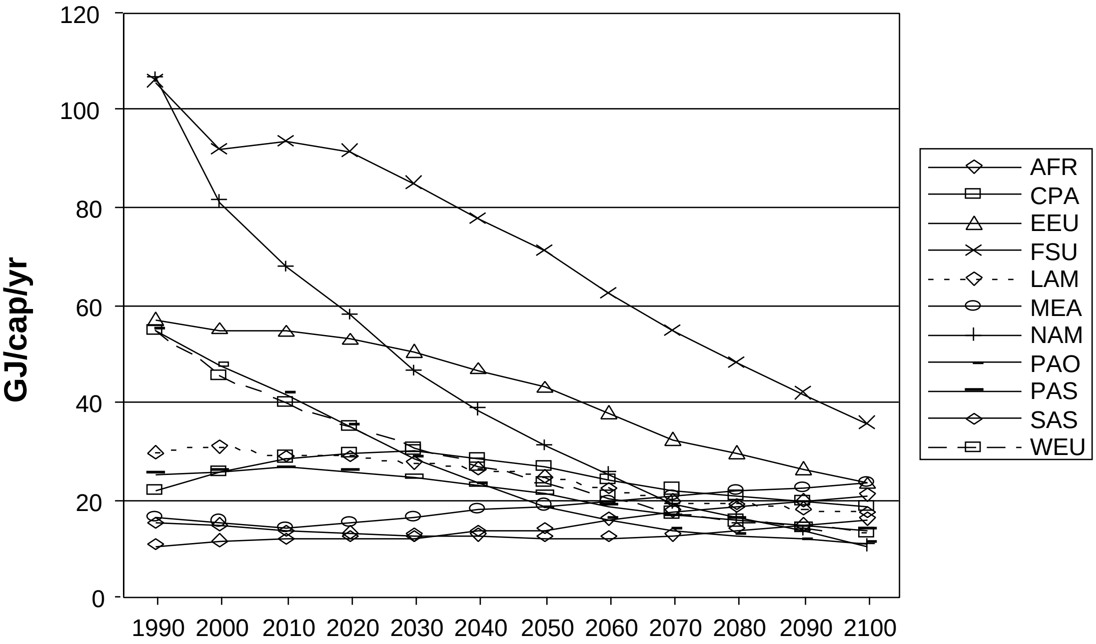

Figure 3.13. Per capita heat demand.
Source: IIASA/WEC (1995).

4. Supply potentials and energy conversion technologies

4.1 Supply potentials

A major factor affecting the choice of hydrogen or methanol in the transportation sector is the availability of biomass. Methanol can be produced from all fossil fuels and biomass, but would in the long run be dependent upon biomass if the fuel supply should be CO_2 neutral.[6] On the other hand, hydrogen can be produced from almost any other primary energy source. This is a clear advantage for hydrogen. Thus, the choice of fuel in the transportation sector is to some extent determined by the availability of biomass. We start this section with a discussion on global bioenergy supply potentials, and then turn to other primary energy sources.

4.1.1. Bioenergy

Bioenergy is the dominant energy source in developing countries at present. It also plays a significant role in several developed countries. For instance, the US has some 10,000 MW of installed capacity of electricity generation from biomass, primarily in the pulp and paper industry. The use of bioenergy in Sweden exceed 30 GJ/cap annually, which is substantially more than the bioenergy use in most, if not all, countries.

Bioenergy supplies can be divided into two broad categories: (i) organic municipal waste, and residues (and by-flows) from the food and materials sectors, and (ii) dedicated energy crops plantations. Residues include wood from forest felling and thinning, sawmill and papermill residues, animal dung, and harvest residues from food and fibre crops production. Residues represent a large potential source for bioenergy. The energy value of residues generated world-wide in agriculture and the forest-products industry amounts to more than one third of the total commercial primary energy use at present (Hall et al. 1993, p. 607). For instance, bagasse (a residue from sugar cane processing) could be used to generate substantial amounts of electricity (some 4 EJ_e/yr by the year 2025 according to Larson & Kartha (2000)).

Dedicated plantations include sugar crops (sugarcane, sugar beet, sweet sorghus), starch crops (corn, wheat, barley), oil crops (rapeseed, soybean, sunflower, oilpalm), perennial herbaceous crops (switchgrass, reed canary grass, miscanthus), and short rotation woody crops (salix, poplar, eucalyptus). The energy balances of traditional row crops are generally very poor or even negative (except for ethanol from sugar cane

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[6] In theory, it is possible to use fossil fuel based primary energy sources to produce methanol, but this would require that CO_2 sequestration is applied at the tail pipe - a technology that we have not considered in this publication. We have also abstained from assessing a-methanol, i.e., methanol that is produced from hydrogen and atmospheric CO_2. Obviously, if the hydrogen supply and the energy supply to the conversion plants are CO_2 neutral, then that also applies to produced methanol. However, it has not been possible to find any reliable cost estimates on what this energy carrier could cost in the future.

in tropical regions). However, woody and herbaceous biomass have substantially better net energy yields since the energy inputs in cultivation is lower and the conversion to modern biofuels is more efficient (Berndes *et al* 2000). Still there are environmental and socio-economic factors that have to be taken into account when assessing the sustainability of plantations (see Carrere & Lohman, 1996). In particular, the potential food-bioenergy conflict warrants special attention (see Azar & Berndes, 1999).

At present, bioenergy supplies are dominated by traditional sources. Roughly some 30-50 EJ/year are supplied in the form of firewood, dung and other agricultural residues. However, once carbon abatement policies are adopted, new markets for bioenergy are created. For instance, following the adoption of a carbon tax in Sweden in 1990, the annual use of forest residues in district heating began to rise rapidly (roughly 10 PJ/year/year, see Kåberger 1997).[7] Thus, bioenergy can be expected to play a more important role in the future if carbon abatement policies are adopted.

There are several estimates of the global supply potential for bioenergy. For instance, Hall *et al* (1993) estimate the potential supplies from residues at 77 EJ and the potential supply from dedicated energy plantations at 128 EJ by the year 2050. The plantations would require 429 Mha of land. This implies an average yield of 300 GJ/ha/year. In the LESS scenarios presented in Johansson & Ishitani (1996), total bioenergy supply is even higher (329 EJ/yr by the end of this century), claiming 572 ha of land. Leemans et al (1996) using the IMAGE model claim that the land use requirement for the LESS scenario is as high as 800 ha. In a study by IIASA/WEC the supply reaches 300 EJ/year, and land demand (in the most extreme scenario) above 1300 Mha. A more detailed assessment of global biomass supply potentials is given in Berndes (1998).

Estimating the potential supplies of bioenergy is a highly contentious task, since it does not only depend upon uncertainties of the actual physical supply (see Berndes 1998, Johansson & Lundqvist, 1999). It does also depend strongly on the assumptions on food and industrial roundwood demand. In particular, a too large bioenergy demand could come into conflict with safeguarding food security in developing countries. In most energy scenarios, bioenergy supplies are treated in a simplified way and that is the case in our model as well. We assume, as a base case, that the maximum potential for bioenergy is 200 EJ/yr. This supply potential can be reached in the year 2060. We then analyse the impact on the choice of fuel in the transportation sector by both doubling and halving this supply potential.

4.1.2 Hydropower and geothermal

The installed capacity of hydropower is 687 GW_e and it generates some 9 EJ_e/year of electricity (ABB 1998). The potential for hydropower depends on economic, technical, social and environmental considerations. In a detailed assessment of the

[7] The carbon tax in Sweden is now roughly 180 USD/ton C for private consumers.

global hydroelectricity potential, Moreira & Poole (1993) notes that the theoretical hydroelectricity potential is 160 EJ_e/year, the technical potential is 70 EJ_e/year and the long-term economic potential may be on the order of 20-30 EJ_e /year. Most of this potential is in the Former Soviet Union and the developing countries. We have assumed a maximum potential of hydro at 15 EJ_e/year.

The installed capacity of geothermal power is much smaller, 9 GW (ABB 1998) which is less than the total capacity of the world's largest hydropower dam, Itaipú in Brazil. We do not consider geothermal as a separate energy source in this report.

4.1.3 Intermittent solar and wind

Wind energy is the fastest growing energy technology in the world, measured in relative terms. The annual average growth rate during the 90s was roughly 20%/year, and the installed global capacity reached 10,000 MW by the end of 1998 (ABB 1998, Neij 1999). This growth has also led to reductions in the cost of wind electricity. The cost of wind power is now in the range 700-1000 USD/kW depending on the size of the wind turbine (Neij 1999). When it comes to building new electricity generating capacity, wind power is next to natural gas, the most cost-competitive technology. Thus, there are reasons to believe that wind power will continue to grow at an impressive rate. Under the assumption that this growth rate remains constant over the next couple of decades, wind power will supply 4 EJ_e/year by 2020, which corresponds to some 5% of the expected global electricity supply in that year.

Although having higher costs in terms of USD per kW, solar photovoltaics (PV) currently gain more interest than solar thermal power plants. Total PV capacity is an order of magnitude lower than that for wind, but PV shows similar features in terms of growth rate and learning. Still, for cost reasons the aggregated installed capacity is much lower. In 1998 the cumulative production reached 1 GWp. Average growth rates during the 90s was roughly 17%/year, and this has led to a significant reduction in PV prices. Module prices are now down to somewhere between 3000 and 5000 USD/kWp. Under the assumption that this growth rate continues, PV will produce some 0.2 EJ_e/year by the year 2020. It is only by the year 2043 that PV reaches 10% of the global electricity supply if the average growth rate remains at 17%.

The global potential for solar and wind electricity is huge. The annual solar influx towards the earth is 5,000,000 EJ/year, some 10,000 times more than the global societal energy use. Roughly, one tenth of the area of Sahara would be sufficient to produce all the energy that is needed to fuel the world. The "gross electric wind potential" has been estimated at 2000 EJ_e/year (Grubb & Meyer, 1993). Obviously, this much electricity will never be produced using intermittent electricity generating technologies. Rather, intermittency problems will limit the total supply potential (unless, e.g., hydrogen is used as an energy carrier). We have limited its potential at 30% of the global electricity supply. Wind is assumed to take a maximum share corresponding to 20 EJ_e/year of this potential, which corresponds to 3,000,000 wind power plants of 1 MW_e each.

Solar energy can also be used to produce heat. Unfortunately, most of the heat is needed in regions where there is little sun. We have assumed that solar heat can produce at the maximum 5 EJ of useful heat. Admittedly this is a rough estimate but even major changes in this assumption would not make any difference for the questions studied in this paper.

4.1.4 Solar hydrogen

Solar hydrogen is used here as a collective term for hydrogen produced from solar and wind electricity, or from solar energy directly. Since these technologies are not limited by being intermittent, we treat them separately. Further, the huge solar energy potential referred to above imply that we have not assumed an upper limit on these technologies.

The cost of the technology is assumed to be 2,000 USD/kW, leading to a fuel price of 18 USD/GJ. This is somewhat less optimistic than the estimates in the IPCC Second Assessment Report (Johansson & Ishitani, 1996) in which the cost of hydrogen from low cost wind or PV and subsequent electrolysis is estimated at 10-18 USD/GJ. On the other hand, our higher cost could be seen to include transportation to city gates. Changes in this parameter were shown to have no significant impact on the development in the transportation sector.

4.1.5 Nuclear

It is beyond the scope of this study, to analyse the future of nuclear power in any detail. We have merely assumed that the maximum annual electricity production in the world's nuclear power stations does not exceed present production.

4.1.6 Fossil reserves

Scarcities of oil and gas may drive changes in the future global primary energy supplies. At present, fossil fuels are abundant and available at low cost. A recent detailed assessment of the world's hydrocarbon resources can be found in (Rogner, 1997). We have assumed that the available reserves of oil and natural gas are 12,000 EJ and 10,000 EJ, respectively, i.e., twice their present reserves. Rogner is optimistic about the prospects for oil and natural gas. A more pessimistic is expressed by Campbell & Laherrère (1998). The availability of coal is substantially higher (50,000 EJ). Rogner (1997) estimates the unconventional supplies of oil and natural gas to be substantially higher than the numbers assumed here. However, since carbon dioxide constraints limit the use of fossil fuels, sensitivity analyses with our model show that extending the reserves does not have any significant impact on the choice of fuel in the transportation sector (see section 6).

4.2. Primary energy costs

Below, we present the assumed costs of various fuels. Obviously, future costs are very uncertain, and the costs will vary by region and point in time.[8] Also, biomass costs vary substantially depending on the source (residues are much less expensive than dedicated crops). The costs assumed for oil, natural gas and biomass increase over time due to rising scarcity rents. The cost of hydrogen from solar is presently much higher than what we have assumed here. The cost for solar hydrogen given in the table reflects the cost that is estimated to be reached by the year 2040.

Table 4.1 Assumed fuel costs

Fuel	**USD/GJ**
Coal	2
Oil	3
Natural gas	2.5
Biomass	3
Solar hydrogen	18

4.3. Hydrogen and methanol production

Methanol and hydrogen are already produced in large quantities. Production capacity in the global methanol industry is 33.5 Mt/year, which can be compared with the actual production of 26 Mt/year (Hart *et al* 1999). Ten percent of this excess capacity would be sufficient to fuel 3 million cars. A similar conclusion holds for hydrogen. The global production is currently roughly six times that of methanol in energy terms, 3 EJ/year vs 0.5 EJ/year. Below and in the appendix, we present our main assumptions as regards capital costs for hydrogen and methanol production. In the appendix, we also present our assumptions on capital costs and conversion efficiencies for electricity and heat production. Onboard reforming of gasoline and methanol into hydrogen is discussed in section 5.

Although the long-term costs are very uncertain, the cost differentials between hydrogen and methanol production from different primary fuels can be understood from basic physical and chemical properties.

First, conversion of natural gas into methanol or hydrogen can be done at higher efficiency and at lower cost than what is the case for biomass and coal. The capital cost of natural gas based production technologies can be expected to be substantially lower than for biomass or coal-based plants. This follows from the fact that gasification of the fuel is not needed when natural gas is used as a feedstock. This also explains the expected higher energy conversion efficiency.

[8] In short the model will be regionalised and regional availability and costs of biomass and natural gas will be considered explicitly.

Second, we have assumed that the costs for converting coal and biomass are equal. Biomass is more reactive than coal, and is therefore easier to gasify. On the other hand, economies of scale work in favour of coal since the optimal scale for biomass conversion plants is smaller than for coal because biomass is more costly to transport (see Larson & Marrison, 1997).

Third, conversion of natural gas, biomass and coal into hydrogen is generally more energy efficient and less expensive than conversion into methanol. The investment cost for hydrogen production is lower for two reasons: higher conversion efficiency (which reduces equipment size for a given output) and the fact that methanol synthesis is more complicated than water-gas shift reaction and hydrogen separation (required for hydrogen production). On the other hand, a compressor is needed for hydrogen production, but this additional cost does not make up for the difference. In total, a 600 MW hydrogen plant is expected to cost 300 USD/kW (Ogden, 1999). This can be compared to the cost of producing methanol. Industry representatives state (cited in Hart et al, 1999, p 20) that present costs of methanol production capacity is roughly 350 USD/ton,yr which translates into 500 USD/kW. These costs are for rather small plants (300 kt/year or 200 MW). Plants in the GW size could be expected to cost some 25% less. Ogden *et al* (1999) report capital costs in the range 330-570 USD/kW for a 3 GW plant.

4.4 Decarbonisation of fossil fuels

There is a growing interest in carbon management, i.e., the employment of technologies that capture CO_2 from fossil fuel combustion. This can be done in two distinct ways: flue gas or fuel gas decarbonisation (Williams 1996).

One option would be to combust fossil fuels (the "traditional" way) to produce heat or electricity and then capture CO_2 from the flue gases. This way would only be applicable to large stationary power or heat plants, since the economics of CO_2 sequestration and transportation would render the technologies very expensive on a small scale. In this paper, we have assumed that 30% of the global energy use in stationary applications (excluding electricity generation) can be equipped with decarbonisation technologies.

The second option involves a transformation of the fossil fuels to produce hydrogen. CO_2 is then obtained as a by-product. The capture cost would be lower than what is the case for the first option since the CO_2 is obtained in the process in a pure form. The hydrogen can be used to produce electricity (in an integrated plant or elsewhere) or be distributed to industries, the transportation sector or households. In this way, the entire energy sector can rely on decarbonised fossil fuels.

It should be stressed that both these ways of capturing CO_2 are commercially available technologies. Capturing CO_2 from gas streams are practised at natural gas explorations as well as from some power plants. Hydrogen production is largely based on steam reforming of natural gas and partial oxidation of oil and coal. Overall, some 3 EJ/yr of hydrogen is produced in the world.

As a general rule, the capture cost is lower the more concentrated the gas is in CO_2. For this reason, flue gas decarbonisation is less expensive than flue gas decarbonisation. Further, as for fuel gas decarbonisation, coal is less expensive than oil which is less expensive than natural gas per ton of captured CO_2. Since coal is a more CO_2 intensive fuel than oil and natural gas in terms of CO_2 emissions per MJ, the difference in sequestration cost per MJ of fuel becomes reversed. This difference grows even larger on a USD/kWh_{el} basis since the conversion efficiency is higher for natural gas than for coal.

The costs of CO_2 sequestration are generally estimated to lie in the range 100-200 USD/ton C if the CO_2 is sequestered from the flue gases (Parson & Keith, 1998). Sequestration from flue gases would be preferable if the fossil fuel is used as a fuel in industries (since there in general would be no benefits from hydrogen production in the plant). Sequestration from flue gases could also be an option in coal fired power plants. Whether that turns out to be the case depends on the relative economics of coal gasification in IGCC (integrated gasification combined cycle) power plants versus standard steam turbines. The capture cost in an IGCC power plant would be relatively inexpensive but the plant would be somewhat more expensive than a steam turbine plant.

The major remaining issue is where CO_2 should be stored. Several options exist, e.g., depleted natural gas and oil reservoirs, deep aquifiers and the ocean. Further, several storage technologies are in commercial use today. The most well-known is probably the Utsira formation (a saline aquifer 1000 m below the ocean floor in the North Sea). The CO_2 is obtained from the Sleipner natural gas field. The gas contains CO_2 that is taxed in Norway, at least if it is emitted to the atmosphere. This tax created the incentive for Statoil to sequester and pump the gas back to the earth crust (Herzog et al., 2000).

Several studies have attempted to estimate the potential for each of these storage options. Socolow (1997) estimates the storage potential in depleted oil and gas reservoirs to 130-1500 Gton C. Bergman (1998) estimates that the storage capacity in aquifiers to lie in the range 87-2700 Gton C.

Accumulative storage requirement in our basecase scenarios over the years 1990-2100 amount to roughly 170 Gton C, which is much less than what most studies suggest can be stored reliably. In an alternative run of the model, we substantially increased the energy demand (see section 6.3), and the aggregate CO_2 sequestration over the period 1990-2100 reached 490 Gton C, which seems reasonably low compared to estimated storage capacities. Finally, much research remains before a large-scale application of this technology can be applied. Surprises may appear, and therefor we also analysed the impact on the energy system in case CO_2 sequestration from fossil fuel is not considered a reliable option (see section 6.3).

5. Fuel infrastructure and vehicle costs

An infrastructure for fuels for the transportation sector can be divided into the following components: production plants, long-way and short-way distribution, refuelling equipment and vehicle components. In section 4, we discussed the costs of production plants. In this section, we discuss distribution and refuelling costs (section 5.1). We then turn to vehicle costs (section 5.2). In appendix A.2, we briefly discuss the possibility of using hydrogen or biomass based fuels in aircraft.

5.1 Distribution and refuelling infrastructure

Mass manufacturing of alternative fuels will not occur before there is an infrastructure for refuelling them, and — vice versa — the development of an infrastructure for alternative fuels is hindered by the fact that there is no market for the use of these fuels. Although this chicken and the egg problem is important, it should not be overstated. For instance, the ethanol programme in Brazil illustrates that a rapid expansion of alternative fuels is possible. It took some ten years from the initiation of the ethanol programme to raise the share of ethanol cars to 96% of all cars sold in Brazil in 1985 (Mancini, 1998).

The main factors explaining this rapid transformation of the transportation sector in Brazil are the higher oil prices in 1973 and declining profits in the sugar producing regions of Brazil. Domestic ethanol production was seen as a solution to these problems and subsidies favouring ethanol were adopted. The strong commitment by the Brazilian government in favour of ethanol was crucial for the rapid expansion of the ethanol programme.[9]

Methanol, like gasoline and ethanol, is a liquid fuel at normal temperature and pressure (NTP), and this strongly facilitates distribution and refuelling. In contrast, hydrogen and natural gas are in gaseous forms at NTP and distribution and refuelling become more complicated.

Insights gained when developing an infrastructure for natural gas can be useful when planning for a hydrogen infrastructure. Kaijser (1996) reviews the political and industrial activities in Holland that preceeded the exploration of the Groningen field. Since there are large investment costs involved when developing such an infrastructure, it is important that a large market for the gas is rapidly built up, that long-term contracts are signed and that a sufficiently large majority in the parliament is secured in favor of the project. The latter factor is important in order to ensure

[9] At present, there are no ethanol production subsidies, the sales of ethanol cars are almost down to zero, and the cost of ethanol is substantially higher than the cost of gasoline. Still the production of ethanol is greater than ever. This is due the fact that gasoline has to be blended with 22-24% (anhydrous) ethanol. Total ethanol use in Brazil is today 14 billion litres, corresponding to 0.3 EJ/year.

industrial actors that the rules of the game will not suddenly change in a direction unfavorable to natural gas users.

In this section, we will look at distribution and refuelling issues. We will consider the costs and the transient phase of an infrastructure for alternative fuels for the transportation sector. Obviously, the distribution costs will be very site specific, in particular for gaseous fuels. Therefore, the numbers given here should be seen as indications of possible average values. It will be shown that infrastructure costs are rather small compared to other costs involved in the methanol or hydrogen futures, and more detailed assessments of the costs of distribution and refuelling would not likely change the overall conclusions developed in this paper.

5.1.1 Methanol

An infrastructure for methanol distribution and refuelling will resemble that of gasoline. The major components will all be similar, e.g., tankers, terminals, trucks and storage. The main difference is that the energy density of methanol is lower. For this reason, the cost of methanol distribution can be expected to be higher.

The costs of the infrastructure components are small when compared to the cost of the fuel production plants and the additional costs for methanol FC cars (see Ogden et al, 1999, below and in section 5.4 of this report).

As regards intercontinental transportation, the cost of a large tanker with a capacity of 250,000 dry weight ton[10] amounts to 50 MUSD (Jack Faucett Associates, 1987, cited in Ogden *et al* 1999). This would translate into only 13 USD/kW (assuming 10 deliveries/year), which is small compared to the costs of producing the fuel (capital costs lie in the range 300-600 USD/kW). Similarly, 50 MUSD/tanker translates into a cost of 8 USD/car, which can be compared to the additional capital cost for the car that is several thousand USD (see section 5.3). Ogden *et al* (1999) report costs for terminal equipment to be of the same order of magnitude as that of the tankers. Also the capital costs of trucks for local distribution are small when compared to the extra costs of cars or to the cost of production plants.[11]

Furthermore, the cost of converting gasoline stations into methanol stations has been estimated at roughly 45 000 USD/station (Ogden *et al*, 1999) for a station with a capacity of 1100 methanol cars per day (75 GJ/day). Hart *et al* (1999) report similar estimates (30000 UK pounds). This corresponds to 34 USD/car (assuming a vehicle fuel economy of 1.2 MJ/km), and equal lifetimes of the station and the cars. This is 100 times lower than the additional cost of a methanol powered fuel cell vehicle compared to a gasoline internal combustion car.

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[10] This capacity is impressive. 70 deliveries would be sufficient to supply the entire energy need for the Swedish transportation sector. Present methanol tankers are five times smaller than that. At present, a 96000 ton tanker is being built (Hart *et al* 1999).

[11] Assume that a truck costs 100,000 USD, has a capacity of 20 ton methanol, and makes four deliveries per day. The truck investment cost would then be 0.02 USD/GJ of methanol delivered.

Thus, investment costs are small for a distribution and refuelling infrastructure. On the other hand, running costs such as salaries and operation and maintenance costs can be expected to make a more noticeable contribution. For gasoline, Ogden *et al* (1994) estimate the distribution and refuelling cost at 2 USD/GJ; for methanol the corresponding estimate is 3.5 USD/GJ.

5.1.2 Hydrogen

Since hydrogen is a gas at normal temperature and pressure, distribution and refuelling is more complicated than what is the case for methanol or any other liquid hydrocarbon. On the other hand, there are several ways hydrogen can be distributed to filling stations, e.g.,

1) pipeline distribution from centralised plants,
2) localised steam reforming of natural gas,
3) distribution by truck of liquid hydrogen, and
4) small scale electrolysis at the filling station.[12]

In the early stages of a transition towards hydrogen in the transportation sector, fleet vehicles (busses, taxis, government and company vehicles etc) would probably dominate. The production technology would be site specific and include steam reforming of methane and electrolysis in hydropower rich countries (having excess capacity night time).

If the market starts to expand rapidly beyond that of fleet vehicles, alternatives two, three and four would probably play important roles. The possibility to produce hydrogen via electrolysis or to ship it as liquefied hydrogen to rural areas where pipelines would be expensive, implies that the hydrogen can be made available even before the ”final” infrastructure is set up.

According to a study by Directed Technologies Inc. the cost of hydrogen distribution in pipelines is roughly the same as distribution in liquid form. They find that "the cost of compression offsets the cost of liquefaction, and the cost of building and operating the pipelines offsets the cost of shipping hydrogen by tanker truck." On the other hand, electricity cost makes up a large share of the cost of liquid hydrogen, roughly 9 USD/GJ, and if, or rather once, energy prices rise in response to higher carbon taxes, distribution by pipeline would probably be the preferred choice. Thus, as the demand for hydrogen grows, cost considerations will favour an increased use of pipelines. More stringent CO_2 constraints will also enhance this development. Localised steam reforming of natural gas would become unfavourable since carbon sequestration would

[12] A more speculative option would be trucks loaded with hydrogen stored in activated carbon vessels. If hydrogen stored this way turns out as promising as some studies suggest (see e.g., Pettersson & Hjortsberg, 2000), both onboard hydrogen storage and the build up of a hydrogen infrastructure would be facilitated. However, because of its speculative nature we will not consider it any further here.

be too expensive (the economics of CO_2 sequestration is strongly favoured if it is carried out in large facilities).

Distribution by pipeline is also favoured by the global urbanisation trends. At present, some 75% of the population in industrialised countries live in urban areas. For Latin America the corresponding number is 71%, for China 33%, India, 26% and Africa 34%. In projections developed by the World Resources Institute, these numbers will rise to 80%, 63%, 39% and 54%, respectively, by the year 2025, and to 85% for all regions by the year 2100 (see Alcamo *et al*, 1994).

In sparsely populated areas, distribution by pipeline would be too expensive. Instead, trucking of liquid hydrogen, electrolysis or perhaps locally PV based electrolysis of water would be interesting options.

The economics of hydrogen distribution and refuelling have been looked at in detail by Ogden (1999a, b) and Directed Technologies Inc. (Thomas et al, 1997, 1998). The cost of distribution is very site specific. In aggregated models like ours, one needs to use representative averages. Ogden (1999b, 254) states that "local pipeline transmission costs vary from about 2 USD/GJ for vehicle densities of 3000 cars per square mile (equal to 100% of cars in densely populated urban areas such as downtown Denver or Los Angeles), to 5 USD/GJ for densities of 300 cars per square mile (equivalent to more sparsely populated areas such as averages for New Jersey or to 10% of urban vehicles). At even sparser demand concentrations (<300 cars per square mile), pipeline transmission costs rise rapidly, and other hydrogen supply strategies are preferable".

Overall, Ogden estimates that the cost of piped hydrogen used as a transportation fuel (including refuelling costs) would be roughly 12-14 USD/GJ depending on vehicle density (see fig 10, Ogden 1999a). Thomas *et al* (1997, figure 1), find both higher and lower costs depending on the scale of the plants and the number of vehicles being fuelled. In an analysis of liquid versus gaseous hydrogen (assuming a 500 MW hydrogen plant), they estimate the costs for piped gaseous hydrogen to be 18 USD/GJ. These estimates include the costs of producing hydrogen. In our study, we assume that the cost of distribution and refuelling is 8 USD/GJ. This estimate lies in between the estimates given by Ogden and Thomas *et al*, and coincides with the assumptions made in IPCC (1996, p 620).

As regards transmissions between countries, there are several options depending on the primary energy source. For instance, in our scenarios, we have two main sources of hydrogen: solar and fossil fuels with decarbonisation. If solar is the primary energy source, long way distribution will only be opted for if the economics of it is better than local production. We have assumed that the solar hydrogen can be produced and supplied to city gates at a cost of 18 USD/GJ, and thus we have not dealt with the issue of centralised production in sunny desserts and long way transmission versus local production.

Similarly, we have not investigated whether natural gas should be transported from the city gates in the form of natural gas, and then steam reformed with the carbon dioxide piped away for storage, or whether the natural gas should be steam reformed at the point of extraction. Rather the stated costs of natural gas and coal are assumed to hold at city gates.

5.1.3 Natural gas - distribution and refuelling for the transportation sector

Since the main purpose of this study is whether hydrogen or methanol will be the future fuel in the transportation sector, we treat the infrastructure costs for distribution of natural gas in a simplified way. The cost of natural gas to residential consumers has remained steady at roughly 6 USD/GJ over the past years in the US (EIA 1999, OECD 1997) and the average price of natural gas for utilities is 2.5 USD/GJ. We assume that infrastructure costs remain responsible for the difference, i.e., 3.5 USD/GJ. We further assume that refuelling equipment and labour costs amount to 2.5 USD/GJ. Thus, total distribution and refuelling costs for natural gas is assumed to be 6 USD/GJ.

5.2 Vehicle costs

Although the internal combustion engine is continuously being improved and emission factors are reduced, competition can be expected from fuel cell (FC) powered vehicles. The two main drivers for such a development would be the demand for reduced air pollution and higher energy efficiency/lower carbon emissions. In our model, we have not looked at issues related to local air pollution. Thus, the introduction of fuel cell vehicles in our model may be delayed compared to a real world scenario in which local air pollution is a major issue, in particular in megacities of the world. This aspect is especially important for busses, where the advantages of fuel cells are even more pronounced. The same consideration applies to vehicles powered by compressed natural gas, which too exhibit very low emissions factors and some 20% lower CO_2 emissions. On the other hand, gasoline powered internal combustion engines are becoming much cleaner, and recently Nissan staked claims to having the world's cleanest car. According to Nissan, the car is now able to meet Super Ultra Low Emission Vehicle (SULEV) standards (Auto 2000). Very low emission standards and higher efficiency can also be met by hybrid vehicles.

In our model, we restrict the choice of technology to internal combustion (IC) engines and fuel cells (FC) with electric motors, combined with four different fuels: gasoline, natural gas (only with IC), methanol and hydrogen. The costs of FC cars are initially substantially higher than the cost of IC cars (as discussed below), but this cost differential is expected to drop over time. These options are also available for trucks, buses and ships.

When assessing the relative cost of fuel cell cars run on hydrogen versus methanol, the cost of hydrogen storage, the cost of the reformer and the efficiency losses associated with the reformer are the major factors determining the relative competitiveness of methanol versus hydrogen.

5.2.1 Fuel cells

Fuel cells convert chemical fuel (in most cases hydrogen) directly into electricity. For traction applications, the PEM (polymer electrolyte membrane) cell is the most promising technology, although other fuel cells (e.g., alkaline fuel cells in the Zevco Taxi) have been tested as well (see Appleby, 1999, Hart & Bauen, 1998, Jung, 1999, Kartha & Grimes, 1994, for overviews of fuel cell applications and technological status).

At present, fuel cells are far too expensive to be used in cars (under normal commercial conditions). For instance, electricity from fuel cells cost some 3000 USD/kW (Lloyd, 1999), and this would translate into a total cost for the fuel climbing well above 100,000 USD (assuming a capacity of 40 kW). Still, rapid development takes place, and car companies are actively participating in the development of this technology (see Maruo (1998) for a detailed discussion of recent activities). The interest in developing fuel cells primarily stems from two factors. First, the increasingly stringent emission standards being imposed in California and other regions of the world, and second, the possibility that fuel cells will turn out to be superior to the internal combustion engine in terms of lifecycle costs, e.g., since fuel cells are roughly twice as efficient as internal combustion engines. This latter fact also implies that the technology would contribute to lower carbon emissions even if gasoline would continue to be the choice of fuel.

The expected costs of fuel cells vary strongly. Mass production would bring down costs significantly. Chrysler (cited in Ogden *et al* (1998)) has estimated that the cost could come down to 200 USD/kW even with current manufacturing technologies. A detailed study by Directed Technologies suggests that the costs may reach levels as low as 20 USD/kW (Lomax, 1998). Note that this targets are very ambitious: natural gas fired power plants, for instance, cost 600 USD/kW, i.e., some 30 times more. Thus, if these lower cost targets can be met, the electricity generating industry may also be revolutionised.

Platinum demand for fuel cells

The use of platinum as a catalyst in fuel cells is an often voiced concern. At present, it seems feasible to reach 0.25 mg Pt/cm^2 (Lomax, 1998). Given a voltage of 0.6 V and an electric current of 1 A/cm^2, we get a platinum loading of 0.4 g Pt/kW. (This can be compared to the 16 g Pt/kW that was needed in 1986, Appleby (1999).) This translates into some 20 g Pt/car (assuming 50 kW fuel cell capacity). In the future, average platinum loading might drop to 10 g/car (Cowley 1998).

In our basecase scenario the fuel-cell car fleet increases by about 5 billion cars from 2050 to 2100. During that half century the platinum stock in the car fleet would increase by 1000 tonnes per year. Platinum demand for fuel-cell trucks would add another 200-400 tonnes per year. These demand figures can be compared to the primary refinery production of platinum in 1998 of about 170 tonnes (Cowley 1999). The stock of platinum metal in the 5 billion cars would amount to about 50 ktonnes. The current platinum reserves, reserve base and total resources are estimated at 35, 39 and 64 ktonnes respectively (assuming 50% platinum in the platinum-group-metal composition, USGS 1999, Råde 2000). Although rough and static in nature, this exercise suggests that platinum scarcities might constrain the growth of PEM fuel-cell vehicles.

On the other hand, scarcity would cause platinum prices to rise, which can be expected to enhance the profitability of platinum extraction and trigger new exploration that could lead to new findings. Rising prices could also induce continued reductions in platinum use. For instance, platinum costs roughly 12 USD/g at present. Let us assume that 50 USD/kW is an acceptable price (for the automotive industry) for a fuel cell and that it could eventually be produced at a cost of 20 USD/kW (with present platinum prices and loading). Then about 32 USD/kW could be paid for the platinum feedstock without causing the fuel cell production cost to exceed the acceptable price. Under the assumption of an average future platinum loading of 0.2 g/kW, this translates into a platinum price of 160 USD/g. At such a price currently uneconomic resources will become economic, but given the small difference between reserves and total resources given above, it is far from certain that the reserves will increase substantially. These issues are discussed in more detail by Råde (2000).

5.2.2 Hydrogen storage

Storage is often considered as a major problem when it comes to hydrogen fuelled vehicles. There are several possible alternatives, e.g., compressed gas, liquid hydrogen, metal alloy hydrides, adsorption in carbon materials, to mention the most commonly discussed alternatives (see Pettersson & Hjortsberg, 2000, or Jung, 1999, for reviews of various options). In this study, our basecase option is hydrogen stored as compressed gas. The estimated cost of storage in the form of compressed gas varies substantially between various authors. For instance, Berry & Aceves (1998) estimate the cost in the range 650-1300 USD/GJ, Ogden *et al* (1998) estimate the cost of a 500 MJ tank to 1000 USD. We have assumed a cost of 2000 USD/GJ in our basecase, although lower costs could be expected if the tanks are recycled.

Storing liquid hydrogen would be somewhat cheaper, and liquefaction would reduce distribution costs. However, the energy penalty of liquefying hydrogen seems prohibitive in most cases (except when distribution to remote locations is necessary). Storage in the form of metal hydrides seems to be too expensive to be of interest for automotive applications.

A novel approach is adsorption in various carbon materials such as activated graphite, carbon nanofibres and carbon nanotubes. Carbon storage materials have the potential to combine high volumetric and gravimetric densities with low cost. On the laboratory scale it has been shown that activated carbon and carbon nanofibres could store about as much energy (hydrogen) per volume and weight as gasoline and methanol (Pettersson and Hjortsberg 2000). Carbon nanotubes has not yet reached as high energy densities but have the advantage that they can operate under ambient pressure and temperature. It remains to be shown to what extent carbon storage vessels are rechargeable or recyclable. Pettersson and Hjortsberg (2000) refer to cost estimates for carbon nanofibres and graphite of 1 and 10 USD/kg respectively. Given an energy density of about 10 MJ/kg, materials costs of about 100 and 1,000 USD/GJ seem feasible, that is, below our cost assumption for pressurised storage tanks. While yet being in an early phase of development it appears far from impossible that production facilities could be in place within two decades, well before hydrogen becomes a transportation fuel of significance in our scenarios (see chapter 6).

5.2.3 On board reformation of liquid hydrocarbons

If the transportation fuel is methanol or gasoline, a chemical reformer is needed before the fuel is fed to the fuel cell. In the future, the development of direct methanol fuel cells may change this situation. We base our estimate of the reformer costs on Ogden et al. (1999), who states a cost of 25 USD/kW. We assume that this cost also holds for reformation of gasoline. It should be observed that the reformer cost is expressed in USD/kW of electricity obtained from the fuel cell (and thus not in terms of USD/kW of hydrogen). Since the fuel cell may be assumed to be 40% efficient, a cost of 25 USD/kWe, actually means a cost of 10 USD/kW_{H2}. It is somewhat paradoxical that the cost of a reformer producing hydrogen from methanol, is forty times less than the cost of hydrogen production from natural gas in a stationary large scale plant. However, this stems from several factors. In automotive applications, one does not need to separate CO_2 from hydrogen and there is no need for a compressor. Further, the thermodynamics of reforming of methanol into hydrogen is more favourable than the reformation of methane. A final reason is that small-scale reformers allow automated mass production, which may have the potential to bring down costs.

5.2.4 Summary of cost estimates

In figures 5.1-5.2, we summarise the major assumptions that we have made for each of these technologies, and the resulting cost estimate for FC vehicles versus IC vehicles. In our base case, all fuel cells are roughly 4000 USD more expensive than gasoline IC vehicles. This stems mainly from our assumption that fuel cells will eventually cost 60 USD/kW. On the other hand if fuel cell cost 20 USD/kW, then parity with gasoline IC cars is reached. Our estimates could be compared to those of Thomas *et al* (1998, table 10) who find that the additional cost of a H2 FC vehicles would be 2000 USD.

Further, the difference in cost between the reformer and the storage tank is only minor (the reformer being somewhat more expensive). This explains why the methanol FC vehicles are estimated to be somewhat more expensive than H2 FC vehicles. We have disregarded the fact that methanol and gasoline FC cars would be heavier, and therefor require more fuel cell power. Also, we have chosen a rather pessimistic value for the cost of the H2 storage tank. Under other assumptions, H2 FC vehicles would have a clearer advantage over methanol FC vehicles. For instance, Ogden et al (1999) estimate that the cost of methanol FC cars will be 500 USD above that of H2 FC. The additional cost of gasoline FC would be even higher, 1000 USD compared to H2 FC. Similar estimates were obtained in a study by Directed Technologies Inc (Thomas *et al*, 1998).

Finally, additional costs for methanol internal combustion cars were based on Johansson (1999). For natural gas vehicles, we used projected future costs once/if mass manufacturing would occur (Ramberg, personal communication, 2000; Johansson, 1999).

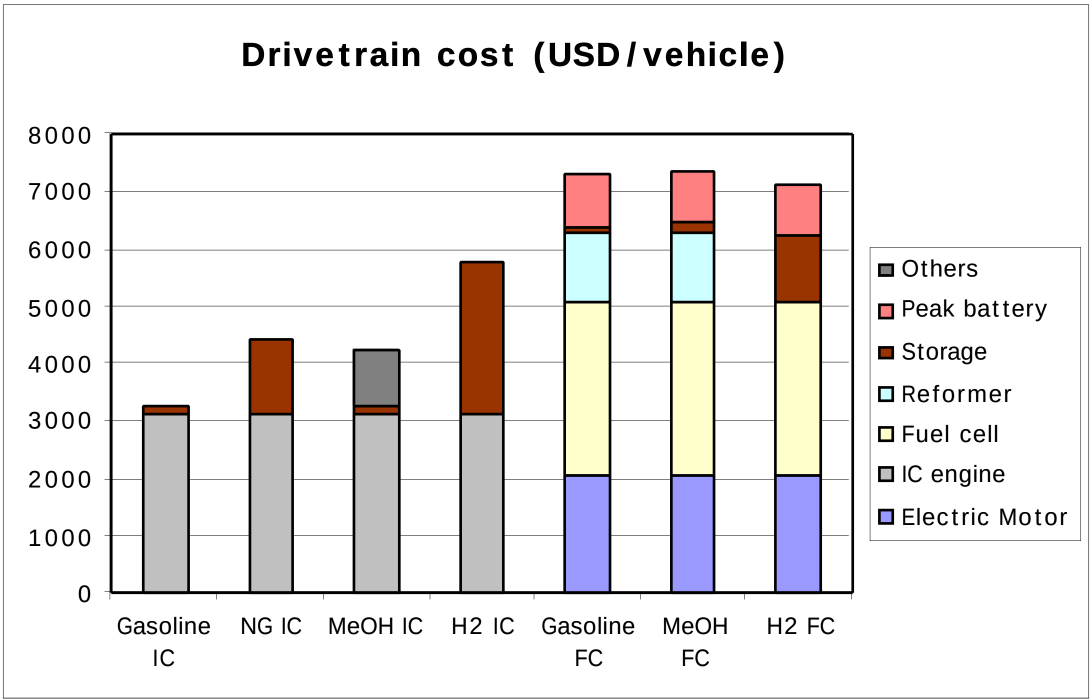

Figure 5.1 Drivetrain costs for cars (USD/vehicle).
Sources: See main text.

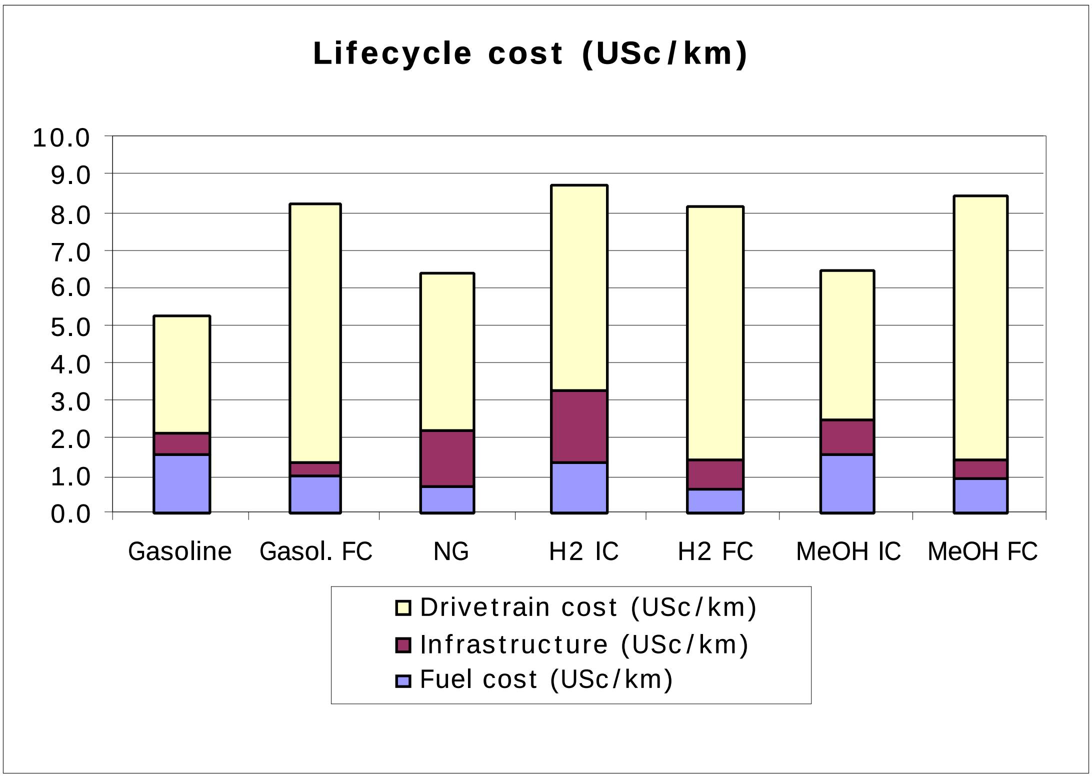

Figure 5.2 Lifecycle cost (US¢/vehicle km) in our basecase. Here methanol and hydrogen is generated from natural gas. Carbon taxes are not included in the price of the fuels.

6. Results

6.1 A scenario with no CO_2 constraints

Under the assumption that there are no carbon constraints, a coal based energy system develops (see figure 6.1). The use of oil and natural gas is roughly constant over the next fifty years. This use then declines because of resource scarcities. Coal expands slowly throughout the first half of the century, and rapidly thereafter. By the year 2100, it completely dominates the world energy supply. The transportation sector is run on gasoline/diesel over the next 50 years, and coal based methanol (in internal combustion engines) for the remaining part of the century (see figure 6.2). This is explained by the fact that we are running out of oil. Further, the low cost of coal does not create incentives enough to pay for the higher cost of using fuel cells. And finally, methanol has an advantage over hydrogen in internal combustion engines since the storage costs for hydrogen vehicles become rather large, since the fuel requirement per vehicle kilometer is much higher with internal combustion engines.

Total carbon emissions reach 23 Gton C/year, by 2100. Aggregate emissions over the period 1990-2100 amount to 1220 Gton C. This is 15% less than the aggregated emissions in the IPCC IS 92a scenario developed by IPCC (1992) and used in several climate impact studies as a baseline emission scenario.

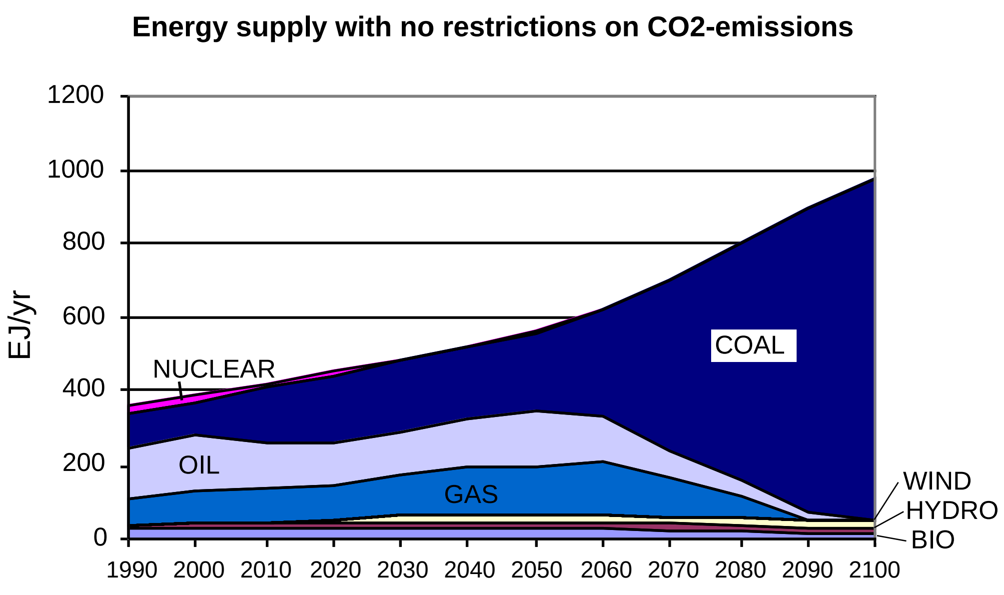

Figure 6.1 World primary energy supply in the absence of carbon abatement policies.

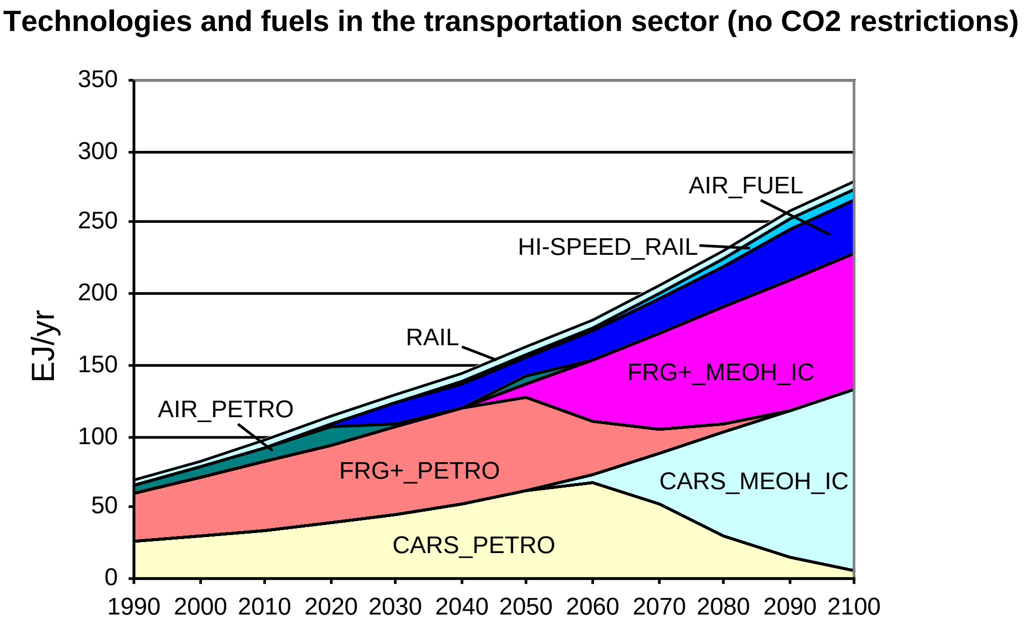

Figure 6.2 Transportation fuels in the absence of carbon abatement policies. In the bottom the car sector is shown, at first fuelled by gasoline in IC engines (CARS_PETRO), then fuelled by methanol in IC engines (CARS_MEOH_IC). On top of that the development of the technologies for larger vehicles are shown (FRG+), which is dominated by trucks, but also includes buses and ships. In this run of the model, these vehicles follow the choice of propulsion technology in the car sector. For aviation, the fuel shifts from oil based fuel (AIR_PETRO) to synthetic fuels (AIR_FUEL) based on coal. At the top, the electricity use in low- and high-speed rail transportation (RAIL and HI-SPEED RAIL) is shown.

6.2 Stabilising atmospheric CO_2 concentrations at 400 ppm

The purpose of this study is to look at the energy and transportation sector under stringent CO_2 targets. In order to meet an atmospheric CO_2 stabilisation target of 400 ppm, energy efficiency as well as changes in primary energy supply are needed (see figure 6.3).

A general feature that is obtained in all runs of the model is that the use of biomass increases rapidly in response to stringent CO_2 targets. Biomass is used for residential heating and process heat. Similarly, all other renewable energy technologies, hydropower, wind and solar, grow. Wind and solar start from very low values and it takes several decades before they make a significant contribution to the global electricity supply.

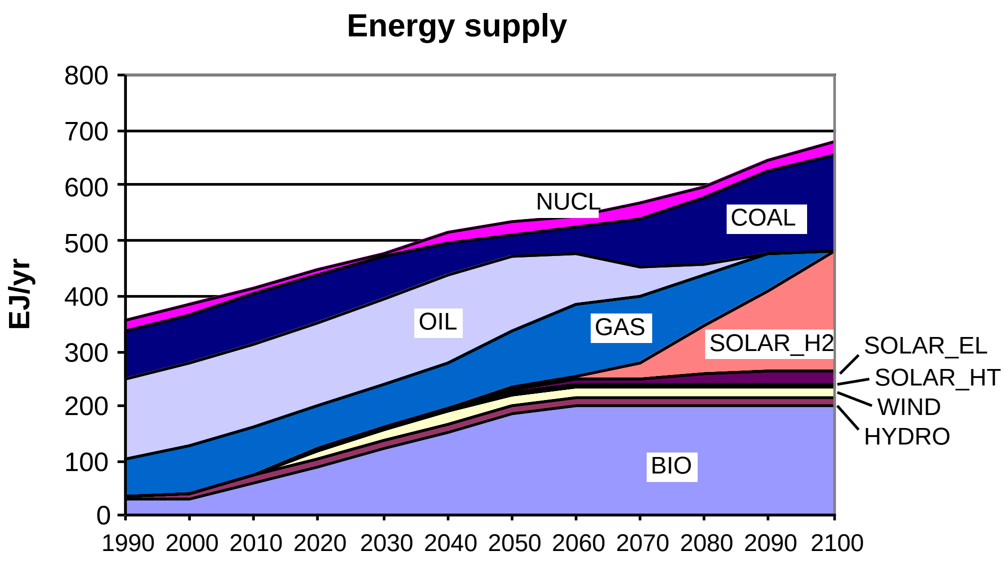

Figure 6.3 World primary energy supply. The three solar energy technologies used in the model (H2, EL, HT) produce hydrogen, electricity (e.g., PV), and heat (for processing and heating), respectively.

The use of natural gas grows as well, but mainly in the electricity sector (see figure 6.4). However, this growth is much less pronounced than that of biomass. Oil is phased out in electricity and heat production, but its use in the transportation sector increases so that the overall use continues to grow, although at a very low rate. The use of coal remains roughly constant over the first couple of decades, and grows rapidly thereafter since carbon sequestration technologies are employed on a large scale.

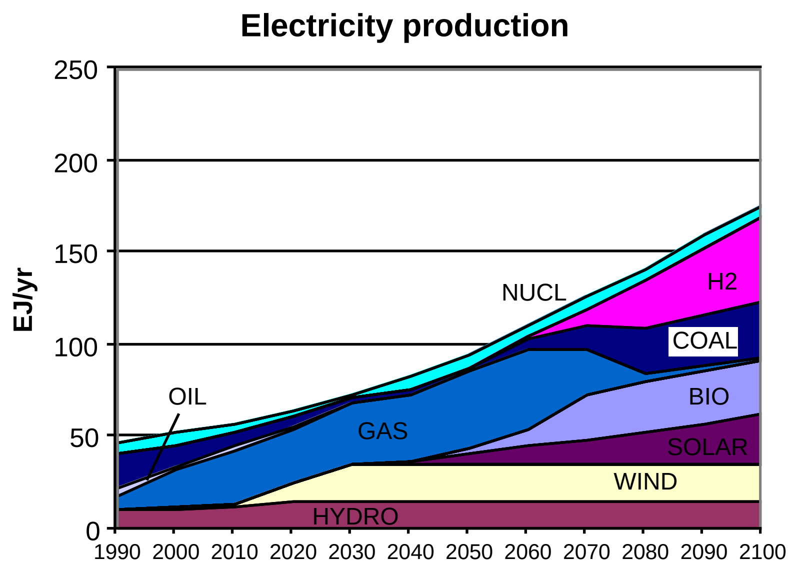

Figure 6.4 World electricity supply by fuel

This results in carbon emissions that remain roughly constant over the next 30 years (see figure 6.5). They are then reduced rather rapidly by the year 2050 and onwards. This is achieved by a rapid expansion of solar hydrogen technologies and decarbonisation of fossil fuels. In the base case some 220 EJ/year is supplied from fossil fuels using decarbonisation technologies at its peak around 2080. A large part of this, 90 EJ/year, is used for hydrogen production. Hydrogen production from solar energy reaches 200 EJ/year by the end of the century.

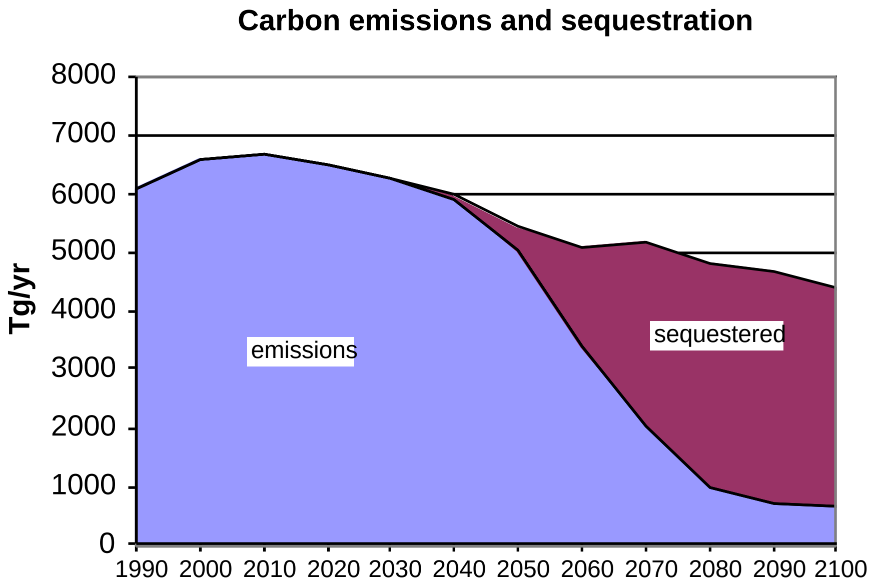

Figure 6.5 The strong decrease in CO_2 emissions from fossil fuels starting around 2050, mainly depends on a rapid expansion of carbon sequestration techniques and solar hydrogen production, and to a less extent on a decreased use of fossil fuels.

In the *transportation sector*, oil remains the only fuel (except for electric use in trains) until the years 2040-2050 when a transition to hydrogen is initiated (see figure 6.6). Hydrogen is produced from fossil fuels (natural gas and then coal, both with decarbonisation technologies) and solar energy. Hydrogen is used both in private cars, trucks, buses, ships and airlines. As for aviation fuel, a transition away from petroleum-based kerosene towards liquid hydrogen or other alternative fuels is initiated around the year 2060.

It is interesting to note that oil remains the dominant energy source in the transportation sector for such a long time, even if stringent CO_2 constraints are applied. However, given the allowable CO_2 emissions (for a 400 ppm target), it should come as no surprise. For such a target, we may emit 500 Gton C over the period 1990-2100. The present oil and natural gas reserves combined contain 200 Gton C. In our scenarios, we have assumed that the available supplies are twice the present reserves. This means that all oil and natural gas reserves can be used even if we stabilise at 400 ppm. Now, since carbon abatement policies will increase their relative competitiveness of oil and natural gas over coal, we can expect that most, if not all, of the oil and gas resources will be used. Further, oil has a competitive advantage in the transportation sector. Thus, this is where most of this energy source will be used.

The view that hydrogen is the long-term option has also been expressed by actors in the automotive industry, e.g., John Williams, the head of GM Corporation's team on global climate issues: "I think I am on pretty solid ground in saying that the long-term vision is hydrogen. But there is a lot of work between here and there" (*New York Times*, October 31, 1999). Similarly, Herman Kuipers, Shell Global Solutions, states that spending money on methanol is like betting on the wrong horse — hydrogen is the winner" (presentation at the seminar "The Hydrogen Society — Reality or Fiction", Stockholm 22/9 1999).

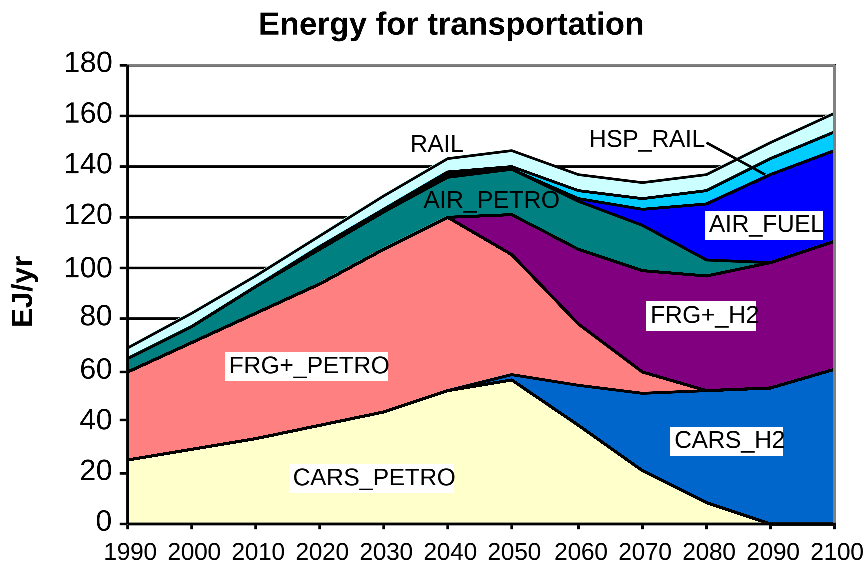

Figure 6.6 World use of transportation fuels. There is a transition from petroleum fuel in IC engines (PETRO) to hydrogen used in fuel cells (H2). The same transition occurs in trucks, buses and ships (FRG+ sector).

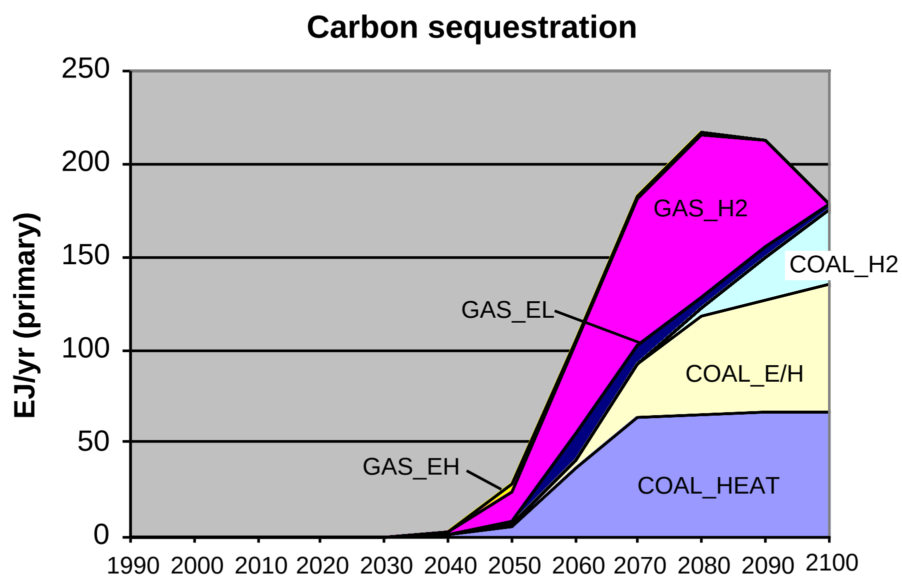

Figure 6.7 Decarbonisation of fossil fuels is mainly used during the second half of the century, and it is applied to coal and natural gas plants producing hydrogen, heat, and electricity, including cogeneration. The technologies are based on gas and coal as fuels and produce hydrogen, electricity, heat or electricity/heat (by cogeneration), denoted by H2, EL, HEAT, and E/H, respectively.

6.3 Sensitivity analysis

In this section, we present a number of sensitivity analyses with respect to certain sets of parameters. We have grouped the parameters into two categories, one group which we refer to as general energy parameters, and the second which we have called transportation parameters. The general energy parameters refer to factors that are not specific to the transportation sector. These include the availability of biomass, the discount rate, the cost of biomass, the cost of solar hydrogen, as well as the costs and conversion efficiencies of heat and power generating technologies.

6.3.1 Sensitivity with respect to general energy parameters

High and low biomass availability
We first assume that biomass supplies are limited to only 100 EJ/year. In this scenario, the higher degree of scarcity of biomass results in earlier introduction of solar hydrogen (10-20 years) and fossil fuel decarbonisation technologies (roughly 10 years). The transportation sector is almost identical to the picture given by the basecase level of 200 EJ/year of biomass supply.

We also increased the biomass supply potential radically to 400 EJ/year. Under this assumption, the introduction of solar hydrogen and fossil fuel decarbonisation technologies is delayed by roughly 10 years. The increased availability of biomass, is used for electricity production. This means that some natural gas is made available for the transportation sector (used directly as natural gas or converted into methanol before use). This use peaks at about 23 EJ/year (natural gas) and 15 EJ/year (methanol) in the year 2070, i.e., substantially more than the total energy use in cars today. The transition phase lasts 50 years. Beyond this transitory phase, hydrogen is introduced.

Doubling and halving of natural gas and oil resources
The choice of fuel in the transportation sector is insensitive to a doubling of the oil resources. Instead, the increased oil availability is used in sectors where carbon sequestration technologies are possible (beyond 2050). On the other hand, a halving of oil reserves leads to a much faster transition to other fuels in the transportation sector: depending on the exact choices of the parameter values, there is a transition period, roughly between 2020 and 2070, when methanol and/or natural gas replaces gasoline, but after that hydrogen takes over.

If the potential for natural gas is twice as large, the main implication is that natural gas rather than coal is used for heat, electricity and hydrogen generation with decarbonisation beyond 2050. The influence of this on the choice of fuel in the transportation sector is insignificant.

Biomass, natural gas and oil costs
We have also estimated the impact of doubled and halved costs of natural gas and oil (changed jointly). The same sensitivity analysis was performed on the cost of biomass. In neither of these cases were there any significant impact on the choice of fuel in the transportation sector.

Maximum limit on biomass used for heat production
Since the model is globally aggregated, energy carriers can be used instantaneously everywhere. This means that biomass, that may become rich in supplies in Africa and Latin America, can be used in Europe and Asia without any transportation costs. Transporting biomass based methanol or electricity is cheaper than transporting hydrogen or wood chips. For this reason, we limited the biomass used for heat to 100 EJ/year. This forces the model to use biomass for electricity, methanol or hydrogen generation. Under this assumption biomass is used for heat (100 EJ/yr), electricity generation and some cogeneration of heat and electricity. Neither methanol nor hydrogen is produced from biomass.

Heat and electricity demand
In order to investigate to what extent the phase out time of gasoline depends on our choice of energy demands (electricity and heat), we have also made a scenario based on the energy demands used in the IIASA/WEC A1 scenario. This involves a much higher increase in both heat and electricity demands, resulting in levels above 400 EJ/year and 500 EJ/year in 2100 for production of electricity and heat, respectively. The transportation demand scenario is kept as in our base case. The total energy supply in the year 2100 is 1300 EJ/year.

The increase in energy demand in this high demand scenario results in an increased use of coal in combination with a much faster introduction of carbon sequestration technologies (in order to meet the CO_2 constraints). Still, the 50% phase-out time of gasoline for cars does not occur before 2050, and again it is followed by hydrogen as transportation fuel.

Discount rate
A decrease of the discount rate from 5%/yr to 2%/yr, leads to a slight change of the fuel use in the transportation sector. In fact, there is roughly a delay of petroleum phase out for cars by 10 years, while trucks shift to hydrogen 10 years earlier instead.

The main implication of the decreased discount rate is that emission restrictions become important already in the beginning of the century. This leads to an introduction of decarbonisation technologies already by 2010, which means that, in total over the century, fossil fuel use increases and the introduction of solar hydrogen is delayed.

Lower stabilisation target
If emissions of fossil carbon are limited to 370 Gton over the period 1990-2100, corresponding to an atmospheric stabilization target of CO_2 level of 350 ppm, the

direct consequence is a decrease of the total coal use, mainly replaced by a somewhat earlier introduction of solar hydrogen. The phase out of gasoline for transportation occurs 10 years earlier than in the base case.

Decarbonisation technologies not used
In case storage of sequestered CO_2 would not be accepted, solar hydrogen production enters the global energy system at an earlier point in time and plays a more important role throughout the second half of the century. Changes in the transportation sector are insignificant compared to the basecase.

6.3.2 Sensitivity with respect to "transportation" parameters

Higher energy demand for transportation
In this run, we assumed that the transportation volumes are the same, but that there are no energy efficiency improvements (technological development is used for other purposes, as has been the case in most countries of the world for the last 30 years, except for the US). In this case, we get no significant changes in terms of fuel choices. The only change is that the transition towards hydrogen occurs roughly ten years earlier.

High and low costs of fuel cells
In the base case, fuel cell cars cost roughly 4000 USD more than IC gasoline cars. In a sensitivity analysis, we tripled the cost of the fuel cell stack (to 180 USD/kW), and doubled the cost of the reformer (to 50 USD/kW). This fuel cell stack cost is an order of magnitude lower than the present stack cost, but it nevertheless has a significant impact on the additional cost of fuel cell vehicles. This is clearly shown in figure 6.8.

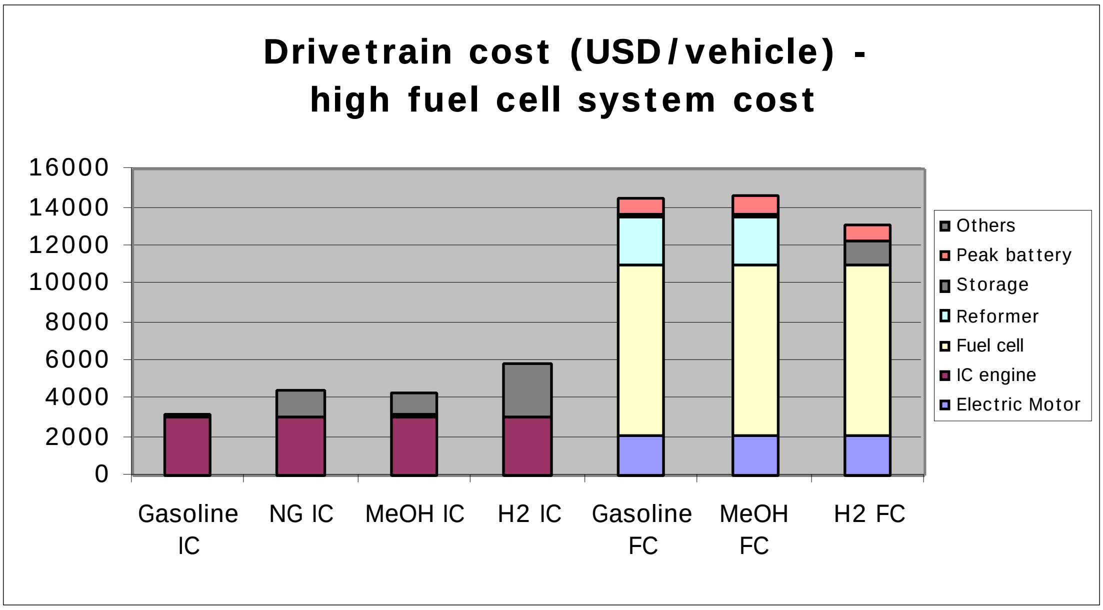

Figure 6.8. The drivetrain cost of fuel cells if the stack costs 180 USD/kW$_e$ and the reformer costs 50 USD/kW$_e$.

In this scenario, the 50% gasoline phase out date remains as in the basecase, but hydrogen is first used in internal combustion engines (both in cars and in trucks). For cars this is the case throughout the century, while trucks switch to fuel cells by 2080. (There is also a transient phase involving natural gas IC engines that is used for a fraction of the car energy demand starting in 2050.)

We have also analysed the impact of more rapid cost reductions of fuel cells. We assume that the cost difference between H2FC and gasoline IC is only 1000 USD by the year 2020. This would be achieved if the cost of the fuel cell reaches 20 USD/kW_e and the cost of the tank 750 USD/GJ (as some analysts judge are feasible cost targets, see section 4). With these numbers the additional costs for the H2 FC truck would be 5000 USD. These more optimistic numbers result in a more rapid introduction of H2FC vehicles (see Figure 6.9). By the year 2040, half of all private cars is hydrogen powered. The rest of the energy system remains rather unaffected (compared to the basecase).

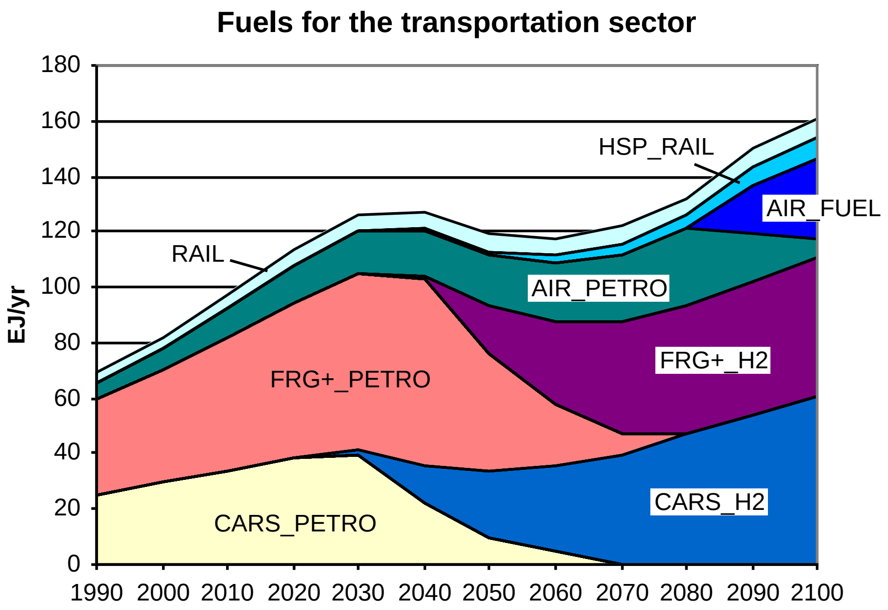

Figure 6.9. With low extra costs for fuel cell vehicles, an earlier introduction of hydrogen to the transportation sector is possible. Here the additional cost of a H2 FC car is 1000 USD/vehicle, and for trucks 5000 USD/vehicle. H2 as a transportation fuel enters the market already in the 2030s.

In figure 6.10, we plot the year at which gasoline use in cars falls below 50% of the car transportation demand as a function of the extra cost for H2 FC cars. It is shown that once the additional cost for the H2 FC car is 1250 USD or more, the 50% phased out date of gasoline occurs by the year 2050.

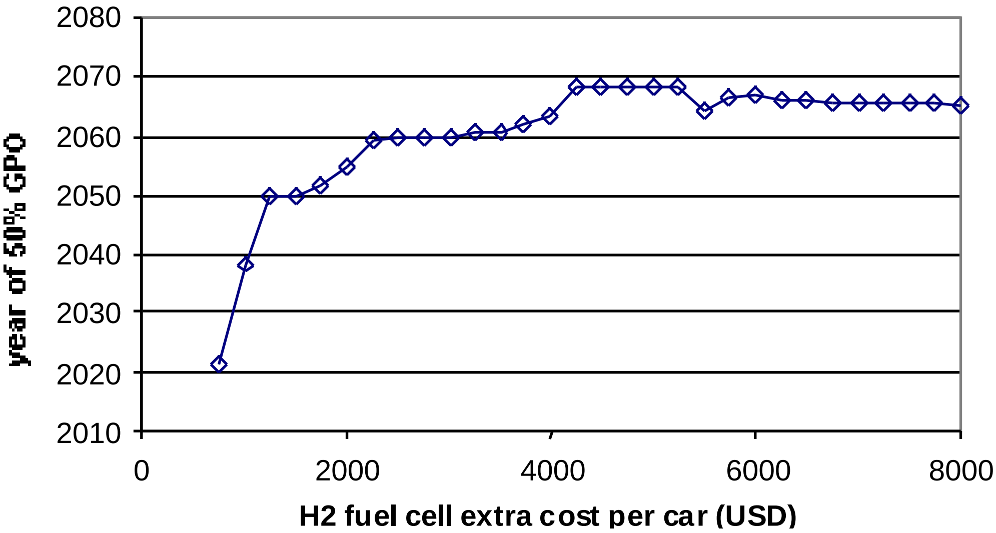

Figure 6.10. The diagram shows the year when the use of gasoline in cars falls below 50% as a function of the extra cost for H2 fuel cell cars. (Trucks are assumed to follow the car costs linearly: the additional cost for the trucks is equal to four times the additional cost for cars plus 1000 USD.) The diagram illustrates the presence of critical cost levels, at which the gasoline phase-out time is more sensitive to the extra cost. The scenario with the 1000 USD/vehicle cost is illustrated in figure 6.9.

High demand for aviation

Below, we illustrate what the transportation sector would look like if the demand for aviation follows the rapid growth scenario (see section 3). The resulting energy use is 50 EJ/yr higher than in the low growth scenario, but choice of fuel is the same, and the transitions occur roughly at the same points in time.

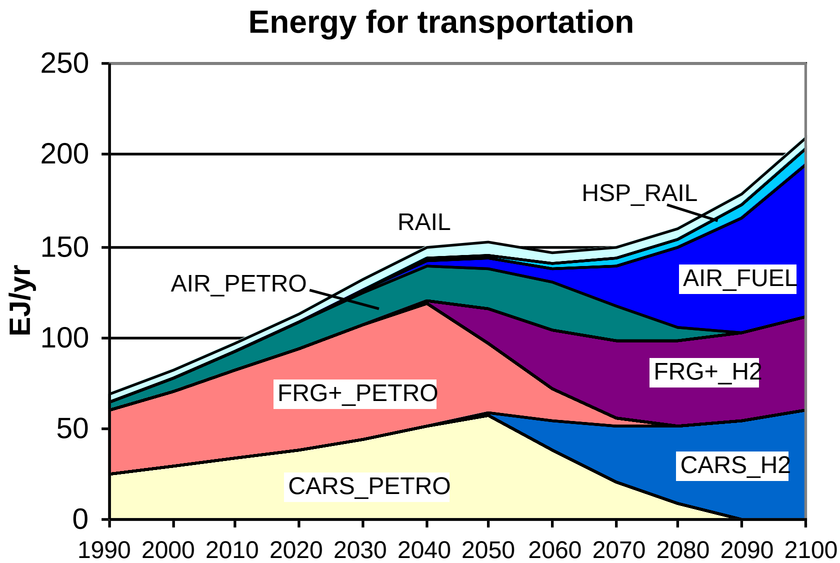

Figure 6.11. In the transportation scenario *with the higher growth of demand for flight transportation*, the energy use in the transportation sector by 2100 is increased from 160 EJ to 210 EJ. The phase out time of gasoline in the transportation sector remains the same as before.

6.3.3 Assumptions favourable to methanol

In order to analyse under what circumstances methanol is used as a transportation fuel, we investigate the impact of lowering the cost of methanol fuel cars in relation to gasoline, natural gas, and hydrogen vehicles. This was done by assuming hydrogen tanks would cost 3000 USD/GJ rather than 2000 USD/GJ, and that the cost of hydrogen infrastructure would be 10 USD/GJ (in order to increase competitiveness over hydrogen fuel cell vehicles). The trucks costs were changed correspondingly.[13] Further, fuel cells are assumed to cost 20 USD/kW$_e$ (so that fuel cell vehicles would be substantially more competitive with internal combustion vehicles). The lifecycle costs with these assumptions favouring methanol are depicted in figure 6.12.

Although the lifecycle cost of methanol is assumed to be lower than that of hydrogen, methanol is nevertheless not used in the transportation sector. The reason for this is that biomass has an even greater cost advantage over solar hydrogen in the heat sector and is thus preferable used in that sector. In figure 6.13, we plot the maximum share of methanol fuel in the transportation sector as a function of hydrogen infrastructure costs. It is shown that the infrastructure cost has to reach levels as high as 15 GJ/USD, before the maximum share of methanol reaches above 50%. The methanol era is (for all values shown in figure 6.13) a transient phase, and by the end of the century hydrogen eventually begins to dominate the transportation sector.

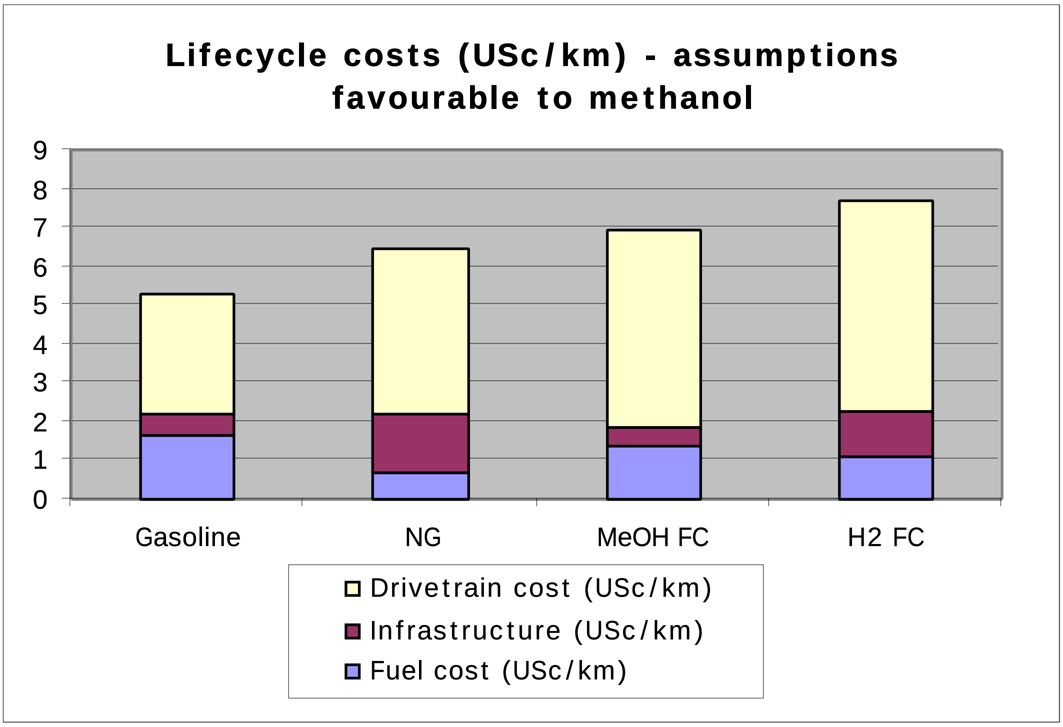

Figure 6.12 Lifecycle costs with technology assumptions favourable to methanol. Note that, in this graph, hydrogen and methanol are derived from biomass. We have not included any scarcity costs caused by biomass availability restrictions, nor are carbon taxes included in the cost of gasoline.

[13] Other costs in USD per vehicle are for cars: MeOH internal combustion, 2000, H2 internal combustion 4000, and for trucks: MeOH FC 8000, MeOH internal combustion 5000, H2 FC 10000.

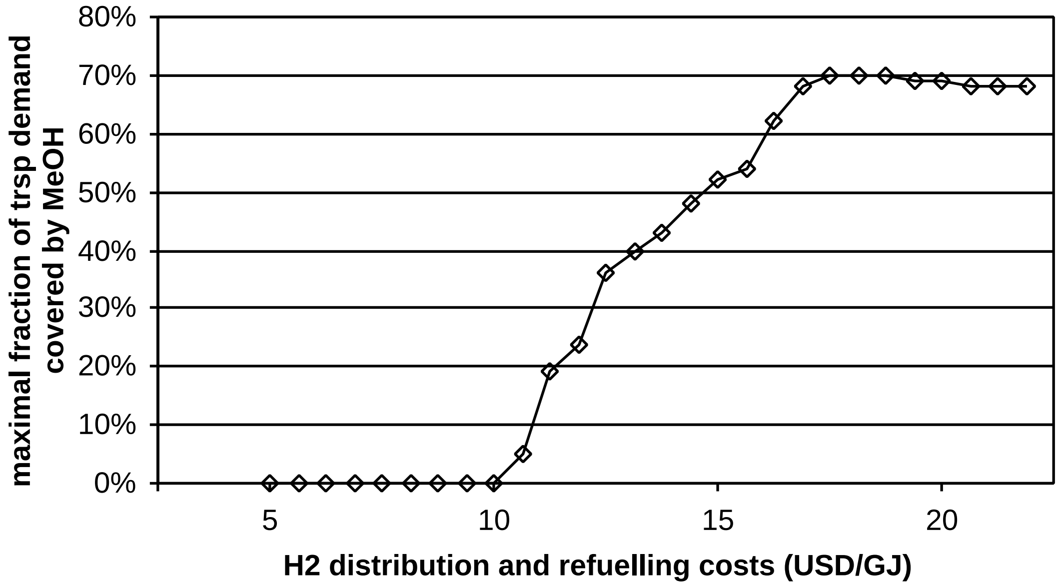

Figure 6.13. When the distribution and refuelling cost for hydrogen is increased the introduction of hydrogen as transportation fuel is delayed and/or combined with a period of time when methanol is used. The figure shows, though, that this happens for high costs, and that, in these cases, methanol does not take the whole car fuelling market. For all costs in the figure, the use of methanol is decaying by the end of the century. The infrastructure cost for natural gas is 75% of the values assumed for hydrogen. Car technology parameters are favourable to methanol.

In figure 6.14, we illustrate the transition towards alternative fuels under the assumption that hydrogen distribution and refuelling cost as much as 17 USD/GJ. In this case, gasoline is replaced by methanol and hydrogen roughly by the year 2050, and both these alternative fuel continue to grow substantially over the next couple of decades. Eventually, hydrogen captures almost the entire sector.

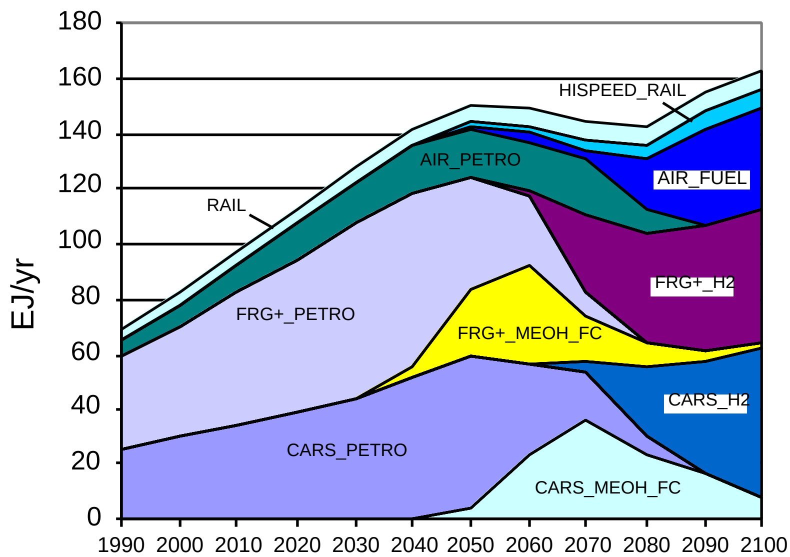

Fig 6.14 Fuel choices in the transportation sector under conditions very favourable to methanol. For details see the text.

Lower costs of methanol internal combustion vehicles
In the base case model, we have assumed that gasoline cars are cheaper than methanol cars when using an internal combustion (IC) engine. If it turns out that methanol IC cars get cheaper due to simpler technologies for meeting local air pollution restrictions, then methanol may enter as fuel for IC engines. If, for example, the methanol IC car is 200 USD/vehicle cheaper, then there is a transition period during which methanol is used as a fuel for cars with a peak demand equal to 20% of the transportation energy demand culminating around 2030.

6.3.4 Random variations of parameters vs. phase-out time of gasoline

In order to characterise the robustness of our model, we have performed a number of sensitivity analyses, in which large subsets of the parameters are varied randomly according to uniform distributions around the basecase parameter settings. Here, we show three such cases, first when plant costs are varied randomly (picked from a uniform random distribution covering the basecase cost +/– 50%), then when additional car costs are varied randomly (picked from a uniform random distribution covering the basecase cost +/– 30%) and finally, when both plants and car costs are varied jointly.

In all these runs (see figures 6.15-6.17 below), the year when 50% of the gasoline is phased out from the transportation sector occurs around 2060-2070. Thus, in our model, the length of the petroleum era in the transportation sector does not critically depend on the exact values of these parameters. In the real world, an earlier shift towards alternative transportation fuels could occur for geopolitical reasons, i.e., concerns about the increasing concentration of oil reserves to the Middle East, or for issues related to local environmental pollution (see section 6.4).

In most of these runs there is no other fuel involved in the transition from gasoline to hydrogen. In some cases there is a period of time where natural gas is used as fuel for cars, but only as a minor fraction of the total fuel use. Note that the "twin peaks" characteristics shown in figures 6.15-6.17 can also be detected in figure 6.10, which shows that there is a critical fuel cell cost in which the gasoline phase out time shifts roughly from 2060 to 2070. The exact mechanism behind the pattern remains to be investigated.

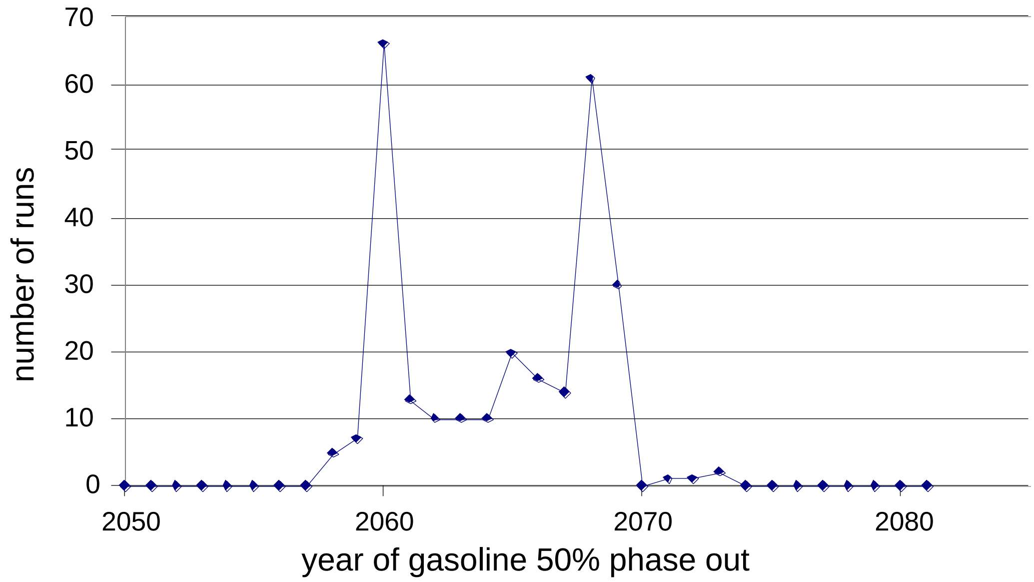

Figure 6.15. Year when 50% of the gasoline is phased out from the transportation sector.
Note: The figure summarises results from 266 runs of basecase w +/- 50% uniform variation on plant costs. The graph shows the number of runs when 50% of the gasoline was phased out for a given year.

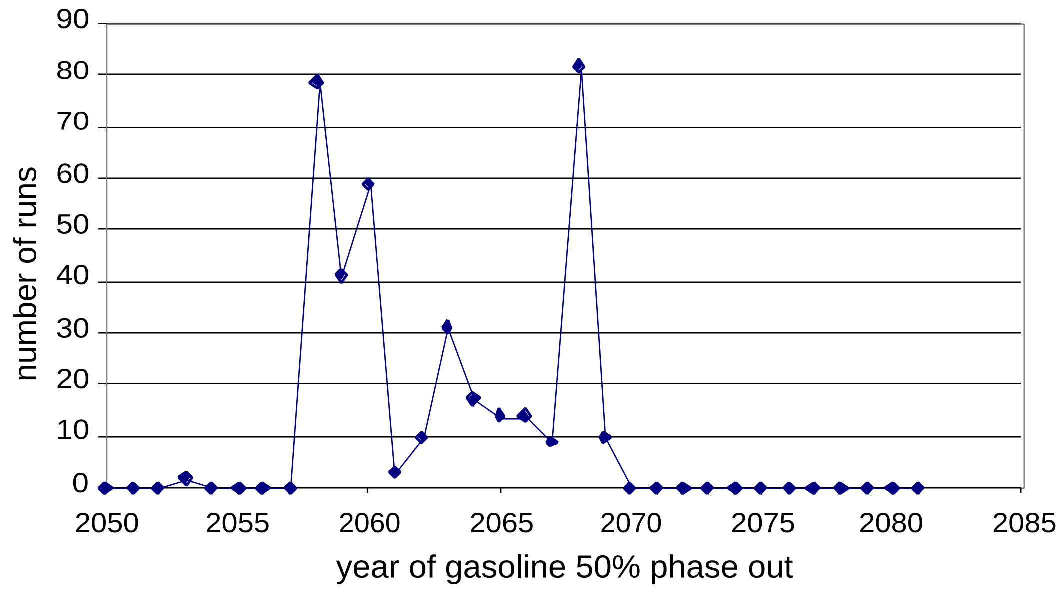

Figure 6.16. The phase out of gasoline for cars, measured by the year when 50% of the cars driving distance is fuelled by alternative fuels. Here we have made 371 runs of the model for which the car engine extra costs have been varied uniformly in an interval ±30% around the basecase values.

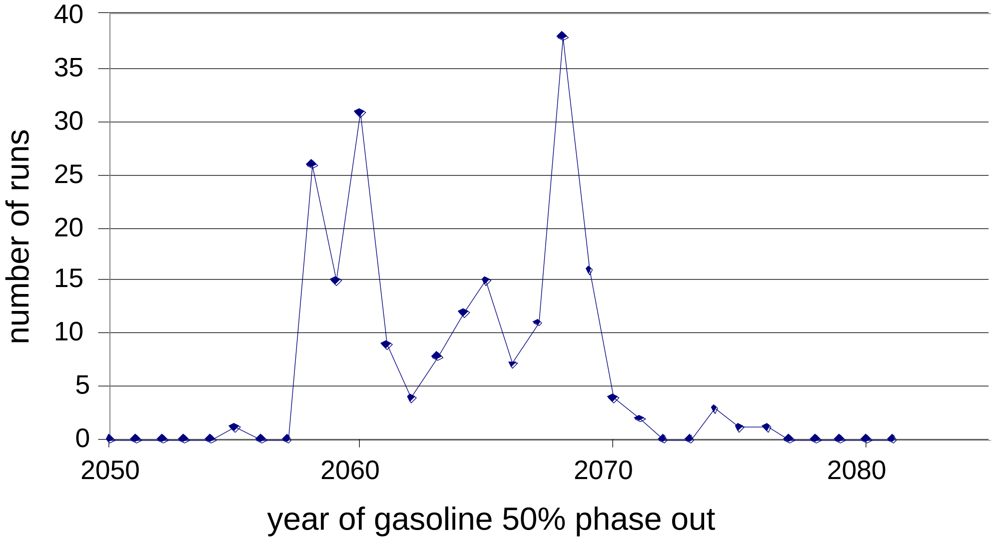

Figure 6.17. 204 runs of basecase w +/- 50% uniform variation on plant costs combined with +/- 30% uniform variation on engine extra costs.

6.4 Alternative scenario towards 400 ppm

In the basecase scenario and the sensitivity analysis towards 400 ppm presented in the previous sections, there are no considerations given to local air pollution. The only environmental factor that drives the energy and transportation system is the upper limit on CO_2 emissions. Under these conditions, we do not get any change in transportation fuels/technologies until the middle of this century, as shown in sections 6.2-6.3.

Still, local air pollution is an important factor that may trigger the introduction of fuel cells at a much earlier stage than what we find in our runs reported above. This could for instance happen as a result of a rapid world-wide expansion of demand for zero emission vehicles. Thus, we have also investigated the energy systems effects and the fuel choices that may occur if local air pollution considerations are taken into account. We have simulated this concern by requiring that the minimum fraction of new cars using fuel cells are 5% by 2010, 25% by 2020, 50% by 2030, and 80% from 2040.)Under these assumptions, we get hydrogen as the transportation fuel that replaces gasoline/diesel. The hydrogen is initially supplied from natural gas, and then by the middle of the century from solar and to a lesser extent decarbonised coal.

However, the choice of fuel in the transportation sector during the transient phase towards hydrogen is sensitive with respect to the cost of hydrogen infrastructure and the cost differential between hydrogen and methanol powered fuel cell cars. On the other hand, it is always natural gas (and not biomass) that supplies the hydrogen and the methanol. In figures 6.18-20 below, we illustrate three different cases.

First, we assume basecase parameters throughout the analysis and find that hydrogen is the preferred choice of fuel for cars while there is an initial period of time during which heavier vehicles run on methanol (see figure 6.18). We then report results from a case where the infrastructure cost for hydrogen distribution and refuelling is raised to 15 USD/GJ. In this case, methanol enters also for cars (figure 6.19). In a third run, we increased the cost of gasoline fuel cell cars with 1000 USD. In that case, methanol use increases and is the dominant fuel around 2050, whereafter it declines in favour of hydrogen (see figure 6.20). This runs show that the question about methanol or hydrogen in the near term is much more sensitive to vehicle cost parameters than in the long term, when carbon constraints are much more stringent.

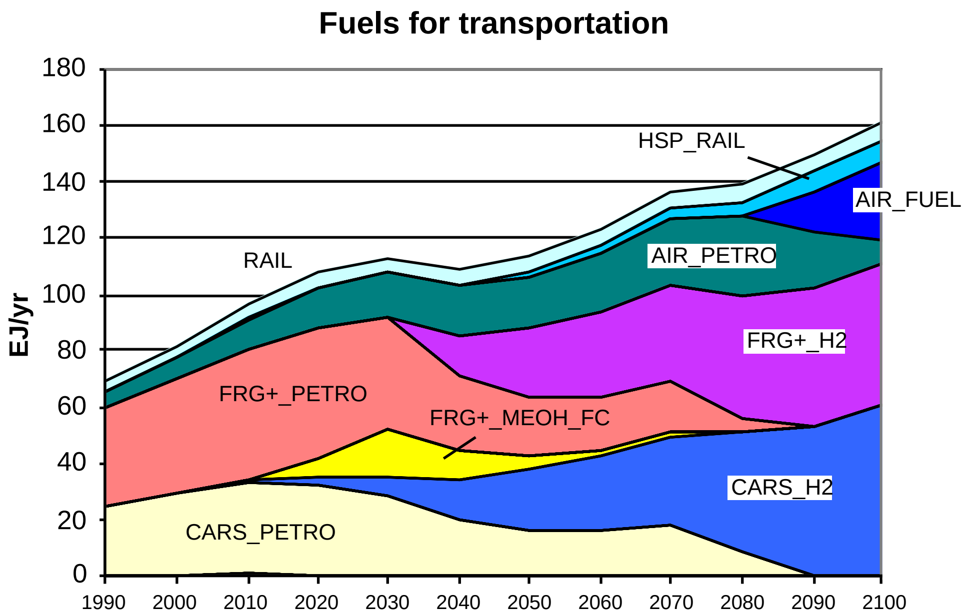

Figure 6.18 Transportation fuels - forced introduction of fuel cells. (For acronyms see list of abbreviation on page 3).

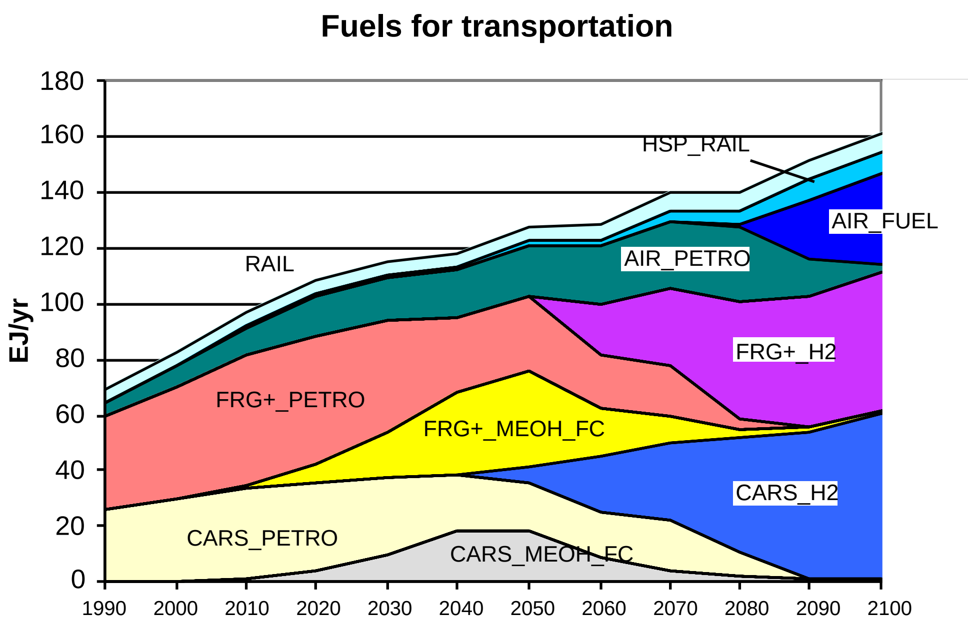

Figure 6.19 Transportation fuels - forced introduction of fuel cells with high costs for hydrogen infrastructure

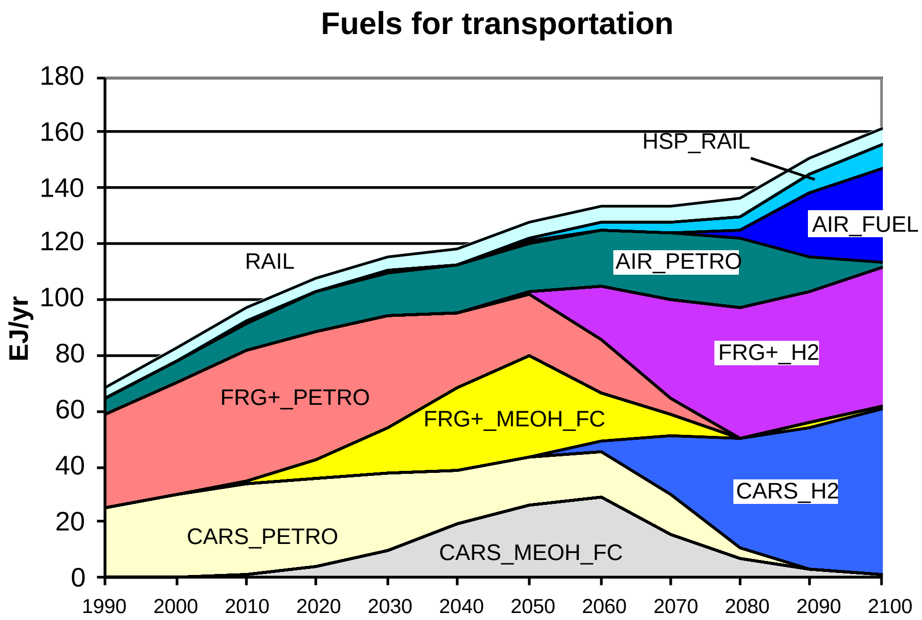

Figure 6.20 Transportation fuels — forced introduction of fuel cells with high costs for hydrogen infrastructure and gasoline fuel cells

7. Conclusions

The *purpose* with this paper is three-fold. First, to analyse the transition towards alternative energy technologies on a global scale under stringent CO_2 emission targets. Second, to analyse whether hydrogen or methanol is more likely to replace gasoline/diesel, and third, to assess the potential for bioenergy in the form of methanol or hydrogen in the transportation sector.

The chosen *methodology* was to develop a global energy systems model with special focus on the transportation sector. The model is globally aggregated. The only environmental concern is CO_2 emissions, although sensitivity analyses are carried out in which it is assumed that local air pollution consideration lead to an early introduction of zero emission vehicles. The model seeks to minimise the cost of the energy system, given that certain energy services have to be delivered (heat, electricity and transportation) and that the CO_2 concentrations have to stay below 400 ppm.

It should be pointed out that studies of future technology choices are *highly uncertain*, not only in the development of costs and efficiencies, but also in what way technologies are introduced and which these technologies are. In the highly aggregated type of model that we have developed for this study, there are a number of niche markets, e.g., taxis, buses and local freight distribution, which are not captured by the model. We have also assumed that technology development is exogenous, i.e., occurs by itself rather than as a consequences of policies, market creation and R&D. An improved modelling of technology development, where technologies grow in response to policies and market opportunities (Azar & Dowlatabadi 1999), could change the timing of the introduction of alternative technologies. Regionalisation of the model, as well as a more detailed modelling of the heat and fuel sector, could also change the relative economics of biomass use. Certain industries may for instance require high quality fuels, and the cost of biomass would then increase, potentially making it more cost-efficient to use it for electricity production or as a liquid or gaseous fuel. Further improvements of the menu of technological options would be to include the possibility to use so called A-methanol, i.e., methanol from solar hydrogen combined with atmospheric CO_2.

Also, we have worked with an optimisation model, which has only one decision maker with perfect foresight throughout the entire period. This means that the model can plan perfectly how emissions of CO_2 should be reduced compared to a scenario with unrestricted emissions. Because of discounting, this reduction takes place as late as possible (given constraints on how rapidly alternative technologies may enter the energy system). This means that the phase out time is perhaps too rapid (since the political difficulties involved when adopting and implementing the required policies are not captured by the model). Having said that, it should also be pointed out that aggregated models such as ours may be used to gain insights into the large-scale dynamics of the energy system, when driven towards lower CO_2 emissions.

Our main *results* can be summarised as follows:

* Until 2050, we get an increased use of biomass, a phase out of oil from heat and electricity generation, increased use of natural gas in the electricity sector and a stabilisation of the use of coal. In the transportation sector, the use of oil increases as the transportation demand increases. Alternative transportation fuels do not enter.

* Beyond 2050 conventional uses of fossil fuels are gradually phased out from the energy sector (because of more severe CO_2 emission constraints). Instead solar hydrogen and decarbonisation of fossil fuels become increasingly important. Hydrogen enters the transportation sector and becomes the dominant transportation fuel by 2060-2070.

* If fuel cell vehicles are forced to enter the transportation sector at a much earlier point in time, the choice of hydrogen or methanol as fuel depends on exact parameter values. In the base case hydrogen dominates, while, e.g., higher costs for hydrogen distribution results in a period of methanol fuelled vehicles, both for personal transportation and freight. In this early phase both hydrogen and methanol is produced from natural gas (see section 6.4).

Sensitivity analyses with respect to certain parameter values show that these results are model robust. The fact that oil remains for so long in the transportation sector can be explained in the following way. The present oil and natural gas reserves combined contain 200 Gton C, which is less than half of the 500 Gton C that we can emit over the period 1990-2100 if we would like to stabilise atmospheric concentrations of CO_2 at 400 ppm. This means that all oil and natural gas reserves will be used, since carbon abatement policies will increase their relative competitiveness over coal. The question is where this oil and natural gas will be used. For obvious reasons, oil has a competitive advantage in the transportation sector, and natural gas has an advantage in the electricity sector.

How then should these results be *interpreted*?

First, the fact that hydrogen, rather than methanol, eventually comes to dominate the transportation sector stems from the fact that methanol eventually would have to be produced from solid biomass and this conversion is expensive and associated with substantial energy losses. The relative advantage of using biomass for heat is larger than any potential advantage involved in using biomass as a source for methanol. The additional costs associated with storage, distribution and refuelling of a gaseous fuel are not large enough to prevent hydrogen from becoming the dominant fuel in the transportation sector.

Second, in order to obtain carbon reductions over the next decades, carbon taxes, tradable permits or some similar instruments have to be employed that bring down the emissions. Carbon taxes of equal size should also be applied to CO_2 emissions from the transportation sector. This may create incentives to increase energy efficiency and thereby reduce CO_2 emissions. Such taxes might also enhance the economics of alternative fuels in niche markets, e.g., natural gas, biogas or excess hydrogen from refineries for use in city buses. Fuel efficiency standards may also be an interesting option, although this measure has not been analysed in this study.

Third, it should be noted that the sensitivity analysis carried out with respect to the longevity of oil in the transportation sector, only demonstrate the robustness of the model. Factors not covered by the model, e.g., such as regional concerns about the expected growing concentration of oil reserves to Middle East countries, could cause an earlier shift towards alternative fuels in the transportation sector in many regions of the world. Still, if certain countries would stop importing oil from the Middle East, the price of oil would go down and other regions would remain on the oil track.

Finally, technology development and diffusion take a lot of time. This means that R&D and the creation of niche markets are needed today in order to improve performance and reduce costs. This is necessary before competition on bulk markets can be successful.

Our scenarios should not be interpreted as if there should not be any policies directed at reducing CO_2 emission from the transportation sector. Rather, policies should be directed against the entire energy system, including the transportation sector. The insight that we gain from our study is that it may be more cost efficient to reduce CO_2 emissions from other sectors and that even if carbon taxes are large enough to keep us on track towards 400 ppm, we should not be surprised if gasoline/diesel remain dominant fuels in the transportation sector over the next fifty years. Further, we also gain the insight, that biomass should mainly be used for heat, and perhaps also for electricity generation, and not as a transportation fuel. Local air pollution consideration may force an earlier introduction of fuel cell vehicles. In both cases, hydrogen is the more likely fuel to replace gasoline, at least in the long run.

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Appendix 1. Capital costs and conversion efficiencies

Table A.1. The cost of power plants

Fuel	Conversion efficiency	Capital costs [USD/kW$_e$]
Coal	50%	1300
Oil	50%	1000
Natural gas	60%	700
Biomass	50%	1300
Hydrogen	70%	1300
PV	n.a	1200
Wind	n.a	600
Hydropower	n.a	1000

Note: These estimates are intended to reflect the efficiency and the costs of the technologies once they are mature.
Sources: The estimates are based on various sources, including Gustavsson (1997), ABB (1998), Neij (1999), Johansson & Ishitani (1996), Larson & Marrison (1997).

Table A.2. The cost of heat plants

Fuel	Conversion efficiency	Capital costs [USD/kW$_{Th}$]
Coal	90%	300
Oil	90%	100
Natural gas	90%	100
Biomass	90%	300
Hydrogen	90%	100

Source: Rounded from Gustavsson (1997) for all fuels but hydrogen, which we set equal to natural gas.

Table A.3. Energy conversion into hydrogen

Fuel	Conversion efficiency (a)	Capital costs [USD/kW$_{H2}$]
Coal	65%	1300
Oil	75%	1000
Natural gas	85%	400
Biomass	65%	1300
Solar hydrogen	n.a	2000

(a) The conversion efficiency is defined as higher heating value of the energy contained in the product divided by the higher heating value of all energy inputs to the process assuming that all external energy requirements are provided using the same type of fuel as the feedstock
(b) We have not included any running costs in our estimates of the total cost of hydrogen. However, these are generally small (some 10-20%) compared with the overall cost.
Source: Conversion efficiencies are from Larson (1993) and Williams et al (1995), capital costs are based on Thomas et al (1997), Ogden *et al* (1999),

Table A.4. Energy conversion into methanol

Fuel	Conversion efficiency (a)	Capital costs [USD/kW_{MeOh}]
Coal	60%	1300
Natural gas	70%	500
Biomass	60%	1300

(a) The conversion efficiency is defined as higher heating value of the energy contained in the product divided by the higher heating value of all energy inputs to the process assuming that all external energy requirements are provided using the same type of fuel as the feedstock.
Source: Conversion efficiencies are based on Larson (1993) and Williams et al (1995).

Appendix 2. Alternative aviation fuels

Potentially dwindling oil supplies and more severe restrictions on CO_2 emissions towards the end of the next century will affect the choice of aviation fuel. There are essentially three alternatives, (i) synthetic kerosene (based on biomass, coal, unconventional oils or natural gas), (ii) liquefied natural gas (LNG) or (iii) liquefied hydrogen (LH2). With growing pressure to reduce CO_2 emissions, these options will be further narrowed down to biomass-based kerosene or LH2. Few analysts expect that any of these options will materialise over the next three or even four decades. In our scenarios, carbon constraints trigger a change in fuel choice by the year 2060-70 (see section 6).

Biomass based kerosene may be produced using the Fischer-Tropsch process. This process is used today in South Africa to produce liquid fuels from coal for use in the transportation sector. An advantage with a continued reliance on kerosene is that no changes in aviation technology are required. The disadvantage is that fuel availability is constrained by biomass based primary energy sources (in order to avoid net CO_2 emissions). Another disadvantage is that the energy losses associated with biomass conversion into kerosene are significant. Preliminary estimates suggest a conversion efficiency of 50% when converting biomass into liquid fuels when using the Fisher-Tropsch process (Larson & Jin, 1999). However, this process would not only yield kerosene but diesel and lighter hydrocarbons as well. Thus, if the aim was to achieve only kerosene, even lower yields would result.

Liquid hydrogen has been used as an aviation fuel in several research or demonstration projects (see e.g., Simon et al., 1994, Contreras *et al*, 1997, Paul & Malychev, 1997). In 1988, one (out of two) engines in a Tupolev was converted and run on hydrogen alone. In the same year, a four-seat aeroplane was converted to be powered by liquid hydrogen. This was the first flight ever of an aeroplane entirely run on liquid hydrogen (Contreras *et al*, 1997). More well known off ground trips fuelled by liquid hydrogen include of course the space shuttle.

The use of hydrogen as an aviation fuel would require several changes in aeroplane technology. This stems from several factors, in particular the fact that hydrogen would have to be stored in liquid form in the aeroplane and the energy content per unit of volume is 4.1 times lower for liquid hydrogen than kerosene (Armstrong *et al*, 1997). This means that hydrogen can not be stored in the wings, instead tanks inside the aeroplane would be required.

On the other hand, there are several major advantages, primarily that the energy content per unit of mass is 2.8 times higher for hydrogen than for kerosene. This saves weight and increases the energy efficiency of the aeroplane. Further, when burnt, hydrogen will only produce water vapour and nitrogen oxides (NOx). The emissions of water vapour are 2.6 times higher (IPCC 1999), and the emissions of (NOx) are lower than those of kerosene powered airlines. Hydrogen powered aeroplane emissions of carbon dioxide, hydrocarbons or soot are obviously zero (although such emissions can be caused where the hydrogen is produced). The environmental impacts of a shift towards hydrogen are thus not unambiguous, but IPCC (1999, 257) suggests that LH2 from carbon neutral primary energy sources has lower net greenhouse gas emissions than kerosene. More detailed assessments are warranted, but lies outside the scope of this report.

Another issue that needs to be considered is the energy expenditures for hydrogen liquefaction. According to Weimer *et al* (1996), commercially available systems have an electricity demand equal to 9.8 kWh/kg H_2, whereas future technologies could be expected to reach electricity requirements as low as 7.3 kWh/kg H_2. This corresponds to 22% of the energy content. On the other hand, Hart (1997) states that the electricity requirement for hydrogen liquefaction is some 30-40% of the chemical energy in the liquefied hydrogen. We have assumed that 30% is required.