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Timing of technology roll-out for climate targets in transport

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Abstract

Reducing CO_2 emissions from transport requires sector-wide application of low CO_2 fuels. However the amount of biofuels available in the year 2050 will probably be insufficient to meet the combined energy demand for heavy duty road transport, aviation and shipping. Therefore, these long distance transport modes need to switch at least partially to other low CO_2 fuels such as hydrogen. This brings about major technological challenges.

For a transition to a low carbon transport sector it is important to prevent disinvestments such as the early closure of fuel plants and production lines of vehicles, or early scrapping of vehicles. Such measures would induce resistance, which would delay this transition. Our exploratory model calculations indicate that stringent 2050 targets (in this study -73% compared to CO_2 emissions in 1990) for most of the new low-carbon technologies can only be achieved if their technology roll-out starts within 5 to 10 years. For the transport modes with the longest development and implementation times, in particular aviation and shipping, there is little time left to act. Reaching an intermediate target of 50% CO_2 reduction in 2020 is even more challenging, urgently requiring decisive choices for all transport modes. The targets in this study are more ambitious than the 60% CO_2 reduction for road transport in the EU White Paper of 2011.

It is questionable if ‘the market’ is able to make this switch in time, since the investments will be substantial and not profitable in a short term. For this reason coordinated policy support is essential for the low-carbon development of the transport sector.

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For a transition to a low carbon transport sector, it is important to prevent disinvestments such as early closure of fuel plants and production lines of vehicles, or early scrapping of vehicles. Such measures would induce resistance, which would delay this transition. Our exploratory model calculations indicate that stringent 2050 targets (in this study -73% compared to CO_2 emissions in 1990) for most of the new low-carbon technologies can only be achieved if their technology roll-out starts within 5 to 10 years. For the transport modes with the longest development and implementation times, in particular aviation and shipping, there is little time left to act. Reaching an intermediate target of 50% CO_2 reduction in 2030 is even more challenging, urgently requiring decisive choices for all transport modes.

It is questionable if ‘the market’ is able to make this switch in time, since the investments will be substantial and not profitable in the short term. For this reason, coordinated policy support is essential for the low-carbon development of the transport sector.

These are the key conclusions of our study “Timing of technology roll-out for climate targets in transport” for the Dutch Ministry of Infrastructure and Environment. The overall aim of our study is to inform policy makers and market participants about the actions and indicative timing required to meet the 2050 CO_2 reduction goals in the transport sector. Technologies and fuel use in the transport sector need to be changed drastically and fast in order to avoid dangerous climate change and to improve security of supply of transport services. To prepare for these challenges we evaluated the roll-out trajectories of low-carbon technologies and fuels to reach in 2050 a CO_2 emission reduction of 73% compared to 1990, averaged over all transport modes. The 73% overall reduction results from 80% reduction in land based transport and 50% in both shipping and aviation. Our 80% reduction target is based on an equal share of land based transport in reaching the overall CO_2 reduction target of 80-95% by 2050 compared to 1990 for developed countries. Note that the White Paper of the EU (EU, 2011) mentions a 2050 reduction target for road transport of 60%[1].

For the year 2050 we project that all transport modes in the Netherlands together will use about 925 PJ. Meeting this energy demand, while at the same time reducing the sector’s CO_2 emissions with 73%, is challenging because fossil fuel use needs to be minimised and the available amount of biofuels is limited. Estimates of the global biofuels availability vary and are inevitably characterized by rather large bandwidths. Nevertheless the literature indicates that the pro rata amount of biofuels available for the Netherlands in 2050 probably will not exceed 250 PJ. Based on this starting point it follows that other low-CO_2 technologies need to be implemented in the transport sector.

Light duty vehicles can relatively easily switch to electricity as energy source. In contrast, electrification is much more difficult for heavy duty road transport and even more for aviation and shipping. Consequently, these ‘long distance’ transport modes need other low-carbon fuels. The situation is further complicated by the rapid growth of aviation and shipping. Currently, non-road transport is responsible for about 38% of total energy use in The Netherlands, but this

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[1] Other targets: a 40% use of sustainable low carbon fuels in aviation and at least 40% cut in shipping emissions.

share will grow to over 50% in 2050. One of the key alternatives is hydrogen, produced from either fossil fuels with CO_2 capture and storage, or from renewable energy.

Based on the above assumptions and considerations, a 2050 picture was constructed, with 73% CO_2 emission reduction for all transport modes combined. The main characteristics are:

- *Light duty vehicles*: 85% electricity and hydrogen; the remainder largely covered by biofuels.
- *Heavy duty vehicles*: 20% electricity and hydrogen; the remainder covered by biofuels.
- *Aviation*: 25% biofuels, 35% hydrogen; the remainder covered by fossil kerosene.
- *Shipping*: 25% biofuels, 40% hydrogen; the remainder covered by fossil bunker fuel.

Reaching these targets requires that new technologies and fuels will be implemented in time. The pace of market implementation of technologies was estimated by considering inertia in the four phases of the roll-out trajectory: (1) policy decisions, laws and regulations; (2) development of new transport technologies, fuel production facilities and infrastructure; (3) demonstration in early markets; and (4) commercialisation, with a focus on vehicle replacement rates. We also included historical data, and considered special conditions, such as the mining of materials required for electric vehicles. We constructed a basic market penetration model to project the roll-out trajectories for the key technologies up to 2050, based on the degree of implementation over time of the four phases indicated above, for each technology up to 2050. The inertia in the trajectory from technology development to market penetration ranges from about 15 to over 35 years, depending on the technology and mode of transportation. Aviation and shipping are characterized by the longest implementation trajectories.

The model allows for estimating the time left for decisive choices on supporting new technologies. The 2050 situation that meets the 73% CO_2 reduction target could be reached at different paces. Two routes were compared:

1) A route where all developments are implemented as soon as possible (ASAP-route).
2) A route where actions are postponed until the latest start time allowing to reach the 2050 target just in time (delay-route).

The difference between both routes shows that for most of the new low-carbon technologies required the 2050 target can only be achieved if their roll-out trajectories start or accelerate within 5 to 10 years from now. Especially for the transport modes with long development and implementation times (aviation, shipping), there is little time left to decide and ramp up the roll-out. The targets for other transport modes may also get out of range if decisions are delayed and/or if the global CO_2 problem proves to be more serious, thereby requiring a faster roll-out of low-CO_2 technologies.

Postponing too long may imply that the targets can only be met at a very high societal and economic losses, such as substantially limiting global mobility and/or the early decommissioning of vehicles, well before their technical end of life. Such measures would meet strong resistance from society and market participants. It is questionable if ‘the market’ is likely to make the switch towards low-CO_2 technologies in time, since the investments will be substantial and not profitable in the short term. Therefore, coordinated support on the national and international level is essential for a stable and low-carbon development of the global transport sector.

Obviously the methodology of our study includes large uncertainties, as for example unforeseen technology breakthroughs could result in a much more prominent role for other technologies and fuels. Although the spectrum of key low-CO_2 technologies may to some extent develop in a different direction, it is unlikely that this would substantially alter the time ranges left for making decisive choices.

The overall picture and timelines identified in our study will be comparable for most other EU and industrialized countries, as energy use in transport in Netherlands is quite comparable to other industrialized countries. In addition, only the bunker fuel use for ships accountable to the size of the Netherlands economy and its structure was considered, rather than overall bunker fuel sales which are much larger due to large bunker oil facilities in the Rotterdam harbour.

Recommendations for policy makers

There is little time left for decisive choices on supporting new low-CO_2 technologies for the main transport modes:

- *Light duty* vehicles: Strong policy support for hydrogen cars can be maximally postponed by about 10 years. For electric cars there is almost no delay possible. This is related to required expansion of the battery market en the decennia it will take for mining or extraction of the required amount of specific battery materials.
- *Heavy duty vehicles*: Strong policy support for hydrogen trucks can be maximally postponed by about 5 years. For electric trucks the maximum allowable postponement is about 10 years.
- *Aviation:* To reach the CO_2 reduction goal also this sector has to shift partly to energy not based on fossil fuels or biomass. The maximum delay in the choice for developing and supporting hydrogen airplanes is about 10 years. However there is a risk of running out of time, not only because of the substantial development costs and time, but also by the time to prove safety and the necessary time to roll-out the hydrogen infrastructure on the main airports. Therefore it is recommendable to make a policy decision already earlier.
- *Shipping*: Given the long time needed for a global decision to use hydrogen as shipping fuel there is only 5 years of delay time possible.

Our analysis shows that biofuel use in heavy duty road transport, aviation, and shipping, with accelerating consumption after 2030, could to a large extent be supplied by the simultaneous phasing out of biofuels in the light duty sector. Managing this shift may require special policy attention, also regarding the type of biofuels involved. The analysis also shows that reaching an intermediate target of 50% CO_2 reduction in 2030 is challenging, urgently requiring decisive choices for all transport modes.

1. Introduction

Climate change and concerns on security of supply of fossil fuels are likely to induce major changes in fuel consumption of the transport sector over the next decades. Around 2050 the transport sector needs to have reduced its CO_2 emission to about 20% of the current values and in addition needs to be virtually independent of oil (Skinner et. al., 2010; EU, 2011).

As a start of this challenging trajectory towards strong CO_2 reduction and independency from fossil fuels, recently CO_2 standards for passenger vehicles have been formulated (EU, 2009). Standards for vans and trucks are expected to follow soon. In addition the use of biofuels and other low-CO_2 fuels is stimulated to reduce transport CO_2 emissions. Unfortunately the decrease of CO_2 emissions is counterbalanced by the growth of transport demand - which has been growing in tandem with the development of GDP (Gross Domestic Product). Reaching climate goals requires therefore, amongst others, that major parts of the transport sector need to switch to low-CO_2 energy carriers, such as advanced biofuels, hydrogen and electricity. Because of their limited availability, biofuels will have to be used preferably by those vehicles where a compact biofuel offers the most advantages, such as in the segments long haul heavy trucking, aviation and shipping. Nevertheless limitations in global biofuels availability (see paragraph 3.2) are likely to force even these long distance transport modes to switch at least partially to other low-CO_2 alternatives.

It is clear that the 2050 goals imply that current policies on vehicle efficiency and biofuels need to be extended soon with measures in support of more drastic switches towards completely different technologies and energy carriers. At the same time, markets of the automotive industry and fuel producers and distributors need to be able to develop these technologies at their own pace. It is important to prevent disinvestments - such as the early cessation of fuels plants and production lines of vehicles - or early scrapping of vehicles, since such measures would induce resistance that would delay the transition.

Objectives

The study aims to clarify at what point in time policy induced changes are needed to achieve the 2050 goals, by evaluating the underlying key factors and boundary conditions. The overall objective is to inform policy makers and market participants now about the actions and their timing required to achieve the 2050 CO_2 reduction goals in the transport sector.

The research questions include:

- What kind of development trajectory between now and 2050 would allow reaching the desired situation for 2050?
- What will be the role of biofuels, especially for heavy duty road transport?
- What are inertia in the roll-out trajectory of new low-CO_2 solutions regarding vehicle development, market penetration, infrastructure construction and fuel production?
- At what point in time could policy measures contribute effectively in inducing the changes required?

Report structure

Chapter 2 gives an overview of the present situation in the transport sector and the expected future trends if no additional climate change mitigation actions were to be taken. In this way a 2050 ‘business as usual’ picture is compiled, as a starting point for our study.
Chapter 3 describes a vision on low-CO_2 fuels and technology options and the compilation of an alternative 2050 ‘picture’ that meets an emission reduction target of 73% compared to 1990.

Chapter 4 provides a compilation of several inertia in the deployment and market penetration of new technologies. Chapter 5 describes the different routes towards the desired 2050 low-CO_2 situation, in terms of market penetration pace, accounting for the inertia defined. Chapter 6 discusses the results and aims to clarify at what point in time policy induced changes are needed to achieve the defined 2050 situation. For the main transport modes it is estimated how much time is left for taking actions that will still allow to reach the 2050 objectives.

2. Business as usual fuel use and CO_2 emissions in 2050

As a starting point for our study this chapter describes the compilation of a business as usual ‘reference picture’ regarding 2050 energy and fuels use in the transport sector, based on the present situation, and the expected future trends if no additional low-CO_2 transport measures would be implemented.

This ‘business as usual’ reference picture is largely determined by the expected growth in transport demand up to 2050. Many studies indicate that the business-as-usual global transport demand will grow substantially between 2010 and 2050, largely driven by economical growth that is strongly coupled to transport demand. For example, IEA (2009, 2010) expects the growth for the different transport modes to be in the following ranges:

• Passenger road transport	~ 200%
• Freight road transport	~ 250%
• Shipping	~ 300%
• Aviation	~ 400%

2.1 ECN reference projection 2040

In 2010 ECN has compiled a reference projection for The Netherlands (Daniëls and Kruitwagen, 2010). This projection included extrapolated results for the transport sector up to 2040. The projection includes the EC policies for more CO_2 efficient passenger cars and renewable energy (EC, 2009). The fuel consumption of the transport sector in the scenario with current policy (business as usual) is shown in Table 2.1, column ‘2010’. It includes 4% biofuels in 2010 and 8.5% in 2020 and thereafter. By using biofuels from wood and waste products this 8.5% is approximately equivalent with the EC target of 10% in 2020 (EC, 2009), because the EC allows double counting of specific biofuels, that are characterised by favourable well-to-wheel CO_2 emission reduction potentials. The 2040 projection shows that electricity is expected to be used only for light vehicles (passenger cars and vans) and no hydrogen use is assumed (Table 2.1, column ‘2040’). Note that the data presented for the Dutch transport sector also include mobile equipment (agricultural tractors, fork lift carriers, caterpillars etc.).

2.2 Reference picture 2050

As a starting point for our analysis we constructed a 2050 reference picture of the energy use related to the Dutch economy and the underlying distribution of fuels. The compilation of this 2050 reference picture involved some assumptions and corrections, as explained in the next sections.

Additional efficiency

To construct a 2050 picture, as a first step the transport figures in the reference projection 2040 are extrapolated to 2050 (Table 2.1 column ‘2050 extrapolation’). For energy saving, as a starting point only the current EU policy is used in this picture. However, up to 2050 this approach would lead to a substantial underestimation of energy savings. To compensate for this underestimation an additional energy saving[2] of 10 to 25% was implemented in Table 2.1, as is visualized in the fourth column ‘2050 efficiency’.

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[2] This involves also a volume reduction of 7% for light vehicles due to road pricing, which was part of the used background scenarios.

Correction for export of bunker fuels

In the Netherlands a lot of fuel is bunkered for domestic and international maritime shipping. This is related to: (1) the large Rotterdam harbour, (2) the large Dutch refinery sector, and (3) the presence of a lot of oil storage capacity. As a consequence, bunker oil in Rotterdam is relatively cheap, being a strong incentive for passing ships to port for fuel bunkering. The Rotterdam fuel bunkering equals about 7% of the worldwide fuel consumption for international shipping. This fraction is very high relative to the Dutch economy and energy use. For comparison: the Netherlands emit approximately 0.7% of the total global $CO_{2\text{-eq}}$ emission. For this reason we assume that only 10% of the fuel bunkering in the Netherlands is directly related to the size of the Netherlands economy and its structure. Similarly, fuel bunkering by inland navigation in the Netherlands is in part related to transport to Germany and Belgium. By assuming 50% of this consumption to be related to national transport a corrected fuel consumption projection was made. This corrected projection, presented in the column '2050 BAU reference, bunkers corrected' of Table 2.1, thus reflects the fuel use attributable to The Netherlands, and is the starting point for our study. Moreover this approach makes the results of the present study more comparable to other EU countries[3].

This final picture (column '2050 BAU reference, bunkers corrected' in Table 2.1) equals a fuel consumption for transport of 925 PJ, directly related to the Dutch economy in 2050. The equivalent figure for 2010 is 768 PJ. Thus, without additional measures, the fuel and electricity consumption (electricity calculated as PJ electricity) of the transport sector is expected to grow by 20% between 2010 and 2050. When this figure is corrected for the additional electricity production (electricity calculated as PJ fuel and other sources for electricity production) the growth is 27%. Note that in 2050 only about 46% of the energy consumption in the transport sector is related to road transport, because future growth in shipping and aviation is expected to be substantially larger than in road transport (see e.g. IEA 2009; 2010).

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[3] In other countries the role of freight transport by diesel trains is comparable with inland navigation with diesel powered ships in the Netherlands, since both fulfil bulk transport of heavy loads. Although not all EU countries have seaports, due to international trade they have a certain share in the fuel the consumption of sea shipping related to their economic activities. So financial consequences of a CO_2 policy for ships will also influence their economy and an increasing biofuel demand from ships will reduce their own biofuel availability. Consequently, the main conclusions of the current study are also for those modes relevant for other EU countries.

Table 2.1 *Fuel consumption NL transport: steps towards a 2050 BAU reference projection*

[PJ]	2010	2040	2050 extrapolation	2050 efficiency correction	**2050 BAU reference** bunkers corrected	[%]
Light vehicles						
Gasoline	164	115	99	74	**74**	8
Diesel	162	135	130	94	**94**	10
Biofuel	14	23	21	16	**16**	2
LPG	12	6	6	5	**5**	1
CNG	0	12	13	9	**9**	1
Electricity	0	30	78	58	**58**	6
Heavy duty vehicles						
Diesel	98	132	149	124	**124**	13
Biofuel	4	12	14	11	**11**	1
Electricity						
Other road traffic						
Gasoline	5	9	9	8	**8**	1
Diesel	17	26	29	25	**25**	3
Biofuel	1	3	4	3	**3**	0
Rail transport						
Diesel	1	1	2	2	**2**	0
Electricity	6	7	7	6	**6**	1
Inland shipping						
Diesel	8	11	13	11	**11**	1
Diesel Bunkering	8	14	16	14	**7**	1
Air transport						
Kerosene	165	311	377	302	**302**	33
Mobile equipment						
Diesel	34	44	48	41	**41**	4
Maritime shipping						
Fishery	12	11	10	9	**9**	1
Bunkering excl fishery	614	1163	1417	1204	**120**	13
Total consumption	1324	2066	2441	2016	**925**	100

Note The BAU reference projection (column 6, bold) shows a substantial lower total energy consumption compared to the previous columns, due to a correction for the large amount of bunker fuels sold in the Netherlands that are not attributable to the Dutch economy (see explanation at the end of paragraph 2.2).

3. Alternative picture with low-CO_2 transport fuels

This chapter describes a vision on low-CO_2 fuels and technologies and the compilation of an alternative 2050 ‘picture’ that meets the emission reduction objective of 73% compared to 1990.

3.1 A vision on the transport sector in 2050

Substantial changes are needed if the Netherlands are to reduce their CO_2 emission from the transport sector by 80 to 95% in 2050 compared to 1990. For land based transport our study assumes a 80% reduction target compared to 1990, based on an equal share in reaching the overall CO_2 reduction target for developed countries. Note that the White Paper of the EU (EU, 2011) mentions a 2050 reduction target for road transport of 60%[1]. The IPCC/Kyoto sector definition excludes the demand for bunkering of fuels by ships and aircrafts. To reach the low CO_2 target in 2050 the energy use of the transport sector will have to be based on three low CO_2 energy carriers: electricity, hydrogen and biofuels, supplemented by a minimised amount of fossil fuels.

International aviation and shipping fall outside the UN Kyoto Protocol, which expires in 2012. As a consequence, emission reduction in aviation and shipping lags behind compared to road transport. Therefore, also taking into account the large growth rates in shipping and aviation, our study assumes a less ambitious reduction target for these latter modes: 50% CO_2 reduction in 2050 compared to the emissions in 1990. Combining the 2050 reduction targets for shipping and aviation (50%) with the reduction targets for the other transport modes ($\geq$ 80%) results in a 73% reduction target for all transport modes combined in 2050, compared to 1990. As will be shown in the sections below, the limited availability of biofuels will determine which transport subsectors have to shift (partially) to other, more disruptive, low-CO_2 energy carriers, especially electricity and hydrogen.

In order to derive an alternative 2050 low-CO_2 transport picture, several assumptions have been made regarding energy carriers (fuels) and their availability for the various subsectors in transport. These assumptions are explained step-wise in the next 3 paragraphs (3.2, 3.3, 3.4). Subsequently, this argumentation results in the alternative 2050 low-CO_2 transport picture that is presented in Paragraph 3.5

3.2 Future availability of biofuels

Biofuels are an attractive low-CO_2 option as they can be applied in conventional vehicles, with limited modifications to equipment. The future global availability of biofuels is thus a key factor that determines the need for additional but more disruptive low-CO_2 technologies such as hydrogen. Therefore the results of our study are very dependent on the pro rata availability of biofuels for the Netherlands in 2050, which is quantified in the next sections.

Limited worldwide availability of biofuels

The total amount of biofuels available for the transport sector will be limited, because the production of biomass requires a lot of land, thereby often competing with land for food production, while in addition other sectors also need biomass (e.g. for heating and electricity generation). The demand for biofuels accelerated in 2008 with blending proposals in the USA and fixed renewable targets for transport in the EU (PBL, 2009). At the same time, scientific and societal debate intensified on whether biofuels are a sustainable solution. The debate is dominated by issues such as risk of biodiversity loss, increase in food prices and the greenhouse gas balance of biofuels (Smeets et al., 2009) and indirect changes in land use[4] (Fargione et al., 2008; Searchinger et al., 2008).

Estimates of the global potential for bio-energy production vary widely, ranging from 100 to 500 EJ/yr (PBL, 2009), taking account of uncertainties in yield increase, sustainability criteria, water availability, fragile states, and other external factors (Dornburg et al., 2008; WBGU, 2009). PBL (2009) assumes a long term global availability of 100 EJ based on integrated modelling analysis of land use and energy (Van Vuuren et al., 2009a; 2009b); see Figure 3.1.

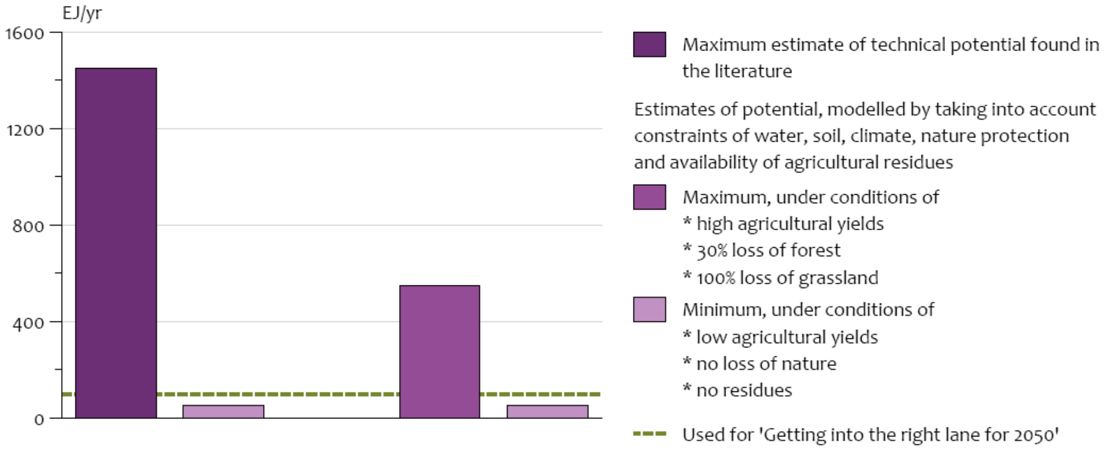

Figure 3.1 *Overview of ranges in worldwide biomass potential*

Note: Left two bars giving ranges in literature estimates; right two bars and horizontal dotted line showing the ranges and best estimate according to PBL (2009).

Only a limited number of studies report on the total availability in 2050 of (liquid) biofuels (rather than solid biomass). Integral views on the biofuel distribution over all transport modes, including shipping and aviation, hardly exist. EREC (2010) reports a combined biofuel availability in road transport (LD and HD) for the EU in 2050 of about 150 Mtoe, equalling about 6300 PJ. Based on the current transport fuel demand of the Netherlands of about 4% compared to the rest of the EU (EU, 2010), this amount of biofuels would indicatively imply some 250 PJ available for the Netherlands in 2050. Similarly, the ambitious IEA 450 Scenario[5][6], shows a use of biofuels increasing from 1.1 million barrels per day (mb/d) in 2009 to 8.1 mb/d in 2035, equivalent to 15% of all transport fuels on an energy-equivalent basis in that year. Extrapolating this trend - thereby neglecting potential production barriers - would indicatively result in some

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[4] The indirect land use change impacts of biofuels, also known as ILUC, relates to the unintended consequence of releasing more carbon emissions due to land use changes around the world induced by the expansion of croplands for biofuels (Searchinger et al., 2008).

[5] Note that the IEA (2009) states that in their BLUE Map scenario, biofuels use is limited to 30% of aviation fuel by 2050, or about 220 Mtoe. This accounts for about 25% of all biofuels in transport in that year. Therefore, according to this scenario the overall global biofuel availability for transport would amount approximately 8800 Mtoe, equalling about 210 EJ.

[6] Note that the IEA BLUE scenarios in 2008 (IEA, 2008) assume that total bioenergy demand will amount to 3.6 billion tonnes of oil equivalent in 2050, with total demand for transport biofuels accounting for around 700 million tonnes and demand from aviation alone accounting for around 165 million tonnes under an assumption of 30% penetration.

15 mb/d in 2050, equalling some 25% of all transport fuels. Compared to the assumed total energy use of about 925 PJ in the transport sector in the Netherlands in 2050 (see Table 2.1), the IEA 450 scenario would also equal some 250 PJ of biofuels available for the Netherlands. This amount corresponds to about 27% of the 2050 energy demand in the transport sector in the Netherlands.

Starting point biofuels for the Netherlands in 2050
On the basis of the various studies described in the previous paragraph, this study assumes an overall biofuels availability of 250 PJ for the Netherlands in 2050. This implies that even ‘long distance’ transport sectors (long haul trucking, aviation, shipping) will have to shift to some extent to other alternatives, especially electricity and hydrogen.

3.3 Assumptions regarding alternative fuels

Production of both electricity and hydrogen is expected to have low - though not zero - well to wheel CO_2 emissions, as briefly explained in the next sections. Nevertheless, in order to focus on the main objectives, the current study neglects CO_2 emissions from both electricity and hydrogen production. Similarly, biofuels applied in 2050 likely have low - though not zero - well to wheel CO_2 emissions, that will be neglected here.

Electricity
In 2050 electricity can be produced from several renewable sources (e.g. wind, solar[7]). In addition electricity production from fossil fuels (coal, gas) can be low-CO_2 if the CO_2 is captured and stored underground (CCS). Furthermore nuclear power plants can be a source of low-CO_2 electricity.

Hydrogen
Similar to electricity, hydrogen can be made from either renewable electricity or from fossil fuels with CCS. Also nuclear power plants can be a source of low-CO_2 hydrogen.

Biofuels
Biofuels are renewable liquid fuels produced from plant material[8]. A variety of (transport) fuels can be produced from biomass resources including liquid fuels, such as ethanol, methanol, biodiesel, Fischer-Tropsch diesel and gasoline, as well as gaseous fuels, such as hydrogen and methane.

Generally, biofuels are divided in two main categories: first generation or conventional biofuels, and second generation or advanced biofuels. First generation biofuels are based on edible feedstocks, using existing refining and fermenting technologies. First generation biofuels are currently produced at a commercial scale. The most important first generation biofuels are: biodiesel (or fatty acid methyl ester, FAME), hydrogenated vegetable oil (HVO), pure vegetable oil and bioethanol (from sugar and starch crops).

Second-generation biofuels are made from non-food woody feedstocks. There are two main technologies to convert whole plant biomass to liquid biofuels: gasification and conversion through a combination of physico-chemical and biochemical conversion steps. A key process in advanced fuel production is gasification of woody feed stocks combined with Fischer Tropsch synthesis. This technique enables the production of a spectrum of fuels that closely resemble conventional fuels like gasoline, diesel and kerosene. Another option to produce high quality

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[7] Global technical potential for solar electricity is much higher than for biofuels. There are two main reasons. Compared to biofuels the energy yield of solar electricity per hectare is much higher (at least a factor 10). Also fresh water is not needed for solar electricity production (solar electricity can be produced in deserts).

[8] Biodiesel can also be produced from (residual) animal fats. However, given the limited availability of this material this is a negligible route.

diesel or kerosene is the treatment of vegetable oils of with hydrogen (e.g. the Neste Oil process). This technique however is still based on edible feedstocks. Biogas is also an option. Because compressed biogas (CBG) has no substantial advantage, in terms of achievable driving range, compared to compressed hydrogen, only liquid biogas (LBG) is considered to be an option in this 2050 study. Although second generation fuel production technologies are not yet available on a fully commercial scale, their large scale market introduction (especially Fischer-Tropsch fuels) is expected to increase substantially after about 2025 (e.g. Elobio, 2011; Refuel, 2011).

All the liquid biofuels can be used with minor or limited changes in new engines. Only the use of ethanol in diesel engines or gas turbines in planes, may require substantial conversions. Application of methanol, ethanol and (bio)methane in aviation is unlikely as these fuels are characterized by unfavourable low energy density and energy per unit mass (IEA, 2009). In general, if started in time all currently used transportation modes can be converted to the use of biofuels. For this reason we decided not to distinguish in detail between the different biofuel types, thereby avoiding additional complexity.

Other alternative fuels
It should be noted that the current report only focuses on the key alternative fuels and does not discuss other fuel options, for example:

- Energizing battery cars by replacing the liquid electrolyte (rather than by electric charging).
- Methanol as biofuel but also as an energy carrier for hydrogen.
- Fuel cells in aircrafts.
- An overhead contact wire system for electricity distribution on highways.

3.4 Assumptions per transport mode

As a final step in the construction of an overview picture for 2050 (as presented in Section 3.5) assumptions have been made on the specific possibilities for fuel substitution per transport subsector. Some subsectors are easier to shift to electricity or hydrogen than others. Biofuels can be applied with limited modifications in most conventional vehicles. In contrast, other low low-CO_2 technologies such as electricity and hydrogen require much more disruptive changes to vehicle power trains as well as to the energy supply infrastructure. In addition, the new low-CO_2 technologies will (initially) be characterised by limitations compared to the conventional alternative, especially regarding fuelling time and driving range. In addition, fast transitions are further complicated by the long lifetimes of aircrafts and ships. Basically, our vision involves an almost complete switch to electricity and hydrogen for the subsectors where this can be done the easiest and allocate biofuels as much as possible for the long distance transport modes, where switching is more complicated.

The 2050 BAU reference picture, as derived in Chapter 2, assumes an indicative energy demand in 2050 for heavy duty vehicles of about 135 PJ, whereas the other sectors competing for biofuels (other road traffic[9], inland navigation, air, mobile equipment, fisheries) require an additional energy amount of about 500 PJ. As concluded in Section 3.2, the biofuel[10] availability for the Netherlands in 2050 will be lower than the total energy demand of all non-passenger car transport modes combined. The limited availability of biofuels results in the choices presented in Table 3.1 regarding the implementation of low-CO_2 technology and fuels in all transport modes. The main choices involve additional application of hydrogen in the long distance transport modes, and to a lesser extent electricity. The key assumptions per transport subsector are briefly discussed hereafter. In addition, Chapter 4 discusses more in depth the technical and organisa-

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[9] See explanation in next sections.

[10] Note that the current study does not distinguish different biofuel types in detail to avoid additional complexity (see also Paragraph 3.3).

tional challenges and the resulting market penetration rates of new technologies for all transport modes.

Light vehicles

Passenger vehicles will be powered almost entirely on either electricity and/or compressed hydrogen (fuel cell vehicle). Several key studies on future transport fuels make comparable assumptions; see for instance the BLUE Map scenario from the IEA (2009) and the recent studies by EEG-FTF (2011) and McKinsey et al. (2010) that is supported by the automobile industry.

Heavy duty vehicles

For the long range transport modes (long distance trucking, aviation, shipping) biofuels are the least complicated low-CO_2 option. However, due to the limited availability of biofuels also hydrogen needs to be applied in heavy duty vehicles. Only some smaller segments of heavy duty road transport, especially goods distribution, can switch to electricity.

Other road traffic

Other road traffic includes buses, special vehicles (refuse collection vehicles, crane vehicles, ambulances, etc.) as well as motor cycles and mopeds. Electricity might be on option for public transport buses and mopeds. In other cases hydrogen or biofuels can be used.

Rail transport

An almost 100% switch to electricity is possible in rail transport.

Inland shipping

Electricity is not seen as a main solution for inland shipping, given the long distances to be travelled. Therefore, similar to the heavy duty road transport segment, the low-CO_2 fuel alternative fuels are biofuels and hydrogen. Hydrogen might be easier to use in inland ships compared to trucks: firstly because of the concentration of the ships on a limited number of waterways, thereby facilitating hydrogen fuelling; and secondly because most ships depart from a main seaport (where large hydrogen storages can be arranged). However, biofuels will also be required as a low-CO_2 fuel over the next decades, because inland vessels have a long life time (up to 40 years), implying that penetration of new technology in the fleet takes relatively long.

Aviation

Air transport is one of the fastest growing sectors. The fuel BAU picture (both shown in Table 2.1 and Table 3.1) already assumes substantial energy savings due to improvement of conventional technology. In line with the IEA (2009) vision that efficiency of aircrafts in 2050 may have improved by as much as 40-50%, based on the combined impact of improved aerodynamic, weight, engines and air traffic control and operations. If further CO_2 reduction is needed, the substitution of kerosene by biofuels is most obvious. However, the future additional fuel demand due to intensification of air traffic alone might even be larger than the overall availability of biofuels. So clearly an alternative is needed, in addition to biofuels. Despite the major technological changes required, we assume hydrogen as the most realistic alternative, as explained and argued in more detail in Paragraph 4.2.3.

Mobile equipment

Mobile equipment includes agricultural tractors, mobile cranes, fork lift carriers, mobile diesel generating sets and equipment for the construction of roads. In the literature no information is available yet on fuel substitution in this sector. In addition to a dominant role for biofuels, a shift to electricity of about 25% may be possible. This number follows from the estimated fraction of the mobile equipment that is used locally, thereby reducing the need for long term operation with limited charging possibilities.

Maritime shipping

In line with the CO_2 emission calculations for the Kyoto Protocol, fuel use by fishery is currently seen as inland consumption. Note that, part of the (diesel) fuel types consumed in fishery is comparable to the fuels used for maritime shipping. Therefore biofuels were selected as future low-CO_2 alternatives for both fishery and maritime shipping (see Table 3.1). However, again because of the limited availability of biofuels, hydrogen will be needed as well.

Table 3.1 *Fuel consumption before and after fuel switch in 2050*

[PJ]	**BAU reference**	-80% overall	-80% road & -50% bunkers	**Selected alternative -73% overall**
Light vehicles				
Gasoline	**74**		4	
Diesel	**94**		15	
Biofuel	**16**	15	71	**15**
LPG	**5**			
CNG	**9**	1	7	**1**
Electricity	**58**	98	76	**98**
Hydrogen	**0**	55	37	**55**
Heavy duty vehicles				
Diesel	**124**		35	
Biofuel	**11**	90	78	**90**
Electricity	**0**	11	6	**11**
Hydrogen	**0**	14	7	**14**
Other road traffic				
Gasoline	**8**			
Diesel	**25**		5	
Biofuel	**3**	18	22	**18**
Electricity		4	3	**4**
Hydrogen		5	4	**5**
Rail transport				
Diesel	**2**			
Electricity	**6**	7	7	**7**
Inland shipping				
Diesel	**11**		3	
Diesel Bunkering	**7**		3	
Biofuel		9	3	**9**
Hydrogen		7	7	**7**
Air transport				
Kerosene	**302**	75	30	**105**
Biofuel		75	30	**76**
Hydrogen		121	193	**96**
Mobile equipment				
Diesel	**41**		10	
Biofuel		30	25	**30**
Electricity		5	3	**5**
Maritime shipping				
Fishery	**9**	2	3	**3**
Bunkering	**120**	30	37	**43**
Biofuel incl. fishery		32	40	**31**
Hydrogen incl. fishery		52	39	**41**
Total consumption	**925**	759[11]	803	**768**

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[11] Note that the electricity and hydrogen powered vehicles have a higher efficiency than the conventional alternatives, resulting in a lower total energy consumption.

3.5 Overall fuel consumption picture of this study

The vision and assumptions presented in the previous paragraphs are summarised in an overview table showing the 2050 fuel use proposed for the various transport modes (Table 3.1). Because electricity and hydrogen powered vehicles have a higher efficiency than the conventional alternatives they replace, their application results in a decline of the total energy consumption of the transport in the sector. The four column headings of Table 3.1 are explained in the text immediately after Table 3.2.

Table 3.2 *Fuel consumption before and after fuel switch*

[PJ]	**BAU reference**	2050 -80% overall	-80% road & -50% bunkers	**Selected alternative -73% overall**
Fossil	**831**	109	153	**153**
Biofuel	**30**	271	268	**270**
Electricity	**64**	126	94	**126**
Hydrogen	**0**	254	288	**220**
Total consumption				
CO_2 emission	**925**	759	803	**768**
[Mton]	**63**	8	11	**11**

Column 1 (*BAU reference*) - shows the 2050 starting point of fuel consumption and bunkering that is directly attributed to the Dutch economy. This column (that is identical to the pre-last column of Table 2.1) already includes substantial, but not maximal, energy saving.

Column 2 (-80% overall) – shows a fuel distribution that results in an overall CO_2 reduction of 80% compared to 1990.

Column 3 '*-80% road & -50% bunkers*'- In this case the CO_2 emission reduction target for Dutch national transport is still 80%, but the reduction target for both air transport and for maritime shipping is only 50%. This situation reflects the vision that 80% CO_2 reduction in 2050 (compared to 1990) for different industrialized countries does not automatically include international shipping and air transport. In this case there is still fossil fuel available for road transport. On the other hand, the hydrogen penetration in air transport has to increase substantially compared to the case presented in column 4.

Column 4 '-73% overall' - involves an average CO_2 reduction of 73% for the entire transport sector. This case allows to reach the same reduction target of 73% as shown in column 3, but now focusing on the overall target of *73%* CO_2 reduction for all modes combined. In this way there is maximum flexibility in choices on fuel distribution over the transport modes. By further reducing the fossil fuel use in road transport modes - where substitution is the least complicated - more fossil fuel is left for application in international aviation and shipping, thereby reducing the amount of hydrogen in these sectors. For this reason this case is selected as our key 2050 low-CO_2 alternative 'picture', and used as a basis for all analyses in our report.

Reducing fossil fuel use in road transport modes is easier for individual countries than lowering emissions of shipping and aviation as these latter modes are not yet included in the UN Kyoto Protocol. This implies that if there would be an integrated policy for CO_2 emission reduction - with an overall emission reduction target for the transport sector as a whole - this would lead to a faster and earlier reduction of land based transport emissions compared to shipping and aviation; i.e. the additional emission reduction in land based transport would compensate for the delayed reductions in shipping and aviation. Adversely, separate targets for land based transport and shipping and aviation would allow slightly less stringent reduction of land based emissions, but additional and faster measures for aviation and shipping.

3.6 Resulting CO_2 emission reduction

Table 3.2 shows that the 2050 picture envisioned still includes some use of fossil fuels. In addition the amount of biofuels is slightly higher than the assumed maximum for the Netherlands of 250 PJ but within the uncertainty range. The resulting CO_2 emission reduction percentages are expressed relative to 1990 transport emissions. The CO_2 emission of the total Dutch transport sector (including mobile equipment) in 1990 was about 30 Mton. But because also the Netherlands share in bunkering of aircrafts and sea ships needs to be taken into account, the 1990 overall transport reference emission is 41 Mton. The 'BAU reference' (column 1) results in 63 Mton CO_2 emission while the '-80% overall' (column 2) corresponds to a CO_2 emission of approximately 8 Mton. The case with split up reduction targets for road (-80%) and bunkers (-50%) shown in column 3 leads to 11 Mton CO_2 with 5 Mton CO_2 from international transport. The -73% overall case (column 4) leads also to 11 Mton emission reductions (mainly from international transport) and is used further in this report.

Finally it should be noted that the emissions of producing biofuels, hydrogen and electricity are neglected for the reasons explained in Paragraph 3.3. For example, if biofuels in reality would reduce emissions with 90% CO_2-eq compared to fossil fuels, than the well to wheel CO_2 emission in our calculation would increase with 2 Mton CO_2-eq. A similar reasoning can be applied to electricity and hydrogen characterised by low - though not zero - well to wheel CO_2 emissions.

4. Inertia in deployment of new technologies

In Chapter 3 a picture of the 2050 transport sector with low-CO_2 fuels and technologies is presented that meets an overall CO_2 reduction of 73%, compared to 1990. This 2050 picture raises the question how to get there. Answering this question requires the identification of realistic routes of market penetration of the technologies underlying the desired 2050 picture (Chapter 5), as well as to clarify at what point in time policy induced changes are needed to achieve the desired 2050 situation in time (Chapter 6). However, before market penetration routes and supporting policies can be proposed, first the inertia in technology development and policies need to be identified. Key inertia include: technology development per mode, market uptake, building of fuel production capacity, infrastructure development and roll-out, as well as (EU) regulations. Therefore this chapter provides an overview of several factors, and their inertia, that control the market penetration of new low-CO_2 technology in the various transport modes. This chapter aims to describe general mechanisms, rather than to provide a complete overview of all specific inertia for all technologies. For this project also earlier studies of ECN have been used[12], so the content of this chapter is not the only source which is used for the model.

4.1 General pattern of market penetration

Skinner et al. (2010) argue that in general two phases can be discerned for light duty road transport vehicles for the coming decades: pre 2030; and post 2030. Between 2010 and 2030 conventional vehicles need to continue to be made more efficient. At the same time experimentation needs to be undertaken with vehicles using alternative power trains that are potentially carbon-neutral. Before 2030 the most viable options among these low-carbon alternatives need to be developed to technological and economical maturity. This must be achieved in part by creating first markets for such alternatives using low-CO_2 fuels. This in turn will generate production volumes and lead to cost reductions through learning effects. It will also create a basis for industry to invest further in the development of optimised products and production methods (see e.g. Schoots et al., 2008 and references therein). By 2030 alternatives must be ready for large scale uptake. Between 2030 and 2050 the market share of sustainable alternatives needs to be increased significantly in order to achieve a significant fleet share by 2050. As a consequence, the market introduction of new transport technologies will usually follow the trend as visualized in Figure 4.1).

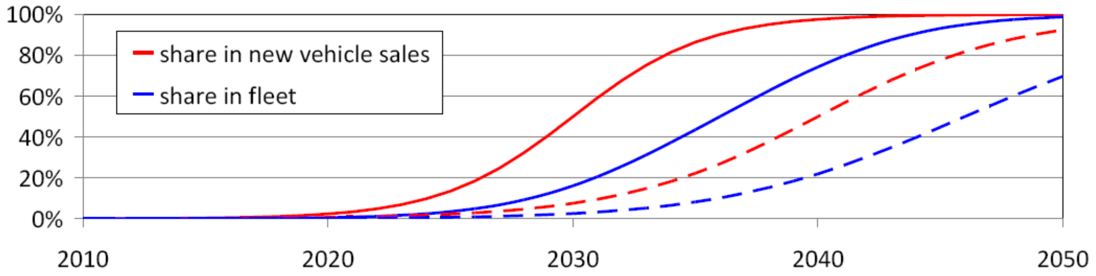

Figure 4.1 *Indicative representation of the evolution of the share of potentially low-carbon-vehicles in the new vehicle sales (red lines) respectively the overall fleet (blue lines)> Dashed lines show the evolution for transport modes with longer lifetimes, such as aviation and shipping*

Source: Skinner et al, 2010.

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[12] (Bakema, 1990), (Schol, 1995), (Bosch, 1999), (Dril, 2007), (Hyways, 2008), (Uyterlinde, 2007a,b,c, 2008), and (Hanschke, 2009).

Figure 4.1 clearly shows that the fleet share of new technologies (blue line) substantially lags behind to the share in new vehicle sales (red line). The time lag depends on the life time of vehicles and the associated fleet renewal rate. The lifetimes of different modes vary considerably. Road vehicles tend to have shorter lifetimes than trains, aircraft and ships and they also tend to have shorter development times. For transport modes characterised by long life-times, the time lag between new sales and market penetration will be the larger. In terms of the potential contribution to GHG reduction by 2050, one could therefore expect a full contribution from the widely implemented new road vehicle technologies by 2050, but the contribution from new technologies for rail, aviation and shipping are expected to be smaller, due to the lower market penetration rates (Skinner et al., 2010). The long lifetimes of rail, aviation and shipping therefore are an argument for the urgent introduction of low-CO_2 technologies for these modes, in order to ensure that cleaner vehicles have a significant market share by 2050.

4.2 Inertia in vehicles

4.2.1 Passenger cars

The development, commercialization and large scale market penetration of new vehicles that are powered by virtually carbon-neutral energy carriers will take at least two decades. According to the European Automobile Manufacturers' Association (ACEA) the development from design to production logistics for a new car takes up to 5 year. Engine design can take even longer. Their product cycle, or the time that cars are kept in production, takes up to over 7 years (ACEA, 2010), See Figure 4.2. The development cycle for trucks follows a compatible pattern, although the evolution of the market share of new vehicles goes faster.

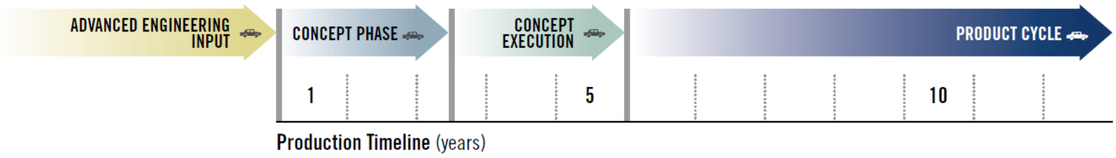

Figure 4.2 *Car development according to ACEA*

So the development of a new vehicle concept will take some 5 years of development, followed by some 10 years of production and sales. Shortly after the introduction of the first new vehicle the developments of the next model will commence with a development of about 2-3 years, and subsequent production and sales. More models will come on the market and competing car manufactures will start to produce too, with again approximately 5 years of development. All in all a major share of a new vehicle type in the market will take about 15 years, usually following the S-curve as shown in Figure 4.1. Moreover, a major share in the vehicle fleet lags behind by about 5 more years, given the replacement rates of vehicles of about ten years. Consequently, the first vehicles using alternative power trains that are potentially carbon-neutral need to come to the market by 2020 or 2025 to ensure a sufficient share in the fleet by 2050.

Historic case of hybrid cars

To see how a real market can work, the development of hybrid cars is interesting. It should be mentioned that in earlier stages research was done on hybrid cars, just like on battery electric vehicles. In 1992 the first development of the Prius was started by Toyota. It took 3 years before it was presented to the public and 2 years before production was started in 1997. It took another 5 years to reach the first 100.000 cars and a market share of 0.1% (in 2003). 10 years after the starting point a new version of the Prius was introduced, which led to a market share in the sales of new cars of about 1% in 2009. The production of the hybrid Honda Civic followed some years later. About the same type of development occurred. The third hybrid producer in the USA was Ford. In 2007 there were 15 models on the market in the USA, but only half of them were also sold in Europe. Also on the Japanese market much more models are sold compared to

Europe. So a new type of car is first sold on the local market, and only if the sales reach large numbers, the selling on other market begins.

Currently (2010) the market share of hybrid cars is about 2-3%. In 2012 it is expected that there will be over 50 models of hybrid cars, and market share in the sales of new cars could reach 5% (ECN estimate). Although about 500 different car types of 35 producers are sold in the Netherlands, this does not directly result in a market share of 10%, because most of the market penetration takes place in the more expensive segment.

The hybrid car example illustrates that it takes about 20 years from the first research on a new car type to a market penetration of 5%. Or 15 years after the first production has been started up. Can it go faster? Yes. Initially there was only one producer in the hybrid vehicle case, two years later followed by a second one. The first producer reached a 1% market share 12 years after the first production. So if 5 companies start almost at the same time, the 5% limit could be reached earlier.

Overall inertia passenger cars
In summary, the development and roll-out time of passenger cars is expected to take about to 25 years.

4.2.2 Heavy duty vehicles

The development and market penetration of trucks is relatively fast compared to passenger cars. In the passenger car segment several electric vehicles already have been developed. Also hydrogen cars are being tested. For trucks the situation is different. There are some experiments with electric trucks. Also a limited number of demonstration trucks and busses are powered by hydrogen. But developments are not far enough to really start up production. For passenger cars components are designed to be used in a car which could be sold, but for trucks this is still in the proof of concept phase. However, profiting from the developments in the passenger car segment, much of the knowhow required is already gained for designing a production ready truck. Therefore, future developments are expected to take place faster compared to the similar trajectory that already took place in the passenger car segment (see Paragraph 4.2.1 and Figure 4.2).

When a truck (engine) builder decides to start with the production of a new type of truck, it will take 3 to 5 years before the first commercial truck can be on the market. In 2007 globally 3.46 million trucks were produced, from which 0.67 million (20%) were manufactured in the European Union. This EU market share is large enough to start innovation. About 50% of the trucks is produced by 4 companies: Isuzu, Daimler AG, Volvo Group, and Toyota Group (OICA, 2008). Another 35% of the production is covered by an additional 8 companies. The smallest company is selling less than 100.000 trucks per year.

Potential market penetration
If the truck manufacturers can be convinced that electricity and hydrogen powered vehicles are needed and also will have adequate market potential (this trajectory may take 5 years), subsequently a development time of 5 years will be needed. Consequently, the first commercial electric and hydrogen trucks could be sold in 2020. However, this does not yet answer the question how many other manufacturers will join from the start. The truck manufacturers will likely take some time (for instance 3 years) before they start with the development of the next model. Taking into account the production cycle of 10 years, it could take an additional 10 years before sufficient types of hydrogen and electric trucks will be produced. So when in 2020 the first types will be on the market, it follows that around 2033 all relevant types could be produced. Because trucks make the most km in the first 5 years, according to Dutch transport statistics, their market penetration is relatively fast, as shown in Figure 4.3. Therefore a 95% market penetration of

new low-CO_2 trucks could be reached in 2040. Figure 4.3 visualizes the market penetration of new technology in the truck segment, based on the assumptions presented in this paragraph.

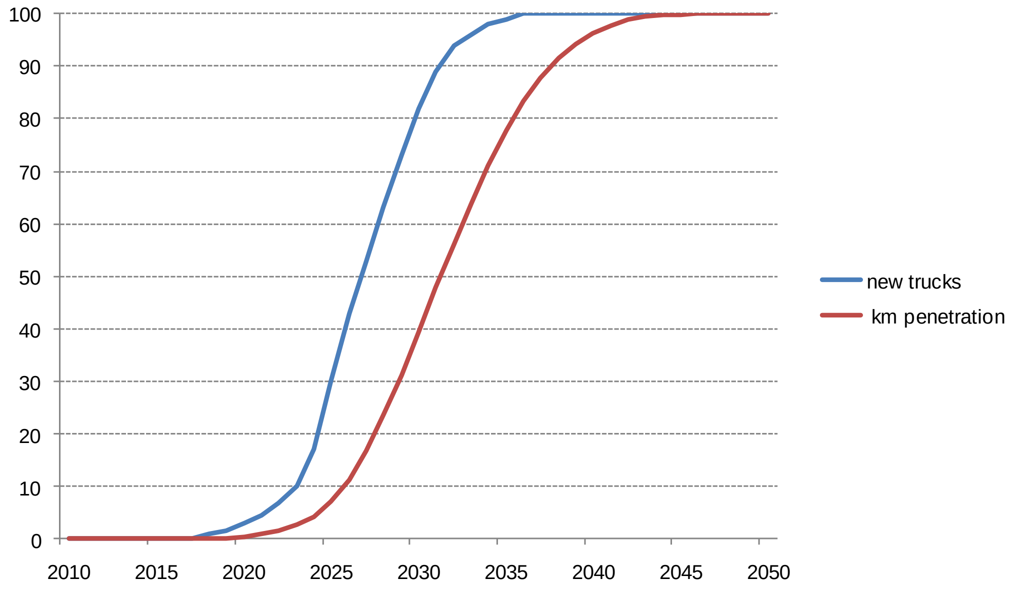

Figure 4.3 *Visualization of technology penetration in new trucks and in km driven*

Bottlenecks for trucks

There might be bottlenecks related to this roll-out scenario, especially related to competition with the passenger car segment. The truck sector will have to compete with the passenger car segment for key feedstock to produces batteries (lithium) and magnets for the electric engines (rare earth metals). In addition the hydrogen fuelled segment of the truck sector will have to compete with the passenger car segments for hydrogen. This competition for materials and hydrogen will increase prices and will possibly slow down market penetration.

Overall inertia heavy duty vehicles

In summary, the above sections indicate that the development and roll-out time of heavy duty vehicles towards a major market share is expected to take about 20 years (see Figure 4.3).

4.2.3 Aviation

We discuss the development and market penetration of aviation somewhat more in depth compared to the other transport modes, because of the major safety issues related to aviation fuels, as well as the rather prudent position of the IEA, that is balanced here by the visions presented in other studies. Compared to the road transport sector, aviation has fewer options to replace conventional fuels. The energy density of jet fuel (i.e. energy per unit of mass) is critical for providing adequate aircraft flying range.

Jet fuel (kerosene) is not radically different from diesel fuel for road vehicles; so high-quality, high energy-density biodiesel is the closest substitute. Therefore bio-kerosene with specifications close to the currently used fossil jet fuel is an attractive low-CO_2 alternative option for the aviation sector, that does not involve major modifications to aircrafts. The use of biofuels in aviation has been confirmed in recent trials as being technically feasible. Consequently, the airline industry shows great interest in biofuels. However, the starting point of our study is that the global biofuel availability will be limited[13] (see section 3.2), forcing the aviation sector to apply

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[13] Note that the IEA BLUE Map scenario, assumes a 30% blend of second-generation (BTL) biofuel, by 2050 (IEA, 2009), implying that other energy sources are required as well.

other low-CO_2 solutions, in addition to biofuels and efficiency improvements. Our study assumes hydrogen to be the most realistic alternative aviation fuel, despite the technological hurdles to be taken, because the challenges for other large scale applicable low-CO_2 alternatives appear to be larger. The feasibility of hydrogen as aviation fuel is discussed in the next sections.

Hydrogen

When demand cannot be met with biofuels alone, liquid hydrogen may be the most attractive low-carbon alternative[14]. Several literature sources assume hydrogen in aviation a feasible option (e.g. Svensson, 2005; Airbus, 2003). Given the limitations in biofuels availability and the need to minimize fossil fuel use, in this study we assume hydrogen be the most realistic alternative fuel. However, application of hydrogen will require major changes in aircraft design. Hydrogen propulsion can be based on gas turbines and the modifications required are relatively straightforward (Svensson, 2005; Marcus, 2010). E4tech (2009) states that hydrogen-fuelled engines for civil aircraft could be developed in the medium term (about 10-15 years). The key technical issues to solve are the on board storage of hydrogen and reduction of drag (Farries and Eyers, 2008). Hydrogen will likely be stored on board in the form of cryogenic liquid hydrogen to minimize volume. Insulation and pressurization requirements make it impossible to store liquid hydrogen in aircraft wings, as is done with kerosene jet fuels. In addition, though liquid hydrogen has a very high energy density per unit of mass, its energy density by volume, even in liquid form, is only one-quarter of current jet fuel. Therefore large storage tanks will be needed for the required large volumes of cryogenically cooled hydrogen. This would increase the weight of large commercial aircraft by over 10% (Daggett *et al.*, 2006), although new designs of aircraft bodies could reduce this disadvantage. Modifications would also be necessary to the fuel management system and temperature controls. Nevertheless several assessments have pointed out that hydrogen fuelled aircrafts will not be less safe than conventionally fuelled aircrafts (e.g. Svensson, 2005). Furthermore, the use of liquid hydrogen would also require substantial modifications to airport infrastructures, including a completely different fuel distribution infrastructure.

In the Cryoplane project (Airbus, 2003) AIRBUS and partners suggest that a hydrogen powered aircraft is feasible and given the appropriate market conditions could be developed in a 15 year timescale. In contrast, the IEA (2009) qualifies liquid hydrogen as not a promising alternative fuel for aviation in the near or medium term. Similarly, IEA (2010) reports that it is unlikely that the aviation sector in 2040 will substantially apply other alternative fuels than kerosene alike biofuels.

Fleet replacement

Currently, aircrafts are kept in service for about 30 years, before being replaced. IEA (2009) states that the average efficiency of the aircraft stock may lag behind by up to 20 years compared to the latest models, because of the slow penetration of new technologies in the stock. However, Boeing (2009) presents an apparently faster scenario on the global airplane fleet dynamics to 2028, as summarised in the following two expectations:

- The 2008 passenger aircraft fleet of 16,860 is expected to increase to 32,350 in 2028. Up to 2028 Boeing expects 28.290 new airplanes; 10,750 will be permanently retired, while an additional 2,050 will be converted from passenger aircraft to freighter.
- The freighter fleet is expected to increase over the same time frame from 1.940 to 3.250, based on: 710 new freighters, the addition of 2.050 converted passenger aircrafts, and a permanent retirement of 1.450 aircrafts. The expectations for the next 2 decades reported by Airbus, the largest rival of Boeing, are rather comparable (Guardian, 2008).

The above numbers indicate that the expected rapid growth in the aviation fleet involves a much faster fleet penetration for the passenger transport segment, than would be expected from the

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[14] Note that CO_2 is just one of several aircraft emissions that has radiative forcing (i.e. climate warming) effects. Others include nitrogen oxides, methane, water vapour and cloud formation.

average lifetime of aircrafts. Aircraft fleet turnover may be further accelerated by the substantial fuel savings potential of new advanced aircraft, and associated lower operational costs. In addition, the faster introduction of new aircraft technologies can be promoted by international agreements that price or limit aviation GHG emissions. The pace of market growth is expected to depend on the intensity of government intervention (IEA, 2009).

Overall inertia aviation
In summary, the development of aircrafts is expected to be in the order of 15-20 years. In addition another 15-20 years will be needed to reach 50% fleet penetration.

4.2.4 Shipping

International sea shipping has grown very rapidly in recent years, in particular as a consequence of the growth in Asian export to other countries. It now represents about 90% of all shipping energy use, the remainder being used by inland and coastal shipping (IEA, 2009). International shipping falls outside the UN Kyoto Protocol. The structure of the shipping industry is fragmented and often related to different countries (flag states). This fragmented structure limits the market incentives to optimise ship efficiency. Ship efficiency has not significantly improved in recent years, apart from size increases. Especially because transport by shipping is projected to triple until the year 2050 (IEA, 2010), there is an urgent need for low-CO_2 technologies.

Only since a couple of years CO_2 emission reduction in shipping is high on the agendas of the EU, individual countries as well as the United Nations International Maritime Organization (IMO). Recently a number of reviews have been published on CO_2 emission reduction in shipping. Most studies indicate that a package of technical solutions, especially regarding drag reduction and propulsion efficiency, may result in efficiency gains up to several tens of % (e.g. IEA, 2010; DNV, 2011). Several of these solutions are also suitable for retrofitting, although the efficiency gain will be lower. However, these efforts on shipping efficiency cannot even compensate part of the expected additional growth in shipping. Clearly, new low-CO_2 fuels are needed to substitute the currently used heavy fuel oil (also called bunker oil). The most frequently discussed low-CO_2 fuels include:

LNG
Although Liquid natural gas (LNG) is often mentioned as one of the most promising alternative future shipping fuels (e.g. Witso, 2010; Brannigan et al. 2009) this relates in part to the substantial impact on air pollution (especially reduction of particulates, NO_x and SO_2 emissions). The CO_2 emission reduction from LNG - due to its relatively low carbon content - is relatively modest, and not sufficient to meet the climate targets required (O'Rourke, 2006; Witso, 2010). Application of LNG requires the development of a land-based infrastructure to transport the gas to the ships. In addition LNG needs bulky storage tanks, which requires up to 3 times more space on board than the currently used bunker fuel. Compressed natural gas demands even more space (Carlin et al., 2010). Solving these bottlenecks for LNG, may be a stepping stone for hydrogen propulsion that is characterised by comparable issues regarding fuelling and on board storage.

Biofuels
The most promising biofuels for ships are biodiesel and crude plant oil (DNV, 2011). Ship engines are capable of using a relatively wide range of fuels, and may be able to use relatively low quality, low-cost biofuels (e.g. Mc Kinsey, 2009). However, as argued in section 3.2, the global availability of biofuels will be much too small to meet the total demand for low-CO_2 fuel of the shipping sector. So other fuels are required.

Nuclear power

Although several hundred nuclear-powered navy vessels exist, few nuclear-powered merchant ships have been built (O'Rourke, 2006). Commercial nuclear ships would have to run on low enriched uranium (DNV, 2011). The main barriers to nuclear shipping relate to uncontrolled proliferation of nuclear material, decommissioning and storage of radioactive waste, the significant investment costs and societal and political acceptance (Tutturen, 2010). Given these uncertainties nuclear propulsion is not further taken into account in our study.

Hydrogen - fuel cells

Several studies mention fuel cells as a future option – either in combination with hydrogen or with other hydrocarbon fuels (e.g. O'Rourke, 2006). Fuel cell propulsion is already applied in a number of submarines. Initially, fuel cells for commercial application are expected to provide auxiliary power, e.g. hotel loads. Marine fuel cell prototype for this purpose currently delivers power in the range of 0.3 MW (DNV, 2011). Ultimately they will provide supplementary propulsion power in hybrid electric ships and on the longer term may be sued as main power source. The key barriers to be solved are cost, weight, size, lifetime, and slow response to load variations. During the next decade fully commercial marine fuel cells will become available, but not yet as main power source (DNV, 2011).

Given the limitations in the global availability of biofuels and the need to minimize fossil fuel use, we assume hydrogen be the most realistic alternative fuel, as other options (apart from nuclear) do not meet the CO_2 reduction goals required. However, as indicated above, the application of hydrogen will require major changes in ship design as well as in land-based distribution and fuelling infrastructure. As explained in the next section, the development and market penetration of hydrogen propulsion in shipping will take a few decades.

Fleet replacement

Figure 4.4 shows, based on Lloyd's data, that the number (red line) and the average size (blue line) of ships has grown over the last decades. Based on the growth in tonnage of new ships - 400 mln Gton between 1997 and 2008 – it follows that about 20% of the tonnage available in 1997 has been taken out of service (TSO, 2009). This would correspond to a lifetime of about 50 years. However, this is probably an overestimation of the lifetime, because the fast growth in recent years has resulted in almost no decommissioning of ships (so old ships are kept longer in service). Focussing on the period 1997 to 2003, a time span with a representative average growth relative to the last decades, indicates a lifetime of about 35 years, in line with values reported in literature (e.g. Skinner et al, 2010, IEA, 2010). In 2008 about 50% of the total transport capacity was less than 11 years old, suggesting a lifetime of only 22 years. However, this figure is substantially influenced by the high growth rate. On balance, and supported by the statistical data, the lifetime of ships lies between 30 to 40 years.

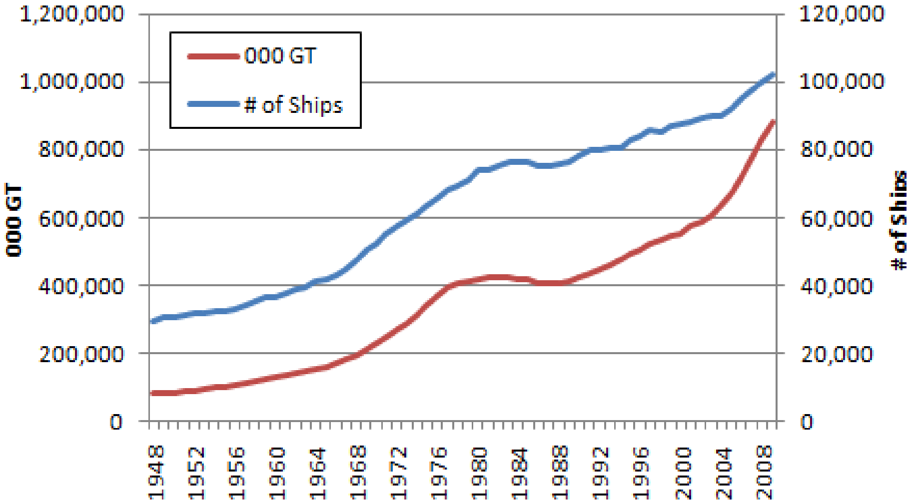

Figure 4.4 *Growth of the world fleet of merchant ships in numbers expressed in gross tonnage (GT) and numbers (#)*

Source: TSO, 2009.

Policies

Policies to promote improved international shipping efficiency and CO_2 reduction may have to come from international agreements. Shipping could be included in a CO_2 cap-and-trade system. The future options in this field are currently discussed by the EU, by individual countries, as well as by the IMO (IEA, 2010; IMO, 2011).

Overall inertia shipping

In summary, the development of ships is in the order of 15 years. The additional time to reach a 50% fleet penetration amounts to another 15-20 years.

4.2.5 Rail

The fuel consumption of rail transport is small compared to the other sectors. According to Hoen (2004), the mean lifetime of a diesel locomotive is 30 years and about 3% of the park is yearly replaced. For a 100% penetration of electricity in the railway sector, all railways have to get a catenary system. For railways with limited use or shunting yards battery electric locomotives may be used (this type of equipment has still to be developed). Those locomotives can be reloaded on partly electrified tracks or at railway stations. To speed up the penetration: new electric locomotives can be used at locations where the catenary system is already in place. The superfluous diesel locomotives of the catenary tracks can be used to replace decommissioned diesel locomotive at other locations. In this way the uneconomical purchase is prevented of new diesel locomotives, that would not be able to serve their full technical lifetime. Furthermore in this way the speed of extension of the catenary system - which may take until 2040 or 2050 - is not a main bottleneck.

4.3 Some examples of inertia in fuels

The introduction of an alternative transport fuel always bears a challenge that is often referred to as a ‘chicken and egg’ problem: while people will only become interested in and start switching to a new fuel if sufficient refuelling stations are available, industry will only start investing in the development of a refuelling infrastructure if the market is sufficiently developed and existing stations are economically viable. But introducing of new fuels is possible, as shown in the next paragraphs. Although infrastructure is needed, the main bottleneck seems to be the number of vehicles on the new fuel.

4.3.1 Historical case study LPG

Backhaus and Bunzeck (2010a) describe how the development of LPG as transport fuel started in the Netherlands in comparison with other countries, thereby concluding that well concerted efforts by policy makers and industry may lead to the firm establishment of an alternative fuel market, if support is targeted at both vehicle uptake and refuelling station availability.

The introduction of LPG as transport fuel started in the Netherlands in 1954. The initiative came from an importer of American trucks that ran on LPG as well as gasoline and that were to be introduced to the Benelux market. Refining companies, a prominent industry branch in the Netherlands, noticed an opportunity to generate additional income by selling LPG which is a by-product in the oil refining process. The Suez Crisis of the 1950s and the oil crisis of the 1970s caused the global oil price to increase significantly. Therefore, fuel prices at the pump soared also in the Netherlands. This created a price advantage for LPG compared to other fuels and helped LPG to establish a quick foothold in the market. LPG was available at about 100 refuelling stations by the end of the 1950s, 200 (~2%) by the end of 1960s and 5500 (~50%) by the end of the 1970s.

Experiences in other countries in developing gaseous fuels in transport differ. Successful cases have in common that the roll-out of fuelling infrastructure and vehicle fleet took more than 2 decades. For example, currently in Argentina over 20% of the passenger car fleet runs on CNG, after a steady and politically well orchestrated station and vehicle build-up commencing in the 1980s. A government action plan supported vehicle conversions and station construction by means of grants and still supports favourable excise taxes for CNG. Thereby, one of the worldwide most successful alternative fuel markets was established and maintained Backhaus and Bunzeck (2010a). Currently CNG is also introduced as a transport fuel in the Netherlands[15].

Often the expected large scale roll-out of hydrogen is compared to the experiences with other gaseous transport fuels in the past (Backhaus and Bunzeck, 2010 b). However, it has to be emphasised that LPG, CNG and hydrogen cannot be compared one-to-one as there are technical, economic, social and other differences associated with each of them.

4.3.2 Hydrogen infrastructure

A main fuel in this report is hydrogen. Hydrogen is already an important energy carrier. The worldwide hydrogen production in 2005 is estimated at 50 mln ton per year (6000 PJ) mainly for use in refineries. More than 90% of the H_2 generated comes from reforming of natural gas. There are already two large hydrogen pipeline networks in the Europe owned by Air Liquide. A 879 km reaches from Rotterdam in the Netherlands via several locations in Belgium to Waziers in Northern France (Axane, 2001). A second 240 km hydrogen pipeline network operates in the Rhine-Ruhr area (Air Liquide, 2011). Both networks have substantial hydrogen production capacity.

A roll out of hydrogen for the transport sector with hydrogen filling stations can start with local production and/or distribution with tanker trucks. If the volume increases this can be followed by distribution with pipelines for instance by extension of the current networks. Firstly the main infrastructure can be built along highways. To illustrate how fast a gas network can be realized the next paragraph describes the roll out of the Dutch natural gas network.

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[15] With 900 passenger cars on CNG, 1200 vans and 600 busses and trucks in January 2011 already 65 new public filling stations are open and 45 are planned in May 2011 (NGV-Holland, 2011). The first CNG station was build in 2007.

4.3.3 Roll-out of natural gas infrastructure in the Netherlands

This paragraph gives an example on how fast a new large scale fuel infrastructure including a pipeline network can be realized if there is enough benefit. The chronological overview below shows that it was possible to achieve this for natural gas in The Netherlands in less than 10 years (‘Gas in beeld’, 2010):

- 1959: The discovery of huge natural gas field near Slochteren.
- 1962: Lower house adopts a memorandum with rules allowing to start selling gas as soon as possible.
- 1963: Formation of the Dutch Petroleum Company (NAM; 50% Dutch State and 25% Shell, 25% Esso).
- 1964: The start of construction of a pipe network for natural gas spanning the entire Netherlands. Late 1964, already 500 km of main network is constructed and nearly 3200 km of regional network (also by using old networks from city gas).
- At the same time the public is prepared by information campaigns for the transition to natural gas. Gas appliances must be rebuilt or replaced[16]. The use of natural gas in the Netherlands increased explosively in the seventies, as well as the export to other countries.
- 1972: After 1964 the amount of sold natural gas increased with a factor 20 in four years. And after doubling in the next four years the great majority of the Dutch households used natural gas 13 years after the gas discovery.

The above chronological overview of the roll-out of natural gas infrastructure in the Netherlands, indicates that a possible future scale up of hydrogen use in transport, will probably meet the largest inertia in hydrogen production, rather than in the roll-out of infrastructure.

4.3.4 Biofuels

In the Netherland the use of biofuels increased from almost zero in 2005 to around 4% in 2010, and it is expected to grow to the EU target of 8.5% (with double counting) to 10% in 2020. So it is possible to substitute a substantial part of the fossil fuel demand in the transport sector by biofuel. The conversion capacity of biofuel feedstock into biofuel appeared to be no bottleneck. Currently there is even a large surplus of conversion capacity. The amount of sustainable biomass feedstock looks also not a major problem although there is the food or fuel discussion. Also in the USA biofuels are already used in gasoline on a large scale (see paragraph 4.4.3). Although the use of biofuels can grow further after 2020 it is not clear if the feedstock production can keep up with the growth rate of biofuel demand. So the 250 PJ biofuel availability for the Netherlands that we expect in 2050, might not be already available in for instance 2030. A shortage of biofuel feedstock will reduce the possibilities CO_2 reduction in the 2020-2040 period.

4.3.5 Case study low sulphur bunker fuels

Early 2007 some of the large shipping companies pushed for a global ban on sulphur rich bunker fuels to reduce air pollution by shipping. Subsequently, the possible ban of sulphur rich bunker fuels, as well as its timing, was seriously considered by the International Maritime Organisation (IMO). Concern was expressed by other shipping companies and by the organisations of oil companies, that there would be insufficient low-sulphur production capacity available in time to meet the targets suggested.

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[16] There was also a second hand market for gas appliances on city gas for use on locations not yet connected to the natural gas network. This second hand market decreased the amount early scrapping. This “second hand market” mechanism can also help in the transformation of the transport sector. The transfer of good vehicles (air planes, diesel locomotives) on an old fuel to locations without the new fuel (or fuel infrastructure), can increase the penetration rate of new fuel vehicles.

Following this, De Wilde and Kroon (2007; 2008) evaluated the technical, economic and energetic impact of converting the 8 million tons of refinery residues in the Netherlands into lighter fuels with a lower sulphur content. They concluded that the production of residual fuel oil could be reduced, by extending and optimising the refinery processes of (vacuum) distillation. Furthermore it is technically possible to convert the heavy and viscous residues that cannot be distilled further into lighter products (deep conversion). Several refineries have shown in practice that this is technically.

Technically, it might be possible to expand capacity for the deep conversion of the marine bunker fuels in about a decade. However, the main challenge will be to increase the deep conversion capacity concurrently with the autonomous activities involving expansion of primary conversion. Potential difficulties involve the availability of technical knowledge and production capacity for the construction of new deep conversion installations, as well as the production decreases due to temporary stoppages in refineries in order to incorporate the new installations.

Negative impacts might include shortages and price perturbations for certain oil products, as well as shortages in the engineering and construction capacity for refining facilities. Gradual introduction over about 6 years, preceded by a preparation phase for the refineries of approximately 6 years, could limit the negative effects. In line with the results of the study by De Wilde and Kroon (2007; 2008), The International Maritime Organisation (IMO) agreed in October 2008 on a maximum sulphur content of 0.5% for shipping fuels in 2020[17].

This example shows that the implementation of major changes in the refinery industry, may take about 12 years. It furthermore illustrates that it is possible to take substantial and elaborate policy measures in the transport sector within a few years on a world wide scale. The policy decision process took less time than implementation. Finally in the next paragraph some other policy decisions will be presented.

4.4 Inertia in policies and regulations

The development time of technologies decrease along a learning curve. Similarly, the development times of new policies and regulations are also expected to be shorter if comparable policies and regulations are already available. For example, the future CO_2 regulations for trucks are expected to be developed much faster compared to the trajectory of regulations for passenger cars as described in the next section.

4.4.1 Example: development time of EU vehicle CO_2 standards

In 1993, the EU has agreed that average CO_2 emissions from new passenger cars should not exceed 120 grams of CO_2 per km by 2012 (EU, 1993). The initial strategy for CO_2 emissions reduction was proposed by the EC in 1995 based on three main subjects: (1) mandatory labeling for consumer information; (2) voluntary agreements with car markers; and (3) promoting fuel-efficient cars through fiscal measures. In 2005, the European Parliament passed a resolution in support for mandatory CO_2 emission standards to replace current voluntary commitments, since some major automakers' performances on reducing CO_2 emission are found unsatisfactory (EU, 2005).

In 2007, a new proposal was initiated for a regulation of the European Parliament and of the Council setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO_2 emissions from light-duty vehicles (EU, 2007a), following an analysis of car manufacturers' CO_2 reduction so far (EU, 2007b).

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[17] At an evaluation moment in 2018 the introduction of 0.5% might be postponed to 2025.

In December 2008, the European Commission determined a new schedule to phase in the CO_2 emission standard from 2012 to 2015 for the 130 g/km mid-term target (EU, 2008). In April 2009, the legislation on CO_2 emissions for passenger cars was published (EU, 2009).

Table 4.1 *Overview of key steps in the development of EU CO_2 transport policy*

Year	Type	CO_2 emission	Remark
1995	voluntary	186 g/km	
2004	voluntary	163 g/km	12.4% reduction from 1995
2008	voluntary	140 g/km	2008 target
2012	mandatory	130 g/km (65%)	proposal
2013	mandatory	130 g/km (75%)	proposal
2014	mandatory	130 g/km (80%)	proposal
2015	mandatory	130 g/km (100%)	proposal
2020	mandatory	95 g/km	long-term target

The Commission considers a new target for passenger car emissions to be reached by 2025. Among other options, the Commission will assess the feasibility of the target suggested by the European Parliament of reaching 70 gCO2/km by 2025 (EU, 2010b).

CO_2 standards for vans

In February 2011 the European Parliament has voted to officially adopt a 175 g/km CO_2 short term and 147 g/km CO_2 long term target for Light Commercial Vehicles (LCVs).

In summary, it follows that the development of the EU vehicle CO_2 standards took about 15 years.

4.4.2 Example: development of ETS

The European Union Emissions Trading Scheme (EU ETS) is the cornerstone of the EU's environmental policy to reduce CO_2 emissions. The development and implementation of EU ETS was remarkably fast, given the complexity and the many stakeholders involved (Sijm, 2010). In summary, the timeline involved the following milestones, see Table 4.2.

Table 4.2 *Development of a main EU policy instrument (ETS)*

Year	Milestone
2000	March Green paper on EU ETS launched
2001	Commission starts to draft proposal ETS
2003	Adoption by Council and parliament; publication of ETS directive
2005	ETS phase I (pilot; substantial free allocation)
2008	Substantial amendment of ETS directive, towards less free allocation
2007-2012	ETS phase II, reduction free allocation of emission permits
2013	ETS phase III; more auctioning, tighter cap, more centralised control, and wider coverage including aviation

Quantification of the development time of the ETS system is ambiguous, because both the starting phase and the mature phase of the ETS are rather a trajectory than a single point in time. The starting point can also be considered earlier than the publication of the ETS Green paper in 2000. Before that time the Commission tried unsuccessfully to implement a carbon energy tax proposal, which was finally withdrawn in 1997. The mature phase of the ETS, can arguably be identified to start in 2013, when the 3rd phase will commence. The changes to be introduced in 2013, notably a progressive move towards auctioning of allowances, will further enhance its effectiveness (http://ec.europa.eu/clima/policies/ets/index_en.htm).

The European Commission - which had failed in its earlier efforts to introduce a carbon energy tax - made the case for ETS with great skill. Convery (2009) identified the following reasons for the fast trajectory of the development of the EU ETS system:

- With a single market for the economy, the development of a single market for the environment is a logic step. The EU 2000 Green Paper emphasised that costs of meeting Kyoto obligations on the part of energy producers and energy intensive industry would be reduced by about 1.7 billion Euros annually, compared to a range of national schemes.
- After the failure of the European Commission to introduce an effective EU-wide carbon energy tax in the nineties, an alternative was urgently needed.
- The Commission fought unsuccessfully against the inclusion of trading, as a flexible instrument in the Kyoto Protocol in 1997.
- Initial free allowances meeting the needs of most industrial emitters, reduced opposition.
- Fear of the alternative: carbon taxes and/or regulation which would be less attractive to much of industry.

Inclusion of aviation into the EU ETS as of 2012

As a result of EU legislation, adopted in 2009, air operators will also be covered in the EU ETS system by 2012. In order to mitigate the climate impacts of aviation, the EU has decided to impose a cap on CO_2 emissions, from the start of 2012, from all international flights – from or to anywhere in the world – that arrive at or depart from an EU airport (DG Clima, 2011)

Like industrial installations, airlines will receive tradable allowances covering a certain level of CO_2 emissions from their flights per year. The intention is for the EU ETS to serve as a model for other countries considering similar national or regional schemes, and to link these to the EU scheme over time. Therefore, the EU ETS can form the basis for wider, global action.

4.4.3 Example: raising of bioethanol blend levels in the US

This example is included in the report to illustrate how complicated a political decision can be if all types of stake holders have different opinions.

In the United States, legislation currently allows for ethanol blends to gasoline of up to 10% (E10), but not beyond. This 10% ‘blend wall’ is seen by many as consistent with the technical limit on how much ethanol can be blended into gasoline without causing problems for conventional vehicles; but it represents a major barrier towards higher blend shares. Extensive testing is being undertaken, with a view to allowing higher blend shares. The Environmental Protection Agency (EPA) decided in October 2010 to allow an increase in the blend rate of ethanol in gasoline to 15% from 10% for cars and light trucks built since 2007. Vehicles sold between 2001 and 2006 are subject to further testing (IEA, 2010).

The question is how to impose a volumetric obligation - almost 140 billion litres (IEA, 2010) - on a market which may be unable to absorb it. Who is to carry the investments risks? Farmers and ethanol producers would be delighted to see the required volumes, but fear that the market will be over-supplied and the obligation will fade away, leaving them exposed. The manufacturers of bioethanol have already suffered widespread bankruptcies, as prices for corn, the main feedstock for ethanol production in the United States, spiked in 2009. They are, therefore, pushing for approval of the use of E15 blends in older cars. Car manufacturers, however, fear they could be sued if owners of older cars buy fuel not suitable for their vehicles (IEA, 2010).

5. Timing of policies towards 73% CO_2 reduction in 2050

In Chapter 3 a picture of the 2050 transport sector with low-CO_2 fuels and technologies is presented that meets an overall CO_2 reduction of 73%, compared to 1990. Next, the inertia in technology development and policies has been evaluated in Chapter 4. The current chapter combines the information of the previous chapters by modelling how and at what pace the 2050 goal can be reached. Therefore we constructed a basic technical penetration model that simulates the market penetration of new technologies and fuels in the various transport sectors towards the defined 2050 situation. To this end the trajectory of the market penetration for each technology was divided in the four main phases described in the next section.

5.1 Factors controlling market penetration of new technologies

The roll-out of new technologies can be divided in several phases. We distinguished the following four main phases: policy decision, innovation phase, demonstration, and market penetration. Our division differs from the generic classical division of invention, innovation and diffusion (Schumpeter, 1939). Firstly we included a separate ‘policy decision phase’ to better address our main research question regarding the timing required for decisive policy choices to start up technology roll-out. Secondly, regarding the defined Research and Development (R&D) phase we focus much more on development than on research, because most technologies considered already passed the research phase. To emphasize this aspect we used the terminology “innovation phase” instead of “R&D phase”. This includes the inventions needed for large scale production and lower production costs. Thirdly we defined a separate demonstration phase between the classical innovation and diffusion phase. The four phases included in our model are described in more detail in the next sections.

Policy decision phase

If a new transport technology is not yet cost effective in an early stage of development, policy support is needed. For example to increase the innovation or to start the demonstration of a new technology. In this phase developers and investors need to be sure there is a real market at the end of the development process. Even if the technology is cost effective in the early stages of the market penetration phase, it must be clear that fuel or electricity taxes or vehicle taxes will not substantially change when the market penetration increases. In all the cases a policy decision must be made before substantial market penetration can start.

Innovation phase

Obviously, a new technology must be developed before its demonstration in small scale projects can be started. A proof of concept is already available for most technologies considered in the current study. That means that a limited number of vehicles with the new technology have already been built and tested under real life conditions. The innovation phase, which is used in our model, does not focus on the proof of the technology, but on the construction of a technology that can be used in large numbers. This involves the development trajectory from prototypes, where costs and construction speed are not yet important, towards the stage where vehicles are built with cheaper components that are easily to assemble, thereby allowing further automating and scale up of production.

Demonstration phase

In the (large scale) demonstration phase vehicles are used in real life situations. The vehicles already look like the ones that will be implemented during the next phase of large scale market introduction. Before the real market penetration can start most vehicle producers must have finished this demonstration phase. Also the buyers must be convinced of the benefits of this new technology and the technical reliability. Although a fuel infrastructure is already needed, the overall demand of fuel or electricity required is still rather modest, and thus not yet complicated to provide.

Market penetration phase

In the market penetration phase most vehicle producers sell the new technology in almost all their new models. Still, for some time, old technology might be sold in old models. In this situation the increasing demand for fuel or the materials needed for the vehicles might pose supply restrictions that can reduce the market penetration speed. If there are no restrictions, it is assumed that all new vehicles will use the new technology[18]. The fleet renewal rate thus determines the penetration rate of new technologies. Nevertheless, some extra time need to be taken into account for overlap between new and old models. In addition, not all the manufacturers will make the switch to the new technology at the same time. Early demolition of older vehicles can speed up penetration of new technologies but is very costly. Therefore in our model it is not assumed that vehicles will be taken out of service before the end of their technical lifetime.

5.2 Market penetration model

To simulate the market penetration of new technologies and fuels we constructed a basic technical penetration model in Excel software, based on the degree of implementation over time of the four phases indicated above, for each technology up to 2050. The technical penetration model takes into account the inertia in the four phases of the roll-out trajectory. We also included historical data, and considered special conditions, such as the mining of materials required for electric vehicles. The model is characterised by 5 year time intervals, ranging from 2010 to 2050.

The market share of a new technology in a transport subsector (e.g. the share of hydrogen in aviation), is projected on the basis of:

- The year of strong policy decisions in support of a new technology.
- The year of start and maturity of the technical innovation phase.
- The year of start and maturity of the demonstration phase.
- The year of start and maturity of the market penetration of new vehicles.

Obviously the basic approach of our exploratory model includes substantial uncertainties, as for example unforeseen technology breakthroughs could result in a much more prominent role for other technologies and fuels. Although the spectrum of key low-CO_2 technologies may to some extent develop in a different direction, it is unlikely that this would substantially alter the time ranges left for making decisive choices.

5.2.1 Timetables market penetration and time remaining for decisions

The 2050 situation that meets the 73% overall CO_2 reduction target can be reached at different paces of technology roll-out. For all transport modes, two routes were compared:

1) A route where all developments are implemented as soon as possible (‘ASAP-route’).
2) A route where actions are postponed until the latest start time allowing to reach the 2050 target just in time (‘Delay-route’).

First the ASAP-route was explored. Subsequently the market penetration of the Delay-route was calculated by back casting from the 2050 situation. The time differences in maximum penetration between the ASAP-route and the Delay-route give an indication of the time margin in the subsequent three phases of innovation, demonstration market penetration. In other words: how much time is left to decide on a full start of the new technologies and fuels required to meet the 2050 CO_2 targets. For the main transport modes the modelled market penetration according to

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[18] In case of competing technologies, such as electricity and hydrogen in passenger cars, the different new technologies may be applied in parallel for many years, although usually serving different market segments.

both the ASAP-route and the Delay-route is described in the next sections, along with summary timetables per transport mode (Table 5.1, Table 5.2, Table 5.3, Table 5.4).

Light duty vehicles (passenger cars and vans)
The concept of a hydrogen fuel cell vehicle is already developed. If a decisive choice for strong and long term policy support is made, the large scale demonstration can start in 2015. Within 10 years this can lead to a substantial market penetration. Twenty years are needed to reach the maximum penetration. Maximum penetration in the ASAP-route can be reached in 2045. When 100% penetration is reached for a technology, in the model new vehicles substitute old vehicles with the same (new) technology. See Table 5.1 for more details.

The development status of electric vehicles is ahead of hydrogen vehicles. The demonstration phase is expected to be well on its way in 2015 and substantial market penetration can start in 2020. A potential problem for the penetration speed may be the mining and quarrying of the materials for the batteries. The amounts of materials required (especially lithium and rare earth metals) are large compared to the current production rate and the world wide reserves. A development time for expanding current mines and opening new ones of 30 years might be more realistic than 15 years. Therefore a time span of 30 years is estimated for a complete penetration of battery electric vehicles.

The percentage of biofuels, as indicated in the tables, depicts the share of biofuels relative to the sum of biofuels and liquid fossil fuels used. In the ASAP-route the biofuel percentage in 2030 is already set at a high level to reach a CO_2 reduction of 50% compared to 1990. Table 5.1 summarises the indicative timing of the controlling phases and the resulting market penetration for light duty vehicles.

Table 5.1 *Timetable market penetration LD vehicles (hydrogen, battery electric, biofuels)*

Light duty vehicles	2010	2015	2020	2025	2030	2035	2040	2045	2050
Hydrogen fuel cell vehicles									
Policy decision		◊◊◊◊							
Innovation phase	◊◊◊◊								
Demonstration phase		◊◊	◊◊◊◊						
Market penetration ‘ASAP-route’				▪	▪▪▪▪	▪▪▪▪▪▪	▪▪▪▪▪▪▪▪▪	▬	▬
Market penetration ‘Delay-route’						▪	▪▪▪▪	▪▪▪▪▪▪	▪▪▪▪▪▪▪▪▪
Battery electric vehicles									
Policy decision	◊◊◊	◊◊◊◊							
Innovation phase	◊◊◊◊								
Demonstration phase	◊◊	◊◊◊◊							
Market penetration ‘ASAP-route’				▪	▪▪▪	▪▪▪▪	▪▪▪▪▪▪	▪▪▪▪▪▪▪▪	▪▪▪▪▪▪▪▪▪
Market penetration ‘Delay-route’				▪	▪▪	▪▪▪▪	▪▪▪▪▪▪	▪▪▪▪▪▪▪	▪▪▪▪▪▪▪▪▪
Biofuels									
Market penetration ‘ASAP-route’ [%]	4	6	9	25	42	59	75	92	100
Market penetration ‘Delay-route’ [%]	4	6	9	17	34	50	67	84	100

Explanation of symbols used:

- Diamonds (◊) indicate the extent of implementation of the phases of policy decision, innovation or demonstration; 4 diamonds depict maximum implementation/maturity of a phase.
- Dots (▪) express the degree of market penetration. Indicatively each dot equals approximately 10% penetration.
- A stripe (▬) indicates that 100% penetration has been reached.
- Market penetration of biofuels is expressed as blending percentage.

The differences between the ASAP-route and the Delay-route in market penetration show that strong decisions on supporting hydrogen cars can be maximally postponed by about 10 years. For electric cars there is almost no delay possible.

Heavy duty vehicles

The indicative timeline for heavy duty vehicles is shown in Table 5.2 although currently some prototypes have been made and some fuel cell buses are in operation, the development of (large) heavy duty vehicles with hydrogen fuel cell power lines has not started yet. There is no broad policy consensus yet that hydrogen fuel cell trucks are an essential part of the transport future. So developments will not start before such a decision is made.

There is a limited market potential for all-electric trucks. Because the development of all-electric trucks can make use of the developments for light vehicles, market penetration can start earlier than for hydrogen trucks. The overall amount of batteries for all-electric trucks is small compared to the light vehicles market, so the penetration speed might be faster. In both cases a time span of 15 years is assumed for reaching maximum market penetration. The penetration rate of biofuels is assumed to be the same as for light duty vehicles.
Table 5.2 summarises the indicative timing of the controlling phases and the resulting market penetration for heavy duty vehicles. The differences between the ASAP-route and the Delay-route in market penetration show that decisive choices on supporting hydrogen trucks can be maximally postponed by about 5 years. For electric trucks the maximum allowable postponement is about 10 years.

Table 5.2 *Timetable market penetration HD vehicles (hydrogen, battery electric, biofuels)*

Heavy duty vehicles	2010	2015	2020	2025	2030	2035	2040	2045	2050
Hydrogen fuel cell trucks									
Policy decision		◊◊◊◊							
Innovation phase	◊	◊◊	◊◊◊	◊◊◊◊					
Demonstration phase			◊◊	◊◊◊◊					
Market penetration ‘ASAP-route’					▪	▪▪▪▪	▪▪▪▪▪▪▪▪	▬	▬
Market penetration ‘Delay-route’							▪▪▪	▪▪▪▪▪▪▪	▬
Battery electric trucks									
Policy decision		◊◊◊◊							
Innovation phase	◊◊◊	◊◊◊◊							
Demonstration phase		◊◊	◊◊◊◊						
Market penetration ‘ASAP-route’				▪	▪▪▪▪	▪▪▪▪▪▪▪	▬	▬	▬
Market penetration ‘Delay-route’						▪	▪▪▪▪	▪▪▪▪▪▪▪	▬
Biofuels trucks									
Market penetration ‘ASAP-route’ [%]	4	6	9	25	42	59	75	92	100
Market penetration ‘Delay-route’ [%]	4	6	9	17	34	50	67	84	100

Explanation of symbols used:

- Diamonds (◊) indicate the extent of implementation of the phases of policy decision, innovation or demonstration; 4 diamonds depict maximum implementation/maturity of a phase.
- Dots (▪) express the degree of market penetration. Indicatively each dot equals approximately 10% penetration.
- A stripe (▬) indicates that 100% penetration has been reached.
- Market penetration of biofuels is expressed as blending percentage.

Aircrafts

Given the limited global availability of biofuels, the use of bio-kerosene is only a temporary option. Bio-kerosene can be used as an intermediate alternative to fill the gap between the current fossil-kerosene fuelled planes and the expected development of hydrogen planes. The stock renewal of aircrafts takes 30 years. In addition long innovation and development trajectories need to be taken into account. Moreover the safety regulations around aircrafts require substantial and lengthy testing and demonstration procedures. Table 5.3 shows that the large scale market penetration of new hydrogen technology is expected to start 15 years after the middle of the innovation phase. At this point the aircrafts in the demonstration phase have only reached half of their lifetime. This time path might be too optimistic. Therefore the ASAP-route includes some room for purchasing bio-kerosene plains after 2030. In the Delay-route after 2040 only purchase of hydrogen planes is allowed.

Table 5.3 summarises the indicative timing of the controlling phases and the resulting market penetration for aircrafts. Note that even in the ASAP-route, the maximum market penetration of hydrogen fuelled aircrafts in 2050 reaches only about 70%. The differences between the ASAP-route and the Delay-route show a maximum allowable delay in the decision for hydrogen planes of about 10 years. But the consequence of such a delay is that the market penetration after the delay time does not allow any more delay. Consequently the risk of running out of time is large. Given the regulations on safety and the necessary roll-out of a hydrogen infrastructure on all airports, it is recommendable to make the policy decision earlier.

Table 5.3 *Timetable market penetration aircrafts (hydrogen, bio-kerosene).*

Aircrafts	2010	2015	2020	2025	2030	2035	2040	2045	2050
Hydrogen aircrafts									
Policy decision		◊◊◊◊							
Innovation phase		◊◊	◊◊	◊◊◊◊					
Demonstration phase				◊◊	◊◊◊◊				
Market penetration ‘ASAP-route’						▪▪	▪▪▪	▪▪▪▪▪	▪▪▪▪▪▪▪
Market penetration ‘Delay-route’							▪	▪▪▪	▪▪▪▪
Bio-kerosene aircrafts									
Market penetration ‘ASAP-route’ [%]				16	42	42	42	42	42
Market penetration ‘Delay-route’ [%]						30	42	42	42

Explanation of symbols used:

- Diamonds (◊) indicate the extent of implementation of the phases of policy decision, innovation or demonstration; 4 diamonds depict maximum implementation/maturity of a phase.
- Dots (▪) express the degree of market penetration. Indicatively each dot equals approximately 10% penetration.
- A stripe (—) indicates that 100% penetration has been reached.
- Market penetration of biofuels is expressed as blending percentage.

Sea ships

A global policy decision for obligatory use on the long term of hydrogen as main propulsion fuel in shipping is a complex process, that needs to be taken within the framework of the IMO[19], with support of sufficient member states and other international organisations such as the EU (see section 4.3.5) for a comparable recent decision regarding the global obligatory use of low sulphur bunker fuels). A decision regarding the obligatory use of hydrogen is not expected before 2020. After such a decision the innovation and demonstration phase could go fast, given the amount of knowhow available.

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[19] IMO: The International Maritime Organization of the United Nations (www.imo.org).

Table 5.4 summarises the indicative timing of the controlling phases and the resulting market penetration of hydrogen and biofuels for sea ships. In the ASAP-route even retrofit towards hydrogen in segments of the existing fleet might be possible, which would decrease the penetration time span to 20 years. If no retrofit takes place the maximum penetration time may take 30 years. For both the ‘ASAP-route’ and the ‘Delay-route’ the penetration of biobased shipping fuel is set on a linear penetration path from 2030 onwards up to a maximum penetration of 40%, given the limited global availability of biofuels. Given the long time needed for a global decision to use hydrogen as shipping fuel there is only 5 years of delay time possible.

Table 5.4 *Timetable market penetration sea ships (hydrogen, biofuels)*

Sea ships	2010	2015	2020	2025	2030	2035	2040	2045	2050
Hydrogen ships									
Policy decision			◊◊◊◊						
Innovation phase			◊◊	◊◊◊◊					
Demonstration phase				◊◊◊◊					
Market penetration ‘ASAP-route’					▪▪	▪▪▪▪▪	▪▪▪▪▪▪▪▪	▬	▬
Market penetration ‘Delay-route’					▪	▪▪	▪▪▪▪	▪▪▪▪▪▪	▪▪▪▪▪▪▪
Biofuel ships									
Market penetration ‘ASAP-route’ [%]					8	16	24	32	40
Market penetration ‘Delay-route’ [%]					8	16	24	32	40

Explanation of symbols used:

- Diamonds (◊) indicate the extent of implementation of the phases of policy decision, innovation or demonstration; 4 diamonds depict maximum implementation/maturity of a phase.
- Dots (▪) express the degree of market penetration. Indicatively each dot equals approximately 10% penetration.
- A stripe (▬) indicates that 100% penetration has been reached.
- Market penetration of biofuels is expressed as blending percentage.

5.3 Trends in energy use, fuel distribution and CO_2 emissions

5.3.1 Energy use per transport modes up to 2050

For each transport mode up to 2050 the development of energy consumption, as well as fuel type applied, was assessed and visualised by using the market penetration model. This assessment is based on the proposed alternative 2050 picture corresponding to overall 73% CO_2 reduction, relative to 1990, as presented in the last column of Table 3.1. As explained in section 5.2.1, the calculations have been split up in a fast transition picture, with all transition actions implemented as soon as possible (ASAP-route) and a ‘slow picture’ where transitions are postponed to the latest time just allowing to reach the 2050 goals (delay-route).

We also defined a ‘Mean-route’ of market penetration. In the next series of figures on fuel split over time per transport mode, first the Mean-route is presented to visualize the general trends. In addition, the key differences for all three routes (ASAP, Mean and Delay) are highlighted in complementary graphs regarding the use of: energy, fossil fuels and biofuels. The complete set of figures for all routes can be found in Appendix A.1. In addition to the graphs, the time lags between the ASAP-route and the Delay-route can be more easily observed in the overview tables presented in the previous paragraph (5.2.1). The main text focuses on the four key transport modes: light duty vehicles, heavy duty vehicles, aviation, and shipping. Figures on the smaller transport modes can be found in Appendix B.

Light duty vehicles
Figure 5.1 shows that the total energy use in the light duty vehicle sector peaks at about 350 PJ in the time window 2010-2015, and gradually decreases to around 175 PJ in 2050.

The use of fossil fuels peaks around 2005, thereafter gradually decreasing to almost zero in 2050. Initially, biofuels are the largest alternative energy source with an increasing contribution up to about 1/3 of total energy use, equalling some 70-75 PJ, in the time window 2030-2035, and thereafter gradually decreasing. The main reason for this initial growth is that biofuel (blends) can be used in conventional vehicles with relatively small modifications. From 2025 on, first electricity, and slightly later hydrogen, gradually phase in. Around 2050 their combined use covers about 90% of total energy demand in the sector. At the same time, the biofuel that was initially applied in the light duty sector is gradually phased out and shifted to other sectors.

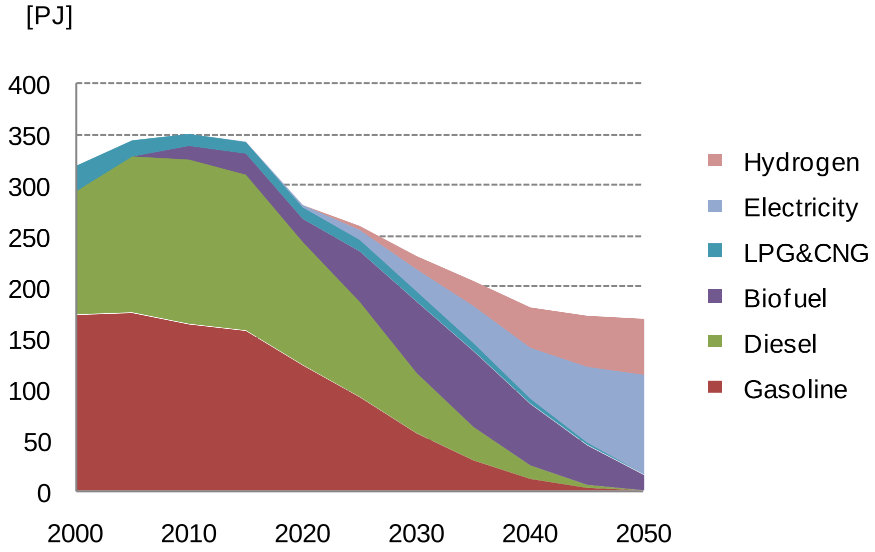

Figure 5.1 *Energy consumption and fuel use of light vehicles [PJ] 'Mean-route'*

It is assumed that hydrogen fuel cell vehicles have a higher efficiency compared to conventional engines. Also the use of electricity is more efficient (in the vehicle) than conventional engines. The decline in fuel consumption in Figure 5.1 initially results from the increasingly efficiency of conventional technology and after 2030 is mainly caused by the strong market penetration of highly efficient electric and fuel cell vehicles. Note that if the current ways of production of electricity (from fossil fuels) and hydrogen (from natural gas) would be taken, the primary energy use (including the production of the energy carriers) would only slightly decrease when switching to hydrogen or electricity.

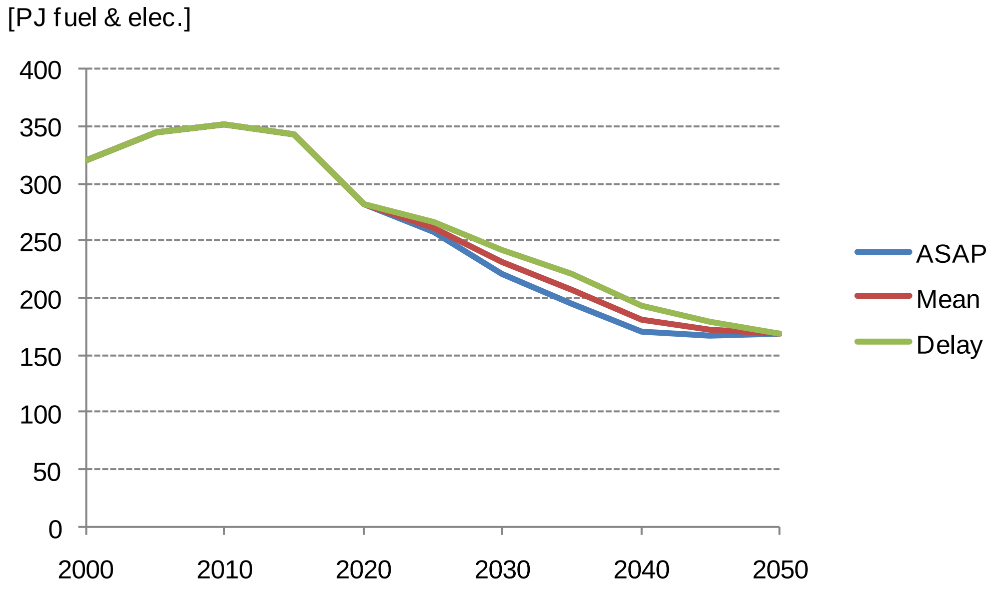

Figure 5.2 *Comparison of the three technology penetration rates for light duty vehicles [PJ]*

The three different routes for the market penetration rate of new technologies (ASAP, Mean, Delay) are compared Figure 5.2 for the total energy consumption. The lower energy use in the ASAP-route is caused by the higher efficiency of electricity and hydrogen compared to fossil fuels or biofuels.

Heavy duty vehicles

Figure 5.3 shows that the total energy use in the heavy duty vehicle sector gradually increases and stabilizes around 120 PJ in 2035. The use of fossil diesel - until recently the only fuel applied in the heavy duty segment - slightly increases up to about 2020, and from then on rapidly decreases, to almost zero in 2050, in line with Table 3.1. Biofuels are gradually phased in from 2005 on, until around 2020 when their share rapidly increases until about a decade later they have become the dominant fuel in the trucking segment, covering a total energy use of about 95 PJ. After 2030, part of the biofuel increase in the heavy duty sector is explained from the shift to other fuels in the light duty sector, thereby increasing the availability of biofuels for other segments. From 2030 on also hydrogen and electricity enter the heavy duty sector. Around 2050 their combined use covers about 20% of the energy demand in the sector.

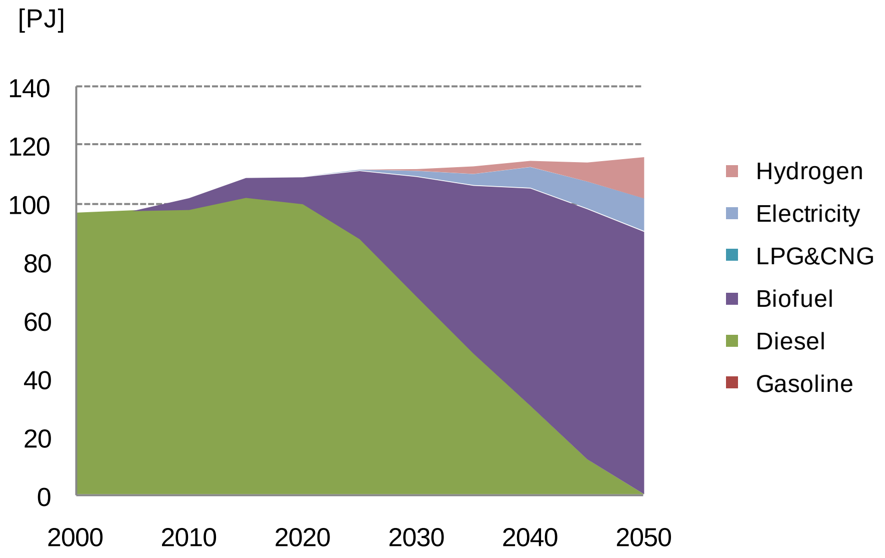

Figure 5.3 *Energy consumption and fuel use of heavy duty vehicles [PJ]*

The three different routes for the market penetration rate of new technologies (ASAP, Mean, Delay) are compared in Figure 5.4 for the total energy consumption. The lower energy use in the ASAP-route is caused by the higher efficiency of hydrogen compared to diesel and bio-diesel.

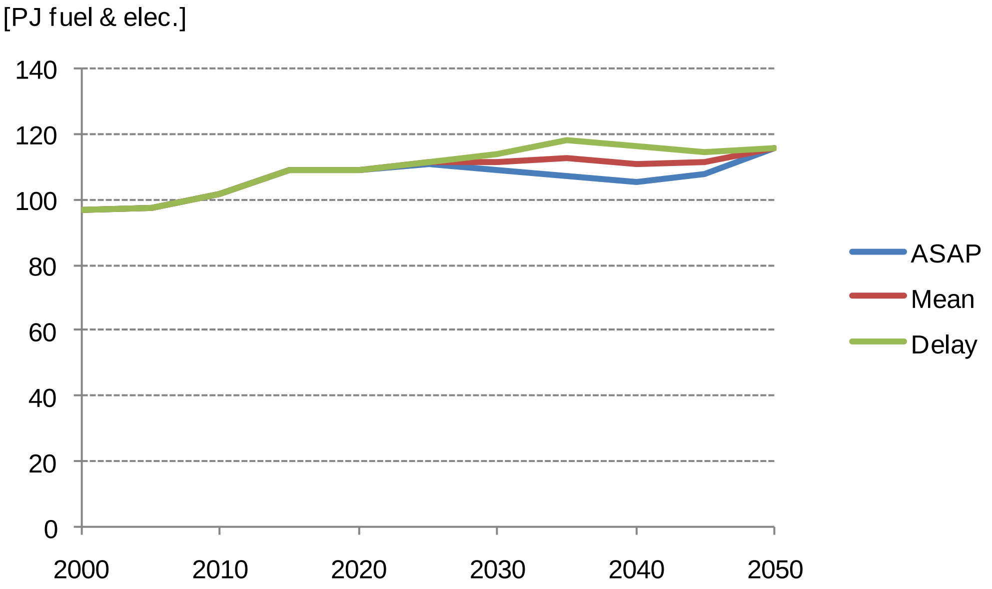

Figure 5.4 *Comparison of the three technology penetration rates for heavy duty vehicles [PJ]*

Road transport

In Figure 5.5 the total fossil fuel use of the entire road transport sector is shown. Although the trend for all the three routes is comparable the energy demand in 2030 differs by as much as 100 PJ or 33%. Clearly the CO_2 emission in 2030 in the ASAP-route will be substantially lower compared to the Delay-route.

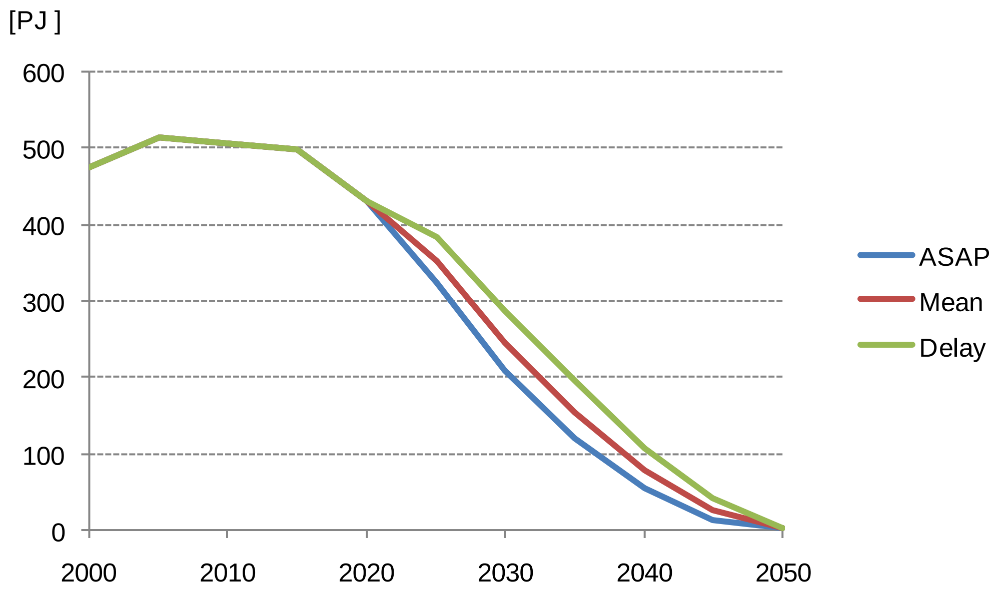

Figure 5.5 *Use of fossil fuels by road transport in the three market penetration routes [PJ]*

Aviation
Figure 5.6 shows that the energy use in the aviation sector rapidly increases, until in 2050 the energy use will have doubled compared to 2000, implying that the projected 3 to 4-fold increase in aviation volume is to same extent balanced by the increasing efficiency of new aircrafts. Kerosene use is expected to increase, along with increasing energy use. Around 2025 kerosene use is projected to peak and from then on decrease steeply till less than 40% of total energy use in the sector by 2050. At the same time, both biofuels and hydrogen gradually phase in, contributing about 25% and 35%, respectively to the sector energy use in 2050. In 2050 the biofuel share equals about 75 PJ. It is assumed that hydrogen is used in the same type of engines (gas turbines) as kerosene, so there is not a big difference in efficiency between both fuels.

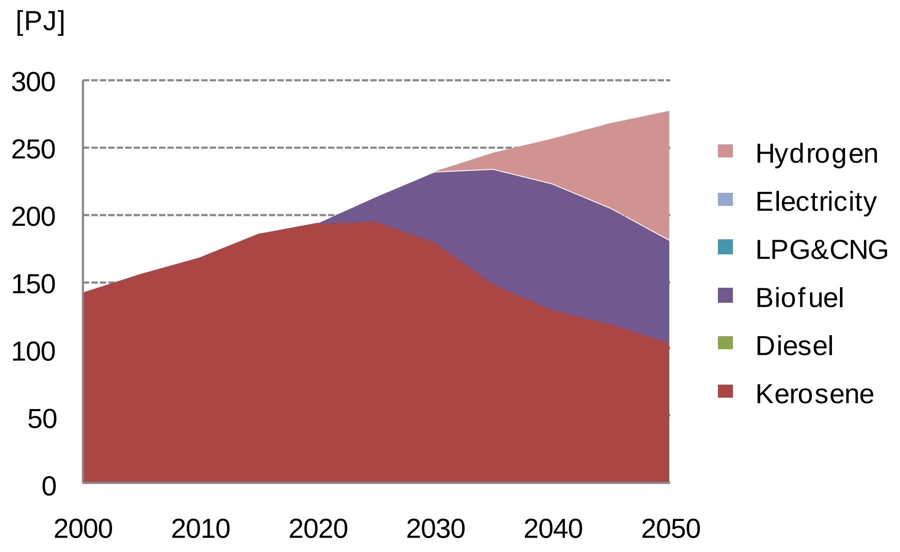

Figure 5.6 *Energy consumption and fuel use in aviation [PJ]*

Shipping

Figure 5.7 shows that the energy use in maritime shipping increases rapidly until about a doubling in 2050 compared to current energy use. Up to about 2025 energy use will be covered almost completely by fossil bunker fuels. From then bunker fuel use is projected to decrease, being substituted by biofuels and hydrogen. In 2050 biofuel use, equalling about 20 PJ, will cover about 25% of the sector's energy use. As explained in Chapter 2 in this figure only 10% of the amount of international bunker fuel for sea shipping (sold in the Netherlands) is taken into account.

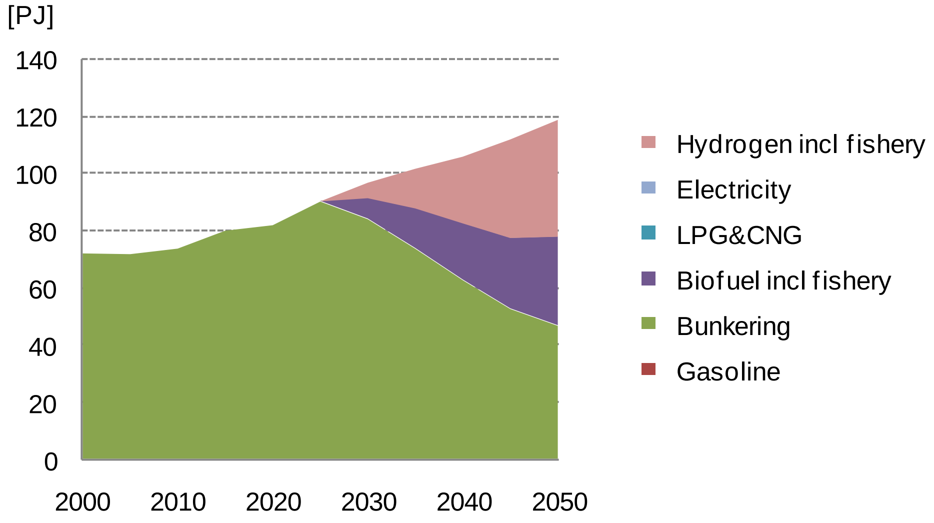

Figure 5.7 *Fuel consumption sea ships [PJ]*

Note In 2050 the combined biofuel use in aviation (~75 PJ), heavy duty road transport (~95 PJ), and shipping (~20 PJ), all accelerating around 2025, can to a large extent be supplied by the simultaneous decrease of biofuel in the light duty sector, after the peak use there of about 125 PJ around 2030.

5.3.2 Total picture of the transport sector

Figure 5.8 provides an overview of the changes in fuel use, that are required to meet the 2050 CO_2 reduction targets. In 2050, the energy use in the form of fossil fuels will only equal about 20% of their consumption level in 2020. (Since all other fuels are assumed to involve very low CO_2 emissions, it follows that this picture also leads to CO_2 reduction in 2050 of about 80% compared to 2000).

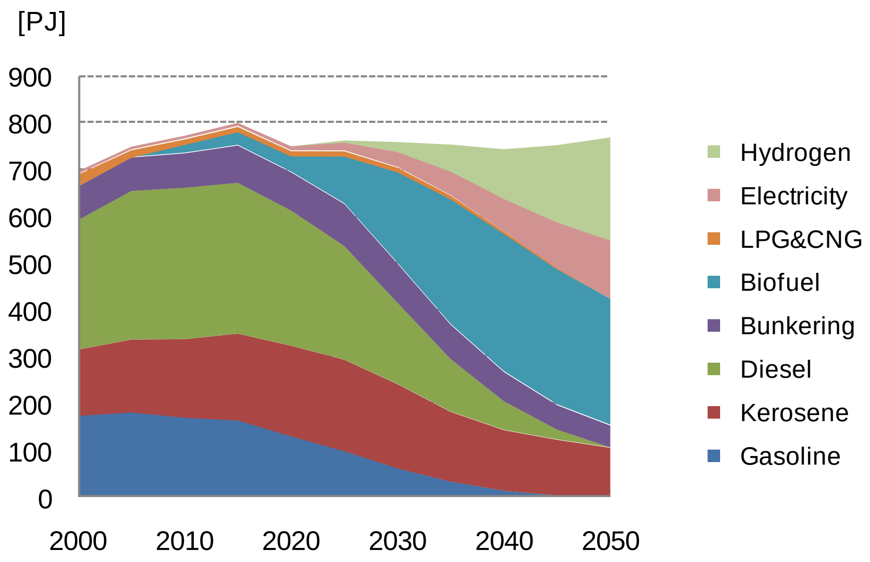

Figure 5.8 *Total fuel consumption per fuel [PJ]*

Figure 5.9 shows the energy use over time for the various transport modes.

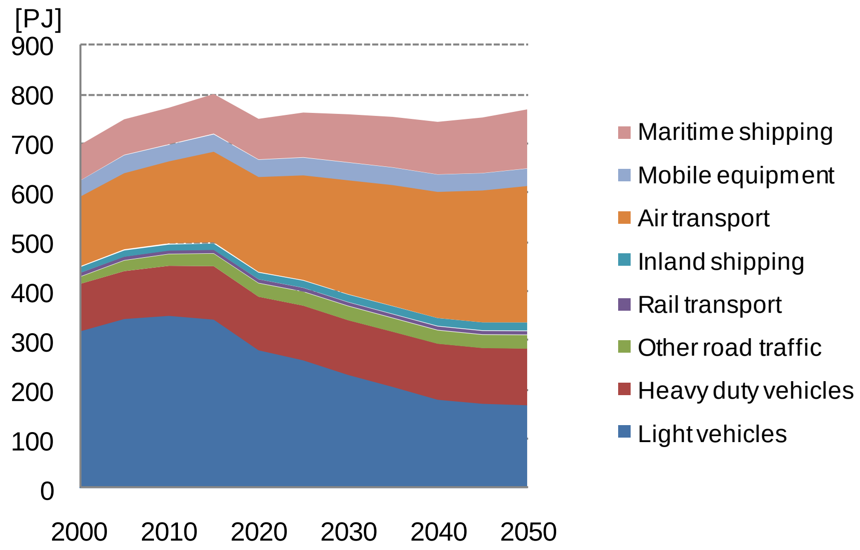

Figure 5.9 *Total energy consumption per type of transport [PJ]*

Despite the projected substantial growth in km driven for the light duty sector, energy use nevertheless decreases by about 50% in the time window 2000-2050, showing the huge impact of increased vehicle efficiency. Up to about 2030 the efficiency gains largely result from incremental improvements in ICE-powered cars and after 2030 mainly from the strong market penetration of highly efficient electric and fuel cell vehicles.

Figure 5.9 shows that energy use in aviation and shipping is projected to increase up to 2050, whereas, in contrast, the energy use in other modes will decrease. By 2050 aviation will be the dominant energy consuming sector by far. Without the expected substantial improvements in energy efficiency, the aviation energy use would have been even much larger.
Figure 5.10 shows the development of biofuel use for the different transport modes. Biofuel use in the light duty segment peaks around 2030, and is then shifted to other transport modes. As already pointed out in paragraph 5.3.1, the biofuel consumption in heavy duty road transport,

aviation, and shipping, accelerates after 2030. This increasing demand could to a large extent be supplied by the simultaneous phasing out of biofuels in the light duty sector after 2030. Managing this shift may require special policy attention, also regarding the type of biofuels involved.

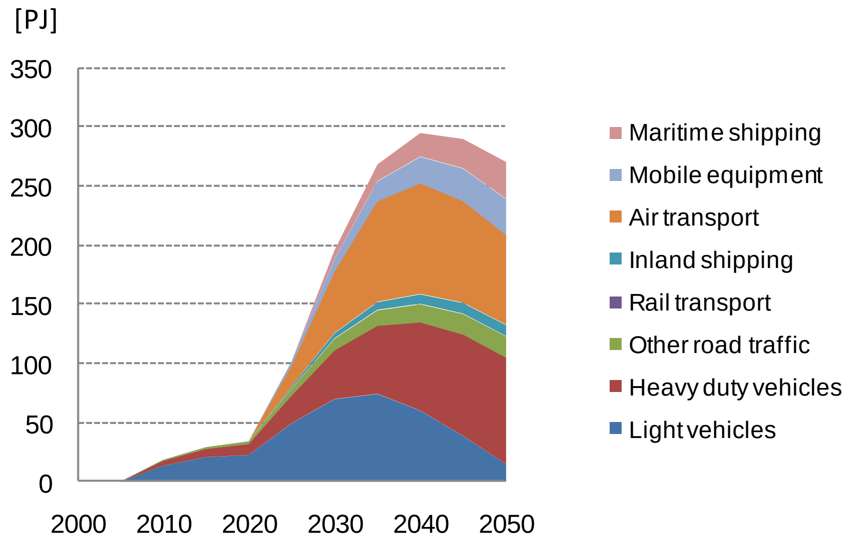

Figure 5.10 *Total biofuel consumption per transport mode [PJ]*

If the biofuel use in the light duty segment around 2030 will include a substantial consumption of ethanol and biodiesel, the shift of biofuel to shipping, aviation and long distance truckling will be more complex, as these latter modes currently only use diesel type fuels[20]. In that case the shift would either require more complicated technology adaptations in propulsion technology, to enable bio ethanol use in heavy duty vehicles and/or aviation and shipping. Alternatively, assuming that bio ethanol in 2030 will to some extent be produced from woody feedstocks (2nd generation), part of the feedstock could be converted to biodiesel rather than bio ethanol. However, this would require (costly) accelerated phasing out of bio-ethanol production facilities, and the simultaneous construction of new biodiesel plants.

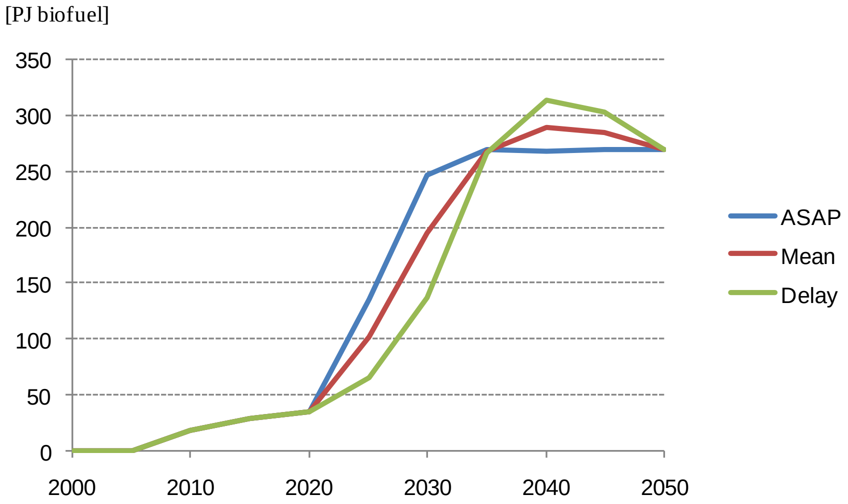

Figure 5.11 *Total biofuel consumption for the three different market penetration routes [PJ]*

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[20] As argued in section 3.2, currently used transportation modes can generally be converted to the use of biofuels, if started in time. However, the current report does not to distinguish in detail between the different biofuel types, especially the split over bio-ethanol and biodiesel. See the textbox in section 6.2 for additional information.

In Figure 5.11 the total biofuel consumption is shown for the three routes of market penetration speed. As already stated elsewhere in this report, there is a big difference in 2030 between the ASAP-route and the Delay-route. In 2040 the Delay route shows a peak in the biofuel use, because the required declining CO_2 emissions in 2040 involves that more biofuel is needed, after which its use can be reduced due to sufficient penetration of hydrogen and electricity. The possible surplus of biofuels in 2050 can be used in other sectors (for instance as chemical feedstock), or alternatively be used by other developing countries which have between 2040 and 2050 a higher growth rate in their transport sector[21] and that are not as far yet in the transition of their transport system.

Figure 5.12 and Figure 5.13 show the developments of consumption of electricity and hydrogen over the various transport modes up to 2050. Note that the vertical axes have different scales and consequently are not directly comparable to the other graphs.

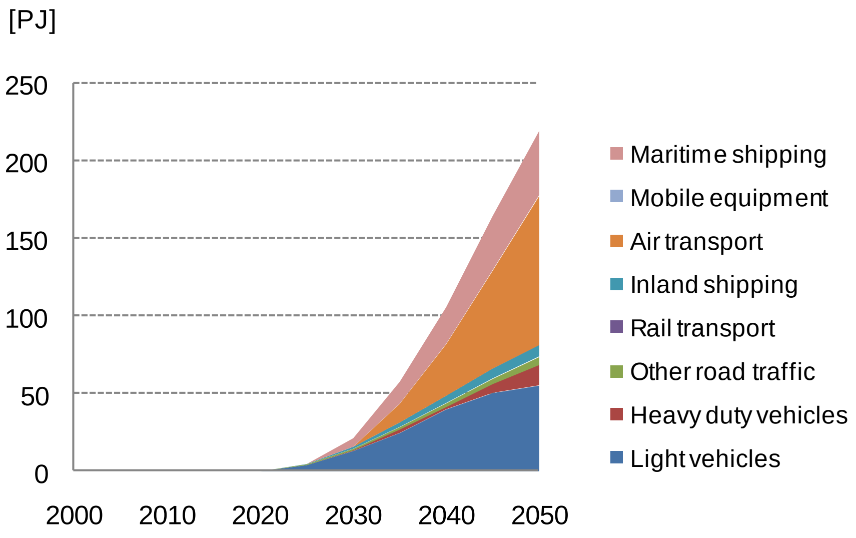

Figure 5.12 *Total fuel consumption of hydrogen per type of transport [PJ]*

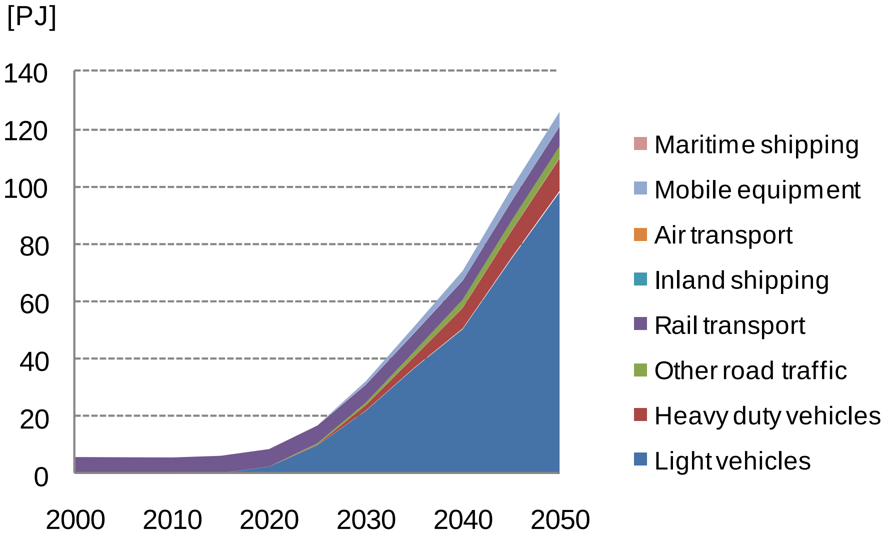

Figure 5.13 *Total fuel consumption of electricity per type of transport [PJ]*

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[21] The temporally higher biofuel demand in 2040 in the delay route can be lowered by the declining the biofuel percentage in 2040. But as can be seen in the tables of Paragraph 5.2 the percentage of biofuels (in biofuels + fossil fuels) is already lower or equal to the ASAF route.

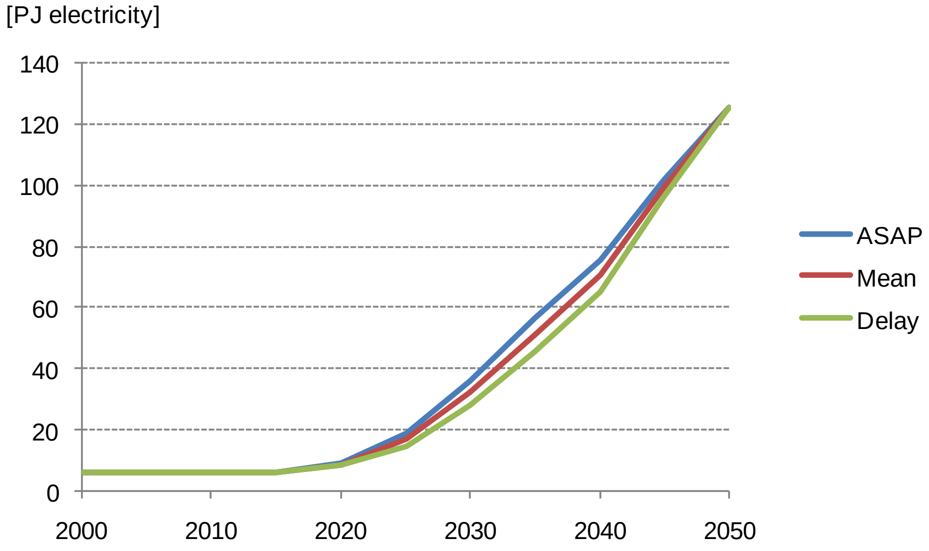

Figure 5.14 *Total electricity consumption in the 3 penetration routes for new technologies [PJ]*

Figure 5.14 shows that there is only a small difference in electricity consumption between the different routes of market penetration speed (ASAP, Mean, Delay). To reach the required 2050 situation, there is little time left to start the roll-out trajectory. If the start of the roll-out trajectory would be postponed even beyond the delay-route, the CO_2 target for 2050 can only be reached by increasing the hydrogen use in for instance the light duty vehicles. This would lead to a 2050 situation with more hydrogen and less electricity. Only in the ASAP-route there is some space for reaching a higher penetration rate in 2050 (see also Figure 5.15)[22]. As can be seen in Figure 5.15 strong policy support for hydrogen can be delayed by about 10 years compared to the ASAP-route. If Europe (and other parts of the world) would follow the delay-route, there is no space for any failures. In that case it is also not possible to further accelerate the roll-out of low-CO_2 technologies if climate change appears to be worse than currently foreseen. So if the CO_2 emissions must be reduced earlier (for instance in 2040) the transport sector cannot contribute to this, without high additional costs.

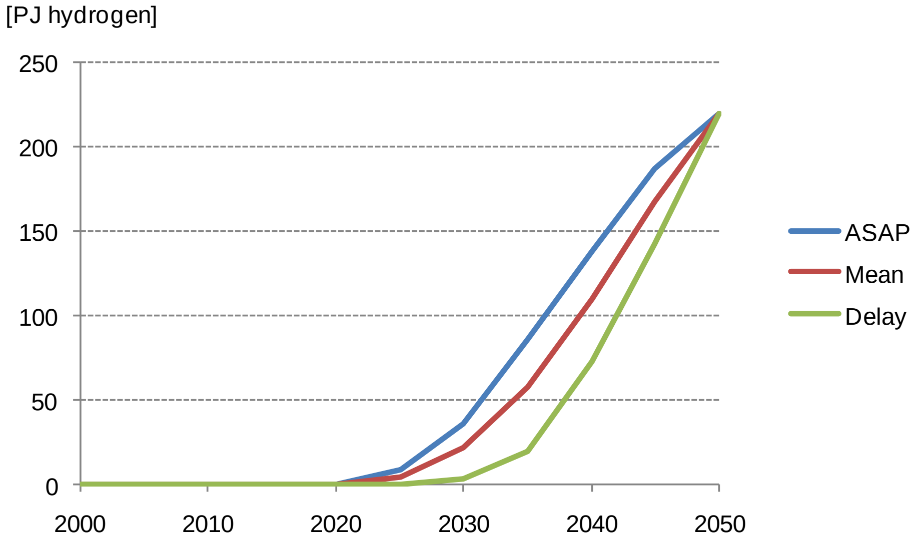

Figure 5.15 *Total hydrogen consumption in the 3 penetration routes for new technologies [PJ]*

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[22] In the Delay route there is, as defined, no room for additional penetration in 2050.

5.3.3 CO_2 emissions up to 2050

Figure 5.16 visualizes the initially calculated CO_2 emissions of the total transport sector in the Netherlands. In this figure the CO_2 emissions related to production of biofuel, hydrogen and electricity are not taken into account. In 2050 the majority of the fossil fuel use will occur in aircrafts and sea ships. Due to the long life times of aircrafts and ships it is not possible to switch to non-fossil fuel at an earlier stage.

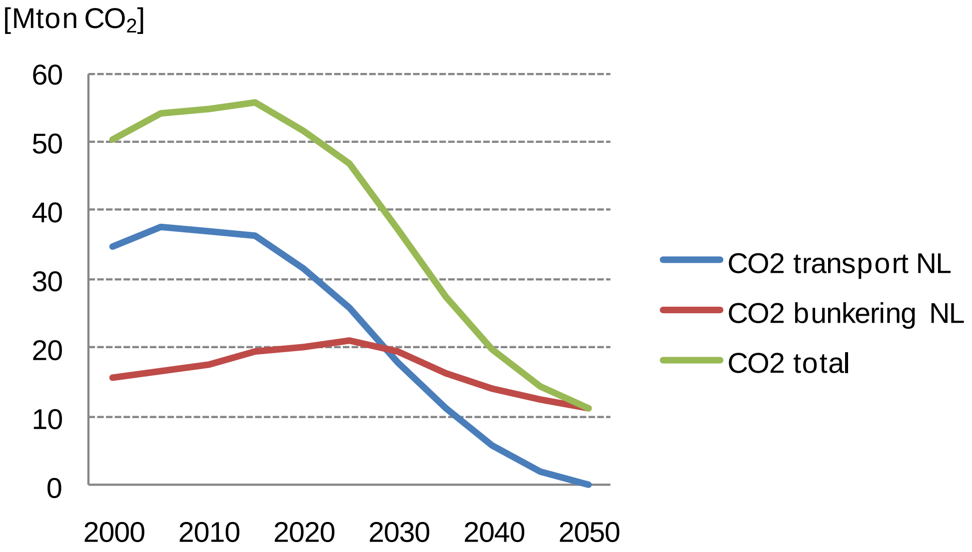

Figure 5.16 *Total transport CO_2 emissions [Mton] (green line), resulting from the sum of land-based transport (blue line) and bunker fuel use for aviation and shipping attributable to the Netherlands (red line)*

The development of the CO_2 emissions of the total transport sector is presented in Figure 5.17, for the different roll-out speeds of low-CO_2 technology. The CO_2 emissions attributable to the Netherlands include all the bunkering for air traffic and a part of the bunkering for shipping. The figure clearly shows the big difference between doing nothing additional (business as usual), compared to the implementation of new technologies. In the latter case the total CO_2 emissions in 2050 are only 27% of the emissions in 1990. If only the emissions related to land transport are taken into account (emissions without bunkering) then the CO_2 reduction in 2050 would almost be 100% (assuming hydrogen, electricity and biofuel as almost CO_2 free). A key conclusion form this study is clearly visualized in Figure 5.17: only in the ASAP-route the CO_2 emission in 2030 reaches the value of 50% of the emissions on land in 1990. The comparable reduction in the Delay route in 2030 is only about 30%.

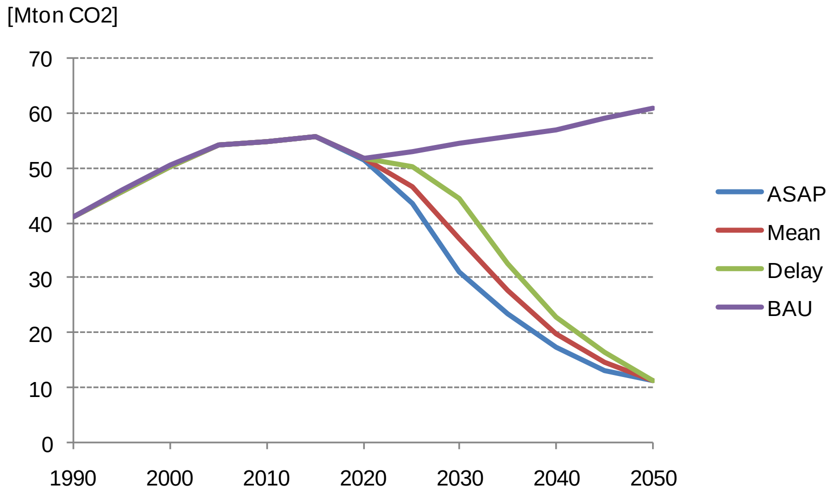

Figure 5.17 *Total CO_2 emission per technology penetration route and for the business as usual case [Mton]*

6. Discussion and conclusions

The overall aim of this study is to inform policy makers and market participants about the actions and their timing required to achieve the 2050 CO_2 reduction goals in the transport sector. After a recapitulation of the challenges, we present the main results about the timely roll-out of technologies. Finally, we discuss limitations and uncertainties related to our exploratory approach and present suggestions for further research

6.1 Recapitulation of the challenges

Chapter 2 projects the business as usual developments in the transport sector, while Chapter 3 describes an envisioned alternative picture based on low-CO_2 transport fuels. Chapter 3 also argues that the biofuel availability in 2050 is likely to be insufficient to meet the combined demand for heavy duty road transport, aviation and shipping in addition to the demand for the same biomass feedstock by other sectors including application as industrial feedstock, biomass for power plants, biomass for heating of buildings etc. Studies on biofuels in transport usually focus on one transport mode and rarely address the issue of biofuel availability, especially not in relation to the additional demand from other transport modes. For example, the aviation sector frequently indicates that they will likely make a complete switch to biofuels (e.g. KLM, 2011). In contrast, our study on all transport modes indicates that also long distance transport modes probably need to switch at least partly to other low-carbon fuels, due to the limited biofuel availability. Hydrogen may be the key low-CO_2 alternative for long distance transport modes, in addition to biofuels. However, application of hydrogen will also involve major technological challenges. Chapter 4 explains that the development and roll-out time of new transport technologies ranges from 15 to over 35 years - depending on technology and sector.

The market penetration model shows that there is little time left to decide on strong policy support to ramp up the roll-out of the new technologies and fuels required to meet the 2050 CO_2 targets. For the technologies with the long development and implementation times (aviation, shipping) roll-out needs to start already now in order to achieve a substantial market penetration by 2050. Alternatively, starting too late and keeping stringent CO_2 caps at the same time, will lead to preferred use of the scarce low-carbon (bio)fuels in the transport segments with the largest added value (commercial activities), thereby constraining other (societal) transport activities.

It is questionable if ‘the market’ (i.e. commercial companies, investors etc.) will be able to switch in time to the low-carbon technologies required, especially since the investments will be substantial and not profitable in the short term. If the trajectories towards the new technologies will not start in time it will become impossible to achieve the 2050 climate goals, without compromising societal transport needs too much, for example by enforcing strong reductions in travel demand. Consequently, coordinated support on the national and international level is essential for a stable and low-carbon development of the global transport sector with minimised negative side effects on economy and society.

6.2 Goals, timely strategies and policy support

The 2050 target situation with 73% CO_2 reduction and the underlying technology roll-out targets require timely strategies to achieve the goals. For each transport mode the key issue of the remaining time for decisive choices to ramp up technology roll-out is summarised in Table 6.1 From the perspective of the different low-CO_2 fuels (hydrogen, electricity, biofuels), Table 6.2 provides an overview of the policy actions and timing in order to achieve the goals.

Table 6.1 *Goals per transport mode and time left for boosting technology roll-out*

Transport mode	2050 goal	Time remaining for decisive choices to ramp up technology roll-out
Light duty vehicles	85% electricity and H_2 remainder biofuels.	Electric vehicles: almost no delay possible H_2 vehicles: max 10 years
Heavy duty vehicles	20% electricity and H_2 remainder biofuels	Electric trucks: max 10 years H_2 vehicles: max 10 years
Aviation	25% biofuels, 35% H_2 remainder fossil kerosene	H_2 aircrafts: almost no delay possible
Shipping	25% biofuels, 40% H_2 remainder fossil bunkers	H_2 ships: max 5 years

Table 6.2 *Goals per fuel type and policies required*

Fuel	2050 goal	Policy actions
Hydrogen	About 20% (200 PJ) of total transport energy demand by road transport, aviation, and shipping combined.	Start or accelerate vehicle technology roll-out within 1 to 10 years (depending on transport mode; see Table 6.1). Provide consistent long term investment perspective, e.g. by early announcement of challenging long term vehicle CO_2 standards and/or future obligations to use H_2. Production and distribution of H_2 expected to follow demand because largest barriers expected on the vehicle side. Nevertheless, ramp up of low-carbon H_2 production capacity and infrastructures is challenging.[23]
Electricity	About 26% (125 PJ) total demand by road transport	Start and ramp up vehicle technology roll-out now for EV's and within 10 years for trucks. Provide consistent long term investment perspective, e.g. by early announcement of challenging long term vehicle CO_2 standards and/or future obligations to use electricity. Although the largest barriers are expected on the vehicle side, the roll out of the distribution infrastructure is also challenging. So is the ramp up of low-CO_2 electricity production capacity and infrastructure.
Biofuels	About 30% (250 PJ) of total demand by road transport, aviation, shipping	All liquid biofuels can be used with minor changes in new engines (i.e. bio-ethanol to substitute gasoline and bio-diesel to substitute fossil diesel). Therefore the main challenge is increasing the global production of biofuels, while meeting sustainability criteria (see section 3.2). In addition coordination is needed to match the supply of bio-ethanol and biodiesel with the successive demand from the different transport modes, shifting over time from light duty vehicles to long range transport modes. Matching demand and supply requires coordinating and/or enforcing, also in terms of fuels type (bio-ethanol versus bio-diesel/kerosene). The main aspects of this challenge are summarized below.

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[23] More detailed deadlines and steps yet identified (see suggested further research 6.5).

Managing the shift of biofuels from light duty vehicles to long distance transport modes
On balance the combined demand for biofuels by all transport modes is expected to increase up to the period 2035-2040 thereafter slightly decreasing towards about 250 PJ - i.e. the assumed maximum availability for the Netherlands. From 2035 on, the increasing demand by trucking, aviation and shipping can be supplied by the surpluses from the light duty sector which will switch to electricity and hydrogen. Therefore, the current investments in biofuel production and fueling infrastructure for passenger cars is not likely to be lost when the passengers car segment will switch to electricity and hydrogen. However, the light duty vehicle sector uses both bio-ethanol and biodiesel. In contrast, heavy duty vehicles, planes and ships all use diesel-type fuels. This implies that the bio-ethanol surplus from the light duty sector, expected around 2035, cannot be simply shifted to trucking, aviation and shipping. First technical barriers need to be solved. Either by adapting the vehicles or by adapting the biofuel production facilities. In the first case, truck engines need to be modified to enable bio-ethanol as fuels. In the second case, assuming that bio ethanol in 2030 will to some extent be produced from woody feedstocks (2nd generation), part of the feedstock could be converted to biodiesel rather than bio ethanol. However, this would require (costly) accelerated phasing out of bio-ethanol production facilities, and the simultaneous construction of new biodiesel plants. Such a bio-ethanol lock-in could be alleviated by policy measures favouring biodiesel use in the light duty sector rather than bio-ethanol. But such policies need to be seen in the global perspective. The Netherlands, as well as the EU, are currently characterized by a large share of biodiesel relative to bio-ethanol, compared to the global average situation. Global bio-ethanol production is about 4 times larger than biodiesel production and is expected to remain so over the next 2 decades (IEA, 2010). In addition the choice for biodiesel versus bio-ethanol relates – from the global perspective of supply and demand - to sustainability issues, especially regarding the production of first generation biodiesel.

6.3 Main conclusions

Reducing CO_2 emissions from transport requires sector-wide application of low-CO_2 fuels. However, in contrast to frequently reported visions, the amount of biofuels available in the year 2050 will probably be insufficient to meet the combined energy demand for heavy duty road transport, aviation and shipping. Therefore, these long distance transport modes need to switch at least partially to other low-CO_2 fuels such as hydrogen. This brings about major technological challenges. For a transition to a low carbon transport sector it is important to prevent disinvestments such as the early closure of fuels plants and production lines of vehicles, or early scrapping of vehicles. Such measures would induce resistance, which would delay this transition. Our exploratory model calculations indicate that the 2050 targets for most of the new low-carbon technologies can only be achieved if their technology roll-out starts within 5 to 10 years. For the transport modes with the longest development and implementation times, in particular aviation and shipping, there is little time left to act.

Furthermore, reaching a substantial intermediate target of 50% CO_2 reduction in 2030 will be rather challenging (see Figure 5.17). Only in the ASAP-route the CO_2 emission in 2030 reaches the value of 50% of the emissions on land in 1990. Also if climate change has more severe effects than now on average expected, thereby necessitating more ambitious actions, little flexibility is left to reach the goals. For example advancing the 2050 CO_2 reduction targets to 2040, would immediately require all possible efforts for all sectors

It is questionable if ‘the market’ is able to make this switch in time, since the investments will be substantial and not profitable in a short term. For this reason coordinated policy support is essential for the low-carbon development of the transport sector.

The overall picture and timelines identified in our study will be comparable for most other EU and industrialized countries, as energy use in transport in Netherlands is quite comparable to other industrialized countries. In addition, only the bunker fuel use accountable to the size of the Netherlands economy and its structure was considered, rather than overall bunker fuel sales.

6.4 Discussion

This report provides a picture of the transport sector in 2050 and a vision on the routes to timely reach this 2050 picture in terms of market penetration trajectories of new low-carbon technologies and fuels. The exploratory approach of our model includes substantial uncertainties. For example:

- Important breakthroughs in battery technology could result in faster increase of electric mobility than assumed in the current study.
- Similarly also other low-CO_2 fuels could play a more important role than envisioned in the current study. For example, a much more prominent role cannot be excluded for sustainably produced ethanol or methanol, partly produced from biomass and/or hydrogen (and possibly CO_2). However, although the spectrum of key low-CO_2 technologies may to some extent develop in a different direction, it is unlikely that this would substantially alter the time ranges left for making decisive choices.
- An important assumption in this study is the availability of biofuels for the Dutch transport sector. There are no indications of large bottlenecks in availability of 10% for the 2020 target, but not only the amount but also the growth rate have to increase after 2020. According to the used studies, this amount can be made available, but is this possible for the time period 2030-2040? Also other factors like for instance the land use of emissions of N_2O might negatively affect the biofuel availability.
- In this study it is expected that hydrogen can be used as a safe fuel in airplanes, see for instance (Faaß, 2001). If this not the case hydrogen might be combined with CO_2 for methanol production or, and that will influence the results of this report, the air sector will need more biofuels than expected, leaving less biofuels for the other transport modes.

Other factors which can affect the key conclusions of this study are:

- The overall global emission target and the allocation of targets over sectors. This can change the 73% reduction target as assumed for transport for 2050. Our 73% reduction target in transport by 2050, is split over 80% reduction in land based transport and 50% in both shipping and aviation. The 80% reduction target for land based transport follows from an equal share in reaching an overall CO_2 reduction of 80-95% by 2050 compared to 1990 for developed countries. Note that the White Paper of the EU (EU, 2011) mentions a 2050 reduction target for road transport of 60%[1]. Nevertheless, emission reduction in transport needs to be continued after 2050 in all scenario's. Therefore, lower emission reduction targets for 2050 will not alter the main conclusions of our study, other than providing some additional time for rolling-out the new technologies.
- Uncertainties in technology development, the competition between technologies such as electricity and hydrogen and on adoption rates can influence the 2050 picture. To handle this kind of uncertainties, solid assumptions have been made on technological developments.
- Uncertainty in the time needed to develop policies and implement them. Although the study shows examples of far-reaching policies decided and implemented in a limited time frame this can certainly be a problem. Far reaching policies need a solid policy decision. Furthermore the development can be delayed by major countries, with another political agenda outside the EU.

6.5 Suggestions for further research

Our study spans a wide range of topics that inevitably could only be briefly addressed, given the exploratory approach and limited time. The impact of the important conclusions of our exploratory study, calls upon a more in depth substantiation of the results, by additional research on:

- More detailed assessment of technology roll-out paths including specific deadlines and steps in the roll-out trajectories for hydrogen, electricity and biofuels.
- Impact of a different allocation of the global warming target to the transport sector, currently 80/50%.
- More in depth underpinning of the likeliness of 250 PJ biofuels availability for the Netherlands in 2050 and a sensitivity analysis regarding the effect of more or less biofuels availability compared to the current starting point of 250 PJ?
- Include cost indications for the roll-out of the various technologies, also as a function of their timing.
- More detailed evaluation of managing the shift of biofuels from light duty vehicles to long distance transport modes, also regarding the type of biofuels involved.
- More detailed analyses of the technology prospects around airplanes on questions like: Is hydrogen a safe option in airplanes with gasturbines? Are fuel cells a more efficient option for airplanes? Which biofuels can be used on airplanes, as pure fuel or as blend with kerosene and which can be used in the current engines?
- Elaboration of a policy framework.
- What are the long-term consequences of current policies? Do they already provide the right incentives, or do they create lock-ins?
- Potential impact of other fuel options, on the results of our study; e.g. the impact of a large role for methanol as biofuel but also as an energy carrier for hydrogen.

References

ACEA (2010): *The Automobile Industry Pocket Guide 2010*. Association des Constructeurs Européens d'Automobiles, Brussel.

Airbus (2003): *CRYOPLANE 2003 GRD1-1999-10014 Liquid Hydrogen Fuelled Aircraft System Analysis*. PROJECT CO-ORDINATOR: Airbus Deutschland GmbH, 2003.

Air Liquide (2011): *Hydrogen A new clean energy working for the environment; Air Liquide, technological partner of the Challenge Bibendum 2011*. May 2011. www.airliquide.com

Axane (2001): *Northern Europe Network map*. Internet site Air liquide: http://www.axane.fr/gb/products/h2/h2.html

Backhaus, J., I.G. Bunzeck (2010a): *Development of an alternative fuel infrastructure: What* H_2 *can learn from LPG. The case of LPG/CNG in the Netherlands and other countries*. ECN rapport ECN-E--10-037, ECN, Petten, pp 1 – 36.

Backhaus, J., I.G. Bunzeck (2010b): *Planning and permitting procedures. Analysis of expected lead times for hydrogen infrastructure build-up in the Netherlands*. ECN-E--10-051, pp. 1-39.

Bakema, G.F., et al. (1990): *Aardgas en elektriciteit bij het gemeentelijk voertuigpark van Amsterdam.* ECN-C--90-045, Petten, October 1990.

Boeing (2009): *Boeing Current Market Outlook 2009-2028*. Boeing Commercial Airplanes Market Analysis. P.O. Box 3707 MC 21-28. Seattle, WA 98124-2207. www.boeing.com/cmo

Bosch, A. van den, et al. (1999): *Assessment of electric vehicle impacts on energy, environment and transportation systems.* ECN-C--99-076, ECN, Petten, October, 1999.

Brannigan C. et al. (2009): *Report on the international and aviation and maritime emission in a Copenhagen (post 2012) agreement*. AEA – Qinetiq, pp. 1-116.

Carlin, P. Et al. (2010): *Leadership through rough seas; piloting shipping to low-carbon growth.* Xynteo report. pp. 1 – 52.

CGPC (2006): *Long-Range Transport Plan - Horizon 2050: Strategic considerations S.l.* Ministère des Transports, de l‟Équipement, du Tourisme et de la Mer, Conseil Général des Ponts et Chaussées (CGPC), 2006.

Convery, F.J. (2009): *Origins and Development of the EU ETS.* Environ Resource Econ (2009) 43:391–412; DOI 10.1007/s10640-009-9275-7; Springer.

Daggett, D., O. Hadaller, R. Hendricks, R. Walther (2006): *Alternative Fuels and Their Potential Impact on Aviation.* Presentation to the 25th Congress of the International Council of the Aeronautical Sciences (ICAS), Hamburg: http://gltrs.grc.nasa.gov/reports/2006/TM-2006-214365.pdf

Daniëls, B.W., S. Kruitwagen (2010): *Referentieraming energie en emissies 2010-2020*. ECN-E--10-004, ECN/PBL, Petten, April 2010.

DG Clima (2011): Website of DG Clima on reducing emission from aviation: http://ec.europa.eu/clima/policies/transport/aviation/index_en.htm (last accessed June, 2011).

DNV (2011): *Technology outlook 2020*. Published June 2011 Available at: www.dnv.com/foresight

Dril, A.W.N. van, et. al. (2007): *Effecten op* CO_2*-emissie en energiegebruik van Green4sure*. ECN-E--07-034 ECN, Petten, June 2007.

EC (2009): *Directive 2009/28/EC on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC*. Official Journal of the European Union, 5 June 2009.

Elobio (2011): Information on the website of the EU project Refuel: www.elobio.eu (last accessed April, 2011).

E4tech (2009): *Use of biofuels and hydrogen in aviation*. Chapter 5.

EEG- FTF (2011): *Future transport fuels.* Report of the European Expert Group on Future Transport Fuels. January 2011, pp 1-81.

EU (1993): *Commission Directive 93/116/EC of 17 December 1993 adapting to technical progress Council Directive 80/1268/EEC relating to the fuel consumption of motor vehicles.* EU, 1993.

EU (2005): *European Parliament resolution on 'Winning the Battle Against Global Climate Change'* (2005/2049(INI)). EU, 2005.

EU (2007a): *Proposal for a Regulation of the European Parliament and of the Council setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce* CO_2 *emissions from light-duty vehicles (*/*COM/2007/0856 final - COD 2007/0297). EU, 2007.

EU (2007b): Communication from the Commission to the Council and the European Parliament: *Results of the review of the Community Strategy to reduce* CO_2 *emissions from passenger cars and light-commercial vehicles* (COM/2007/0019 final). Feb. 7, 2007.

EU (2008): http://ec.europa.eu/clima/policies/transport/vehicles/index_en.htm

EU (2009): *Regulation (EC) No 443/2009 of the European Council: Setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce* CO_2 *emissions from light-duty vehicles*.

EU (2010): *EU energy and transport in figures. Statistical pocketbook, 2010.* ISBN 978-92-79-13815-7, Luxembourg: Publications Office of the European Union, June 2010.

EU (2010b): *Road transport: Reducing* CO_2 *emissions from light-duty vehicles*. Website http://ec.europa.eu/clima/policies/transport/vehicles/index_en.htm. visited December 2010.

EU (2011): *European Commission White paper: Roadmap to a Single European Transport Area - Towards a competitive abd resource efficient transport system.* Brussels, 23 March 2011.

EREC (2010): *RE-thinking 2050; a 100% Renewable Energy Vision for the European Union*. EREC - the European Renewable Energy Council, the umbrella organisation of the major European renewable energy industry. April 2010, pp. 1-75.

Faaß, R. (2001): *Cyroplane; Flugzeuge mit Wasserstoffantrieb*. Airbus Deutschland GmbH, Hamburg, 6 December 2001.

Farries, P., C. Eyers (2008): *Aviation* CO_2 *Emissions Abatement Potential from Technology Innovation*. Pamela, Chris Eyers. QINETIQ/CON/AP/CR0801111. UK Office of Climate Change.

Gas in beeld (2010): *De geschiedenis en toekomst van het aardgas in Nederland*. Website: http://www.gasinbeeld.nl; (consulted December 2010).

Guardian (2008): *Aircraft numbers may double by 2026.*Website of the UK newspaper The Guardian: www.guardian.co.uk/business/2008/feb/08/theairlineindustry.transport (visited December 2010).

Hanschke C.B., H.P.J. de Wilde, M.A. Uyterlinde (2010): *Internationale Quick Scan Duurzame Mobiliteit* (Dutch, with summary in English). ECN report ECN-E--10-093, November 2010, pp. 1- 91.

Hanschke, C.B., et al. (2009): *Duurzame innovatie in het Wegverkeer. Een evaluatie van vier transitiepaden voor het thema Duurzame Mobiliteit*. ECN-E--08-076, ECN, Petten, January 2009.

Hoen, A., R.M.M., van den Brink, B. Kampman, R. Kortmann, B.H. Boon (2004): *Optiedocument Verkeersemissies; Effecten van maatregelen op verzuring en klimaatverandering. Options for reducing transport emissions: effects of measures on acidifying and climate-changing emissions*. RIVM Rapport 773002026, RIVM, Bilthoven, July 4 2004.

Hoen, A., K. Geurs, H. de Wilde, C.B. Hanschke, M.A. Uyterlinde (2009): *CO_2 emission reduction in transport Confronting medium-term and long term options for achieving climate targets in the Netherlands.* PBL publication number 500076009, Netherlands Environmental Assessment Agency (PBL)/ECN, Bilthoven/ Petten, July 2009.

Hyways (2008): *The European Hydrogen Energy Roadmap*. Hyways Consortium, February 2008.

NGV-Holland (2011): *Tankstations in Nederland.* Internet site http://www.ngv-holland.nl/content_tank.php, 4 may 2011.

IATA (2009): *Carbon-Neutral Growth by 2020*. Press release, 8 June: www.iata.org/pressroom/pr/2009-06-08-03.htm

IEA (2007): *Biofuel Production*. IEA Energy Technology Essentials ETE02, OECD/IEA, January 2007 http://www.iea.org/techno/essentials2.pdf.

IEA (2008): *Energy Technology Perspectives*.

IEA (2009): *Transport, Energy and CO_2: Moving Toward Sustainability.* Draft report. July 2009. Chapter 3. Light-duty vehicles.

IEA (2009): *Transport, Energy and CO_2: Moving Toward Sustainability*. Final report. October 2009. pp.1-414. ISBN: 978-92-64-07316-6.

IEA (2010): *World Energy Outlook 2010*. pp 1-731. ISBN: 978-92-64-08624-1.

IMO (2011): Website of the International Maritime Organization: www.imo.org (last accessed June, 2011).

ITF (2008): *International Transport Forum. Greenhouse gas reduction strategies in the transport sector*. OECD/ITF (2008).

KLM (2011): *Road to sustainable aviation fuels - KLM's approach*: www.klm.com/csr/en/climate/footprint/biofuels/index.html. (website last accessed July, 2011).

Marcus (2010): *Developing revolutionary, energy-efficient airplanes*. Scientific American, July 26, 2010: http://www.scientificamerican.com/article.cfm?id=nasa-green-aircraft (last visited December, 2010).

McKinsey (2009): *Pathways to a low-carbon economy*; *version 2 of the global greenhouse gas abatement cost curve*. pp 1-190.

McKinsey (2010): *A portfolio of power-trains for Europe: a fact-based analysis. The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles*. McKinsey & Company 19 November 2010. http://www.europeanclimate.org/documents/Power_trains_for_Europe.pdf

OICA (2008): *World Motor Vehicle Production 2007*. International Organization of Motor Vehicle Manufacturers, Paris, 2008. http://oica.net/category/production-statistics/2007-statistics/

O'Rourke, R. (2006): *Navy ship propulsion technologies: options for reducing oil use – background for congress.*

Planets (2010): *Probabilistic Long-term Assessment of New Energy Technology Scenarios.* www.feem-project.net/planets.

PBL (2009): *Getting into the Right Lane for 2050; A primer for EU debate*. PBL publication number 500159001. Netherlands Environmental Assessment Agency (PBL), Bilthoven, October 2009.

Refuel (2011): Information on the website of the EU project Refuel: www.refuel.eu (last accessed April 2011).

Rijkee, A.G., H.P. van Essen (2010): *Review of projections and scenarios for transport in 2050 Task 9.* Report V produced as part of contract ENV.C.3/SER/2008/0053 between European Commission Directorate-General Environment and AEA Technology plc. www.eutransportghg2050.eu

Schol, E.; P. Kroon, R.T.M.Smokers (1995): *Save-module transport: de modellering van energieverbruiksontwikkelingen.* ECN-I--95-003, ECN, Petten, November,1995.

Schoots, K., F. Ferioli, G.J. Kramer, B.C.C. van der Zwaan (2008): *Learning curves for hydrogen production technology: an assessment of observed cost reduction*. International Journal of Hydrogen Energy 33 (11), 2630–2645.

Schumpeter, J., (1939): *A Theoretical, Historical and Statistical Analysis of the Capitalist Process,* New York Toronto London : McGraw-Hill Book Company, 1939.

Sijm, J.P.M. (2010): Personal Communication. December 2010. Researcher at the Energy Research Centre of the Netherlands, Department of Policy Studies.

Skinner I, H. van Essen, R. Smokers, N. Hill (2010): *Towards the decarbonisation of EU's transport sector by 2050.* Final report produced under the contract ENV.C.3/SER/2008/0053 between European Commission Directorate-General Environment and AEA Technology plc: www.eutransportghg2050.eu

Smokers, R. (2010): *EU Transport GHG: Routes to 2050. Policy framework for reducing GHG emissions by decarbonising transport fuels and improving vehicle efficiency*. Presentation at final stakeholder meeting, 15 March 2010.

Svensson F. (2005): *Potential of Reducing the Environmental Impact of Civil Subsonic Aviation by Using Liquid Hydrogen*. Scientific report FOI-R--1636--SE, April 2005, ISSN 1650-1942.

TSO (2009): *Transport Statistics Report; Maritime Statistics 2008*. TSO, London, September 2009.

Tutturen J.P. (2010): *Pathway to Low Carbon Shipping -Nuclear Powered Ships*. DNV, presentation given 8 March 2010.

Uyterlinde, M.A., C.B. Hanschke, P. Kroon (2008): *Effecten en kosten van duurzame innovatie in het wegverkeer. Een verkenning voor het programma 'De auto van de toekomst gaat rijden'.* ECN-E--07-106, ECN, Petten, March 2008.

Uyterlinde, M.A., H.M. Londo, P. Godfroij, H. Jeeninga (2007a): *Long-term developments in the transport sector - comparing biofuel and hydrogen roadmaps*. ECN-M--07-075, June 2007.

Uyterlinde, M.A., G.H. Martinus, H. Rösler, et. al. (2007b): *The contribution of technological progress to a sustainable energy system. Volume 5 in the CASCADE MINTS project*. ECN-E-06-052, ECN, Petten, March 2007

Uyterlinde, M.A, et. al. (2007c): *A sustainable energy system in 2050: Promise or possibility*? ECN-E--07-082, ECN, Petten, October 2007.

WEO (2010): *World Energy Outlook 2010*. OECD/IEA, International Energy Agency, Paris, France, 2010

Wilde, H.P.J. de, P. Kroon, M. Mozaffarian, Th. Sterker (2007): *Quick Scan of the Economic Consequences of Prohibiting Residual Fuels in Shipping*. Published by the Energy Research Centre of the Netherland, Report ECN-E--07-051, July 2007; 76p.

Wilde, H.P.J. de, P. Kroon (2008): *Cleaner shipping: trade off between air pollution, costs and refinery CO_2 emissions*. 2nd international conference on Harbours, Air Quality and Climate Change, Rotterdam, The Netherlands, May 2008.

Witso, J.E. (2010): *LNG a key to cleaner shipping. DNV press release 2010*. http://www.dnv.com/press_area/press_releases/2010/lngakeytocleanershipping.asp (last accessed June, 2011).

Appendix A Comparison of model results: ASAP’, ‘Mean’ and the ‘Delay-route’

In this appendix the results of three routes are compared:

- The route where all developments are implemented as fast as possible (ASAP-route).
- The route where actions are postponed until the latest start time allowing to reach the 2050 target just in time (Delay-route).
- A ‘Mean-route’, characterised by a pace in between the ASAP and the Delay route.

The figures for the three different routes are always given on the same page, to facilitate comparison. At first sight the differences appear to be small, especially because the long time window considered (2000-2050), hampers to notice differences on relatively small timescales (years). In each figure the 2000-2020 data are the same as the routes only differentiate after 2020. Furthermore all routes have to fit the 2050 picture, so the 2050 situation is also the same in all routes.

At the end of this appendix, with the figures for biofuel, hydrogen and electricity, it is easier to notice the differences. The penetration in the ASAP-route is earlier, resulting in substantially lower CO_2 emissions in 2030 and 2040 compared to the Delay-route.

A.1 Energy use of transport modes up to 2050

Light duty vehicles

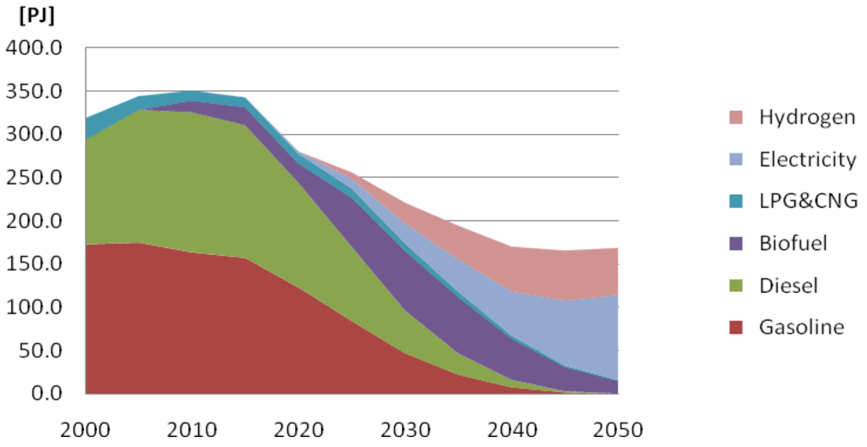

Figure A.1 *Energy consumption and fuel use of light vehicles [PJ] 'ASAP-route'*

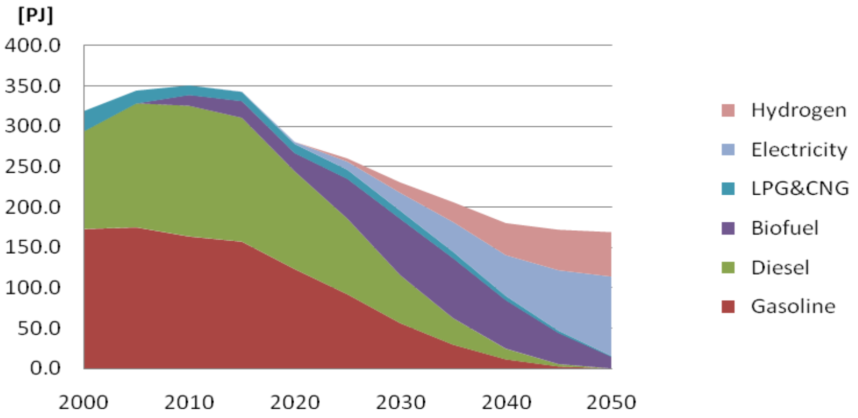

Figure A.2 *Energy consumption and fuel use of light vehicles [PJ] 'Mean-route'*

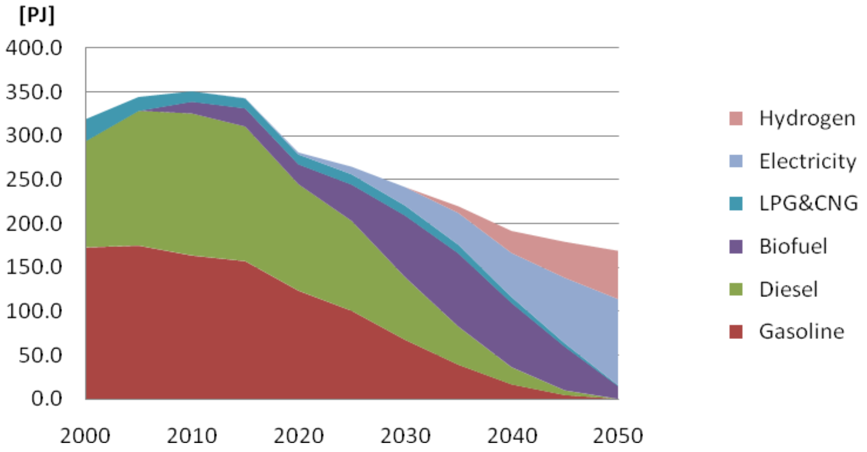

Figure A.3 *Energy consumption and fuel use of light vehicles [PJ] 'Delay-route'*

Heavy duty vehicles

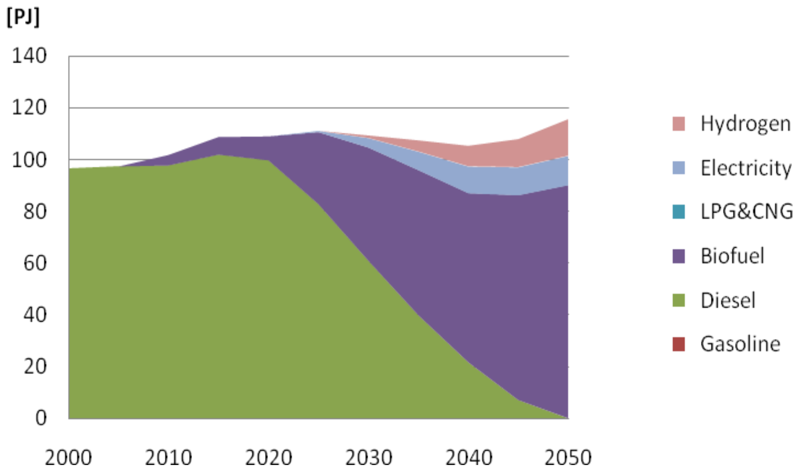

Figure A.4 *Energy consumption and fuel use of heavy duty vehicles [PJ] 'ASAP-route'*

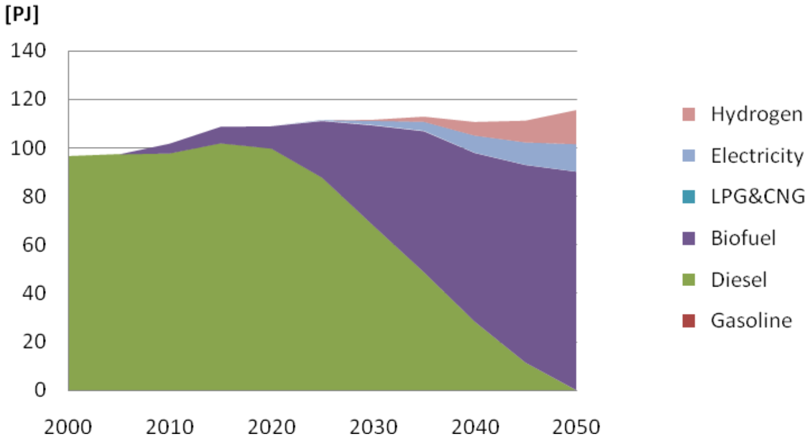

Figure A.5 *Energy consumption and fuel use of heavy duty vehicles [PJ] 'Mean-route'*

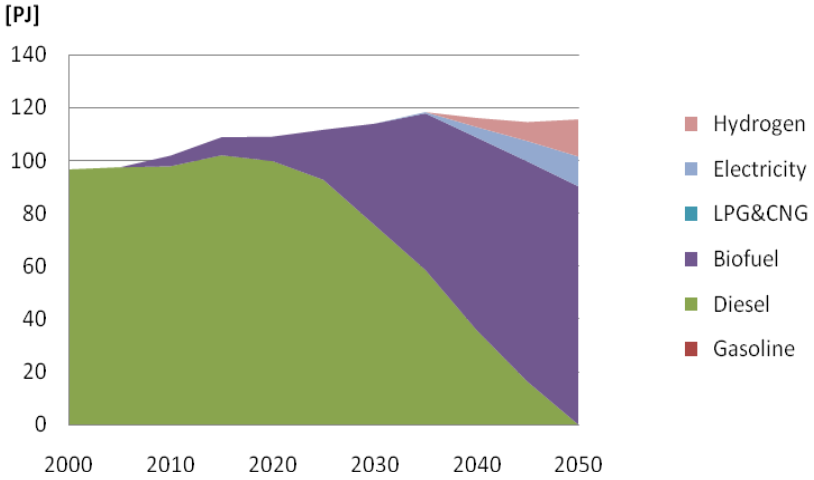

Figure A.6 *Energy consumption and fuel use of heavy duty vehicles [PJ] 'Delay-route'*

Aviation

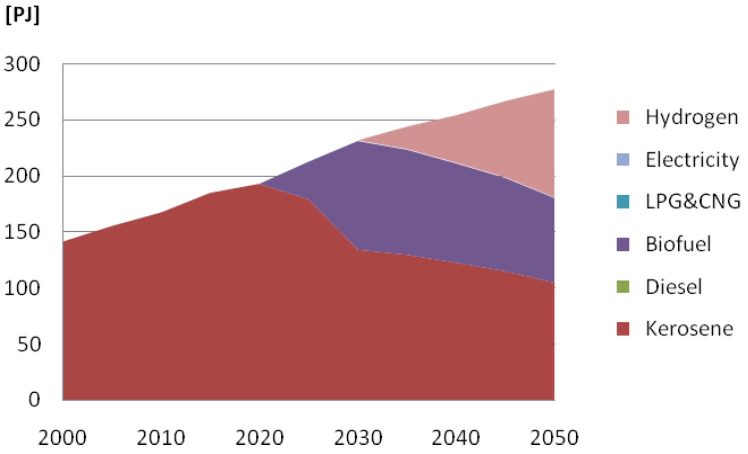

Figure A.7 *Energy consumption and fuel use aviation [PJ] 'ASAP-route'*

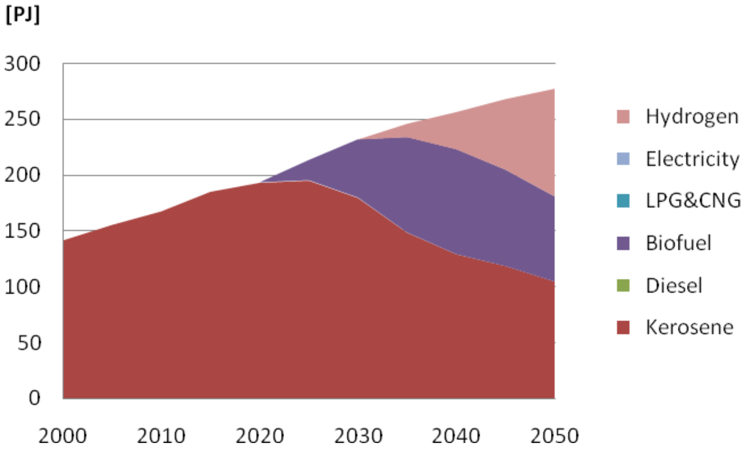

Figure A.8 *Energy consumption and fuel use aviation [PJ] 'Mean-route'*

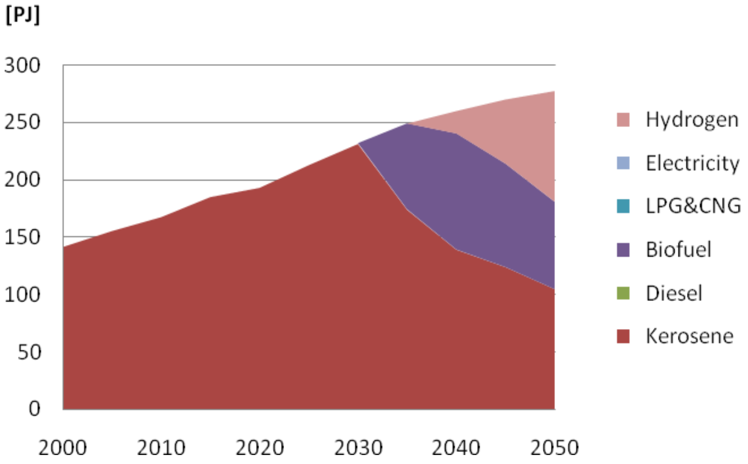

Figure A.9 *Energy consumption and fuel use aviation [PJ] 'Delay-route'*

Shipping

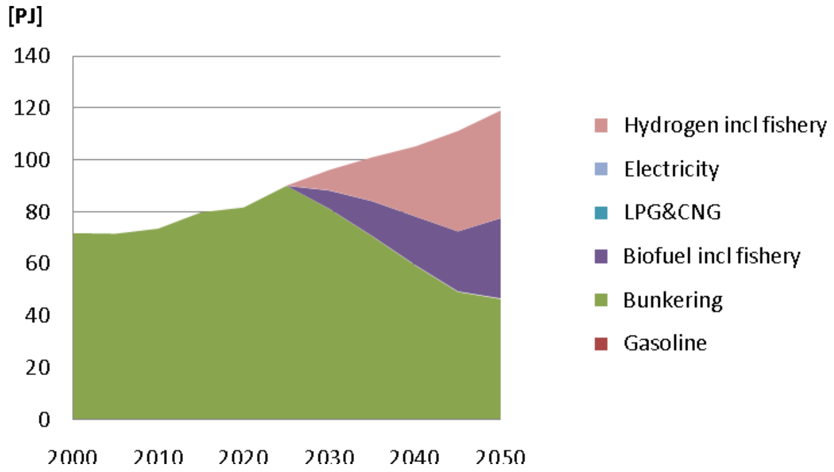

Figure A.10 *Fuel consumption sea ships [PJ] 'ASAP-route'*

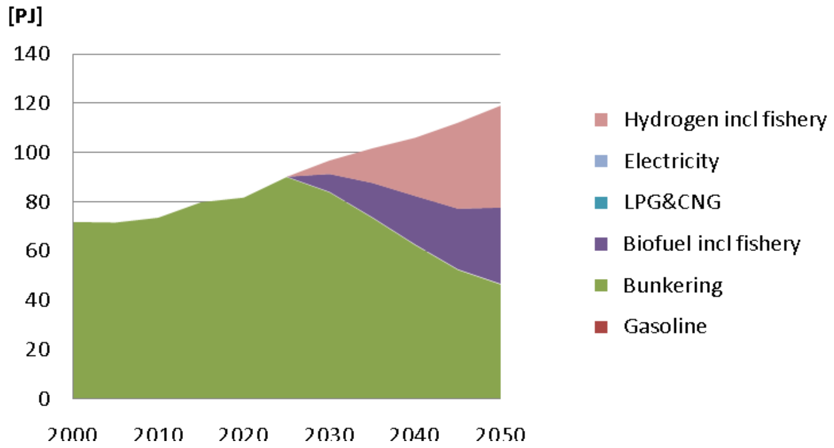

Figure A.11 *Fuel consumption sea ships [PJ] 'Mean-route'*

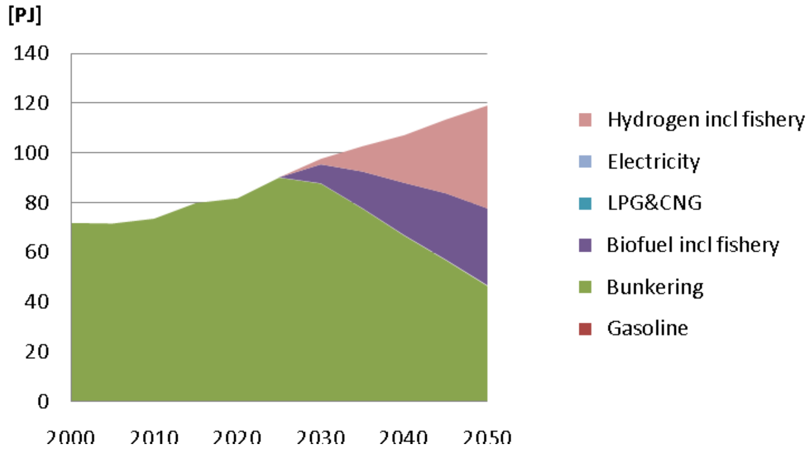

Figure A.12 *Fuel consumption sea ships [PJ] 'Delay-route'*

A.2 Total picture of the transport sector

Consumption per fuel type

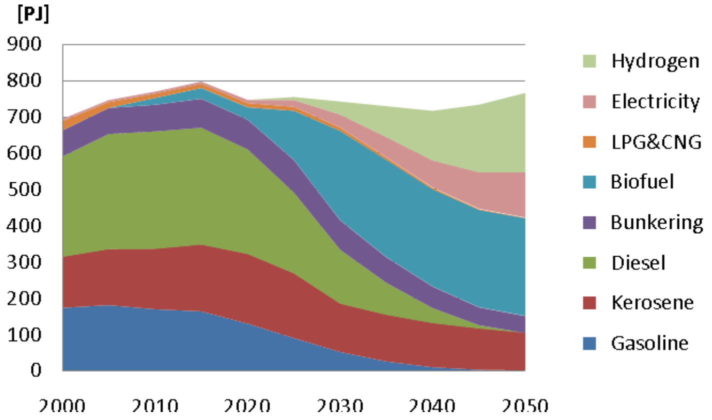

Figure A.13 *Total fuel consumption per fuel [PJ] 'ASAP-route'*

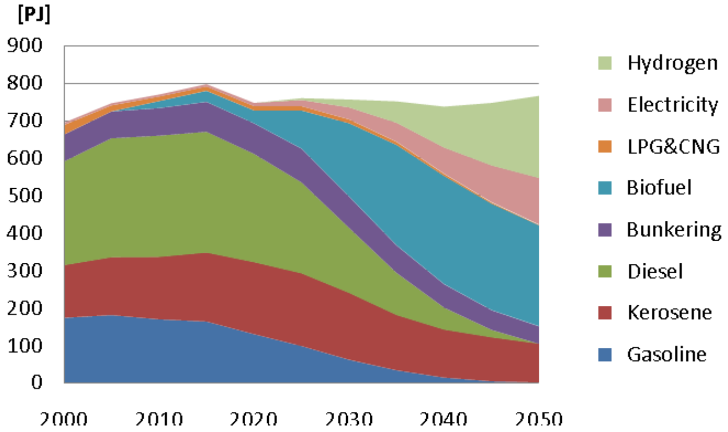

Figure A.14 *Total fuel consumption per fuel [PJ] 'Mean-route'*

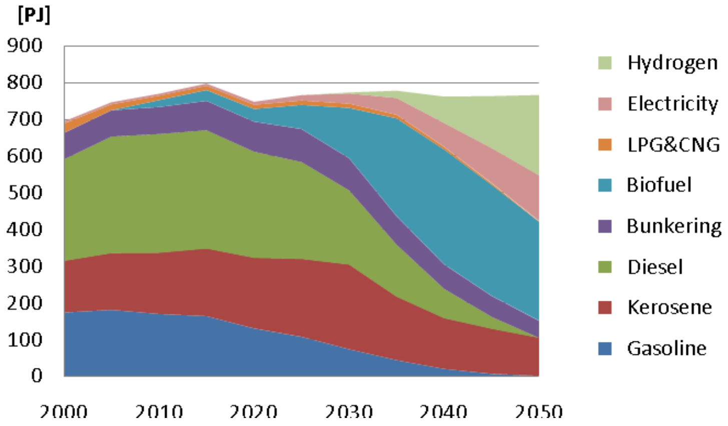

Figure A.15 *Total fuel consumption per fuel [PJ] 'Delay-route'*

Consumption per transport mode

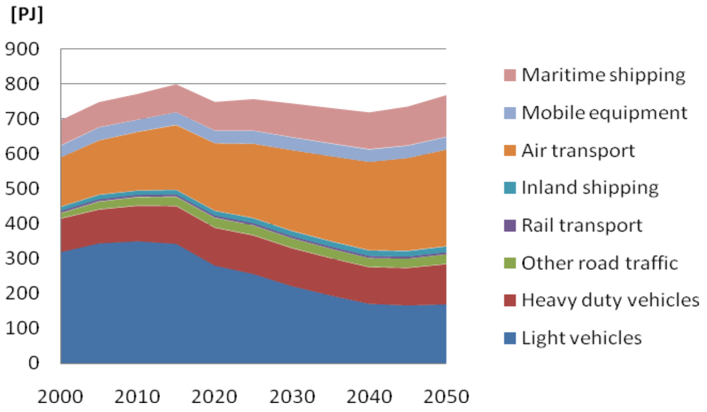

Figure A.16 *Total energy consumption per type of transport [PJ] 'ASAP-route'*

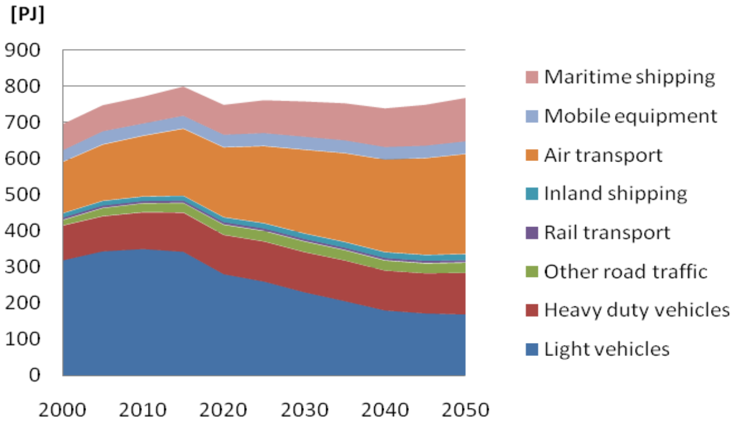

Figure A.17 *Total energy consumption per type of transport [PJ] 'Mean-route'*

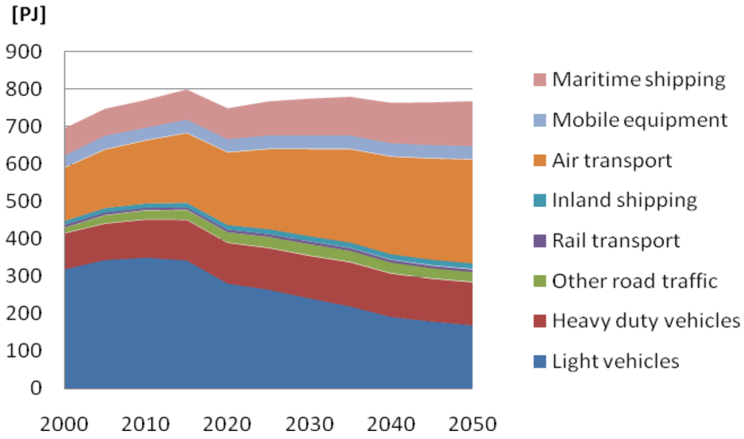

Figure A.18 *Total energy consumption per type of transport [PJ] 'Delay-route'*

Consumption of biofuels

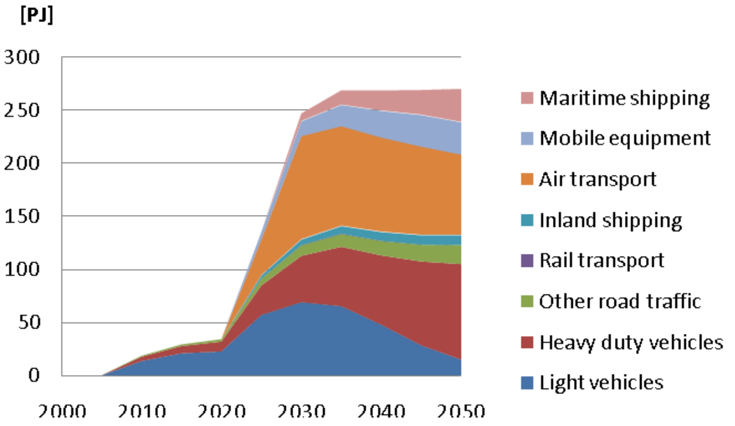

Figure A.19 *Total biofuel consumption per transport mode [PJ] 'ASAP-route'*

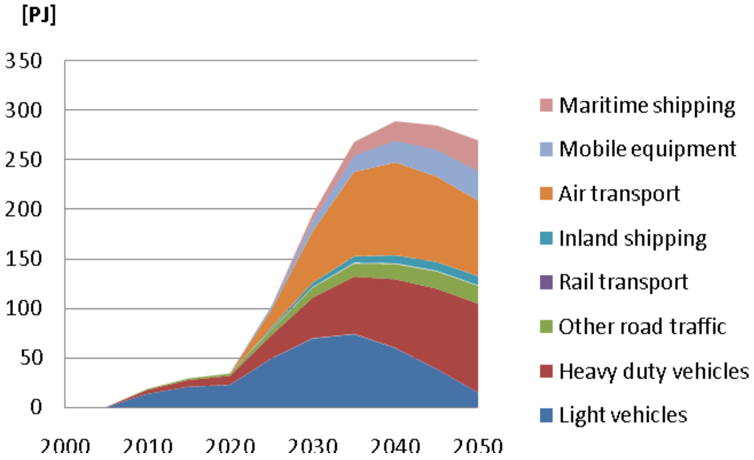

Figure A.20 *Total biofuel consumption per transport mode [PJ] 'Mean-route'*

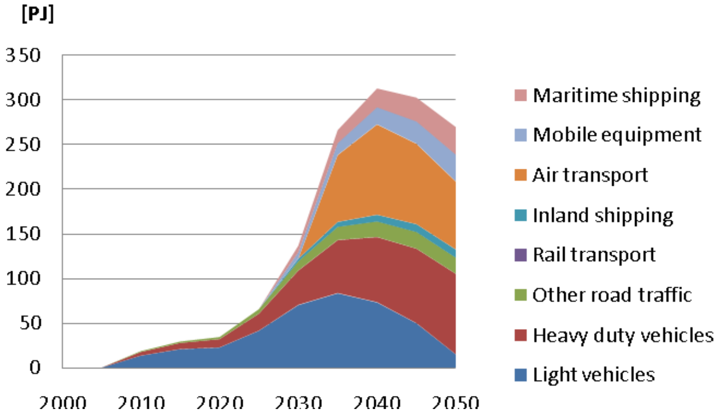

Figure A.21 *Total biofuel consumption per transport mode [PJ] 'Delay-route'*

Consumption of hydrogen

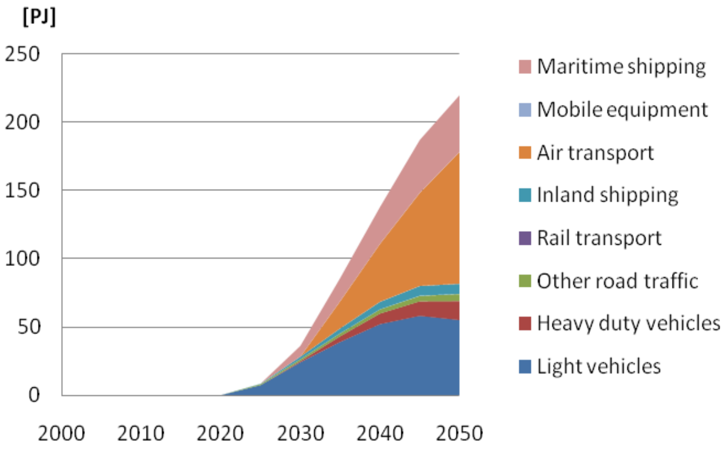

Figure A.22 *Total fuel consumption of hydrogen per type of transport [PJ] 'ASAP-route'*

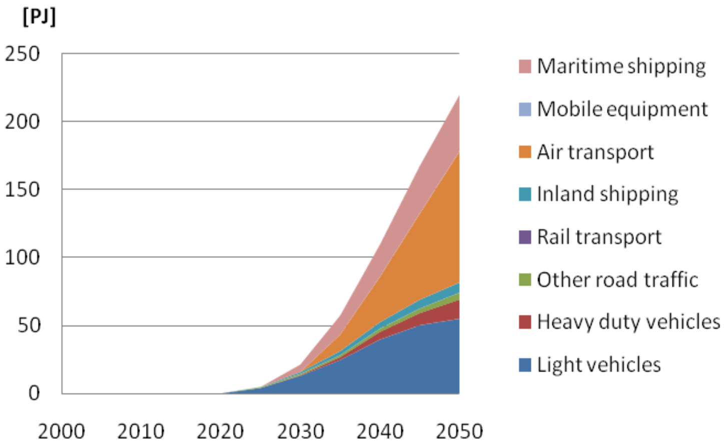

Figure A.23 *Total fuel consumption of hydrogen per type of transport [PJ] 'Mean-route'*

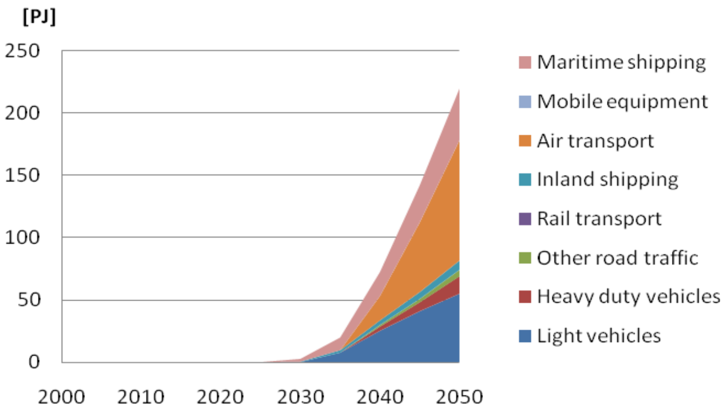

Figure A.24 *Total fuel consumption of hydrogen per type of transport [PJ] 'Delay-route'*

Consumption of electricity

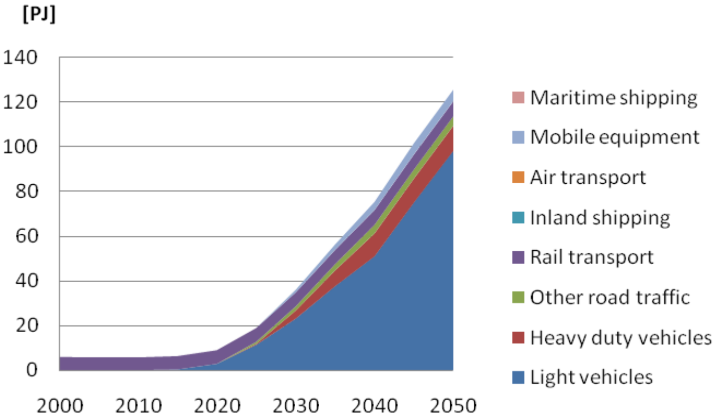

Figure A.25 *Total fuel consumption of electricity per type of transport [PJ] 'ASAP-route'*

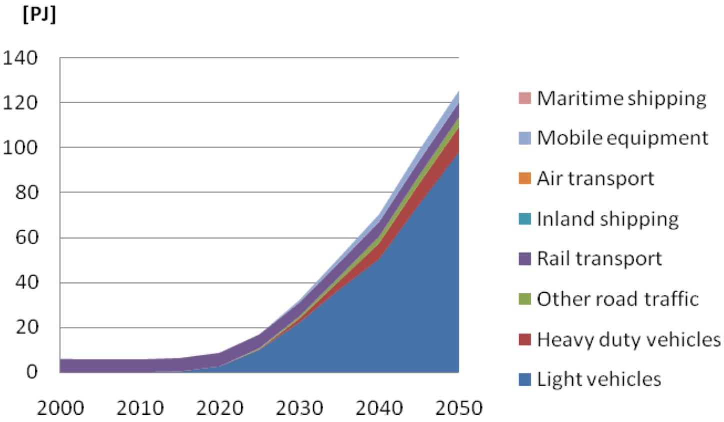

Figure A.26 *Total fuel consumption of electricity per type of transport [PJ] 'Mean-route'*

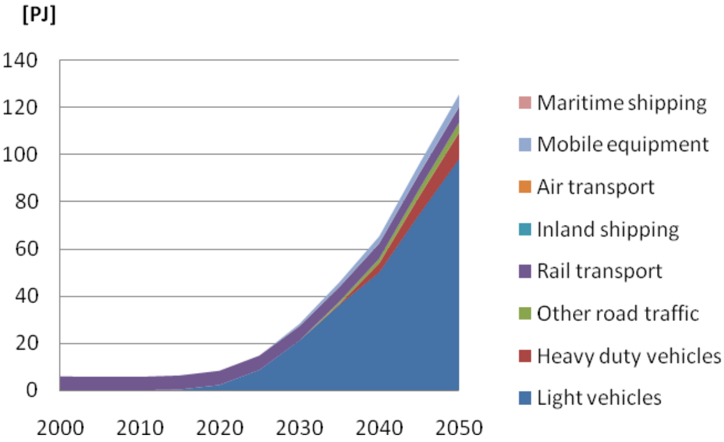

Figure A.27 *Total fuel consumption of electricity per type of transport [PJ] 'Delay-route'*

A.3 CO_2 emissions

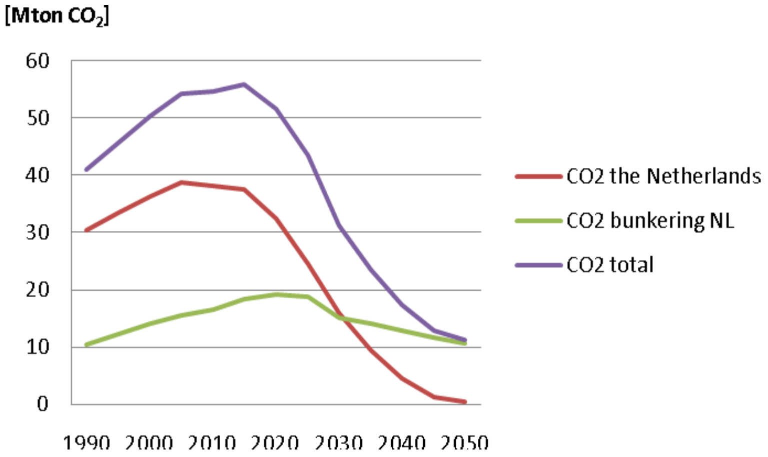

Figure A.28 *Total CO_2 emission (excl some minor corrections) [Mton] 'ASAP-route'*

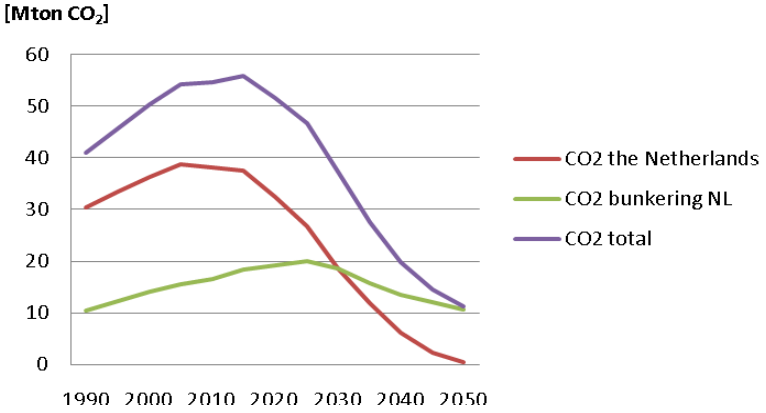

Figure A.29 *Total CO_2 emission (excl some minor corrections) [Mton] 'Mean-route'*

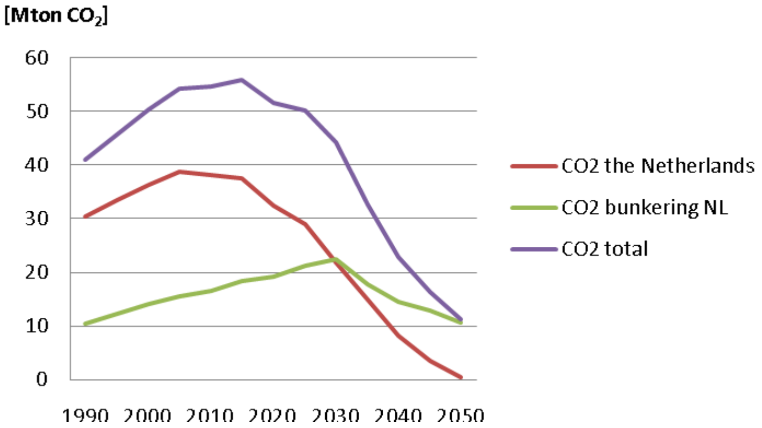

Figure A.30 *Total CO_2 emission (excl some minor corrections) [Mton] 'Delay-route'*

Appendix B Figures of smaller sectors in the ‘Mean-route’

In this report the focus is on four main fuel consumers of the transport sector, namely: light vehicles, heavy duty vehicles, see ships and airplanes. To get a complete picture of the sector assumptions has been made for other transport vehicles and modes. In this appendix the energy figures are presented for the other 4 categories of the transport sector. Only the mean figures are presented.

The four smaller transport categories are:

- Other road transport: mainly buses and coaches but also two wheelers and special vehicles like fire fighting vehicles, cleansing vehicles, breakdown lorries. See for the energy data Figure B.1. Hydrogen is an option for buses; electricity is an option for buses and two wheelers. Just like for heavy duty vehicles some biofuels are also needed for the category other road transport.
- Rail transport. In the Netherlands almost all passenger transport and about 50% of the goods transport is already electric. See for the energy data Figure B.2. A change to almost 100% electricity is possible.
- Inland shipping. The Netherlands has several big rivers and canals. The role of inland shipping in the Netherlands can be compared with the transport of heavy goods by rail in other countries. See for the energy data Figure B.3. The situation for inland shipping is comparable to sea ships, but transformation to sustainable fuels can start earlier.
- In the Netherlands mobile equipment is in some statistics reported as part of the transport sector. Mobile equipment includes from the agricultural sector: Mobile machinery, mainly tractors, including contracting and hire firms. In addition to agriculture the category ‘mobile equipment’ includes non-agricultural mobile machinery, such as forklift trucks, cranes and building equipment. See for the energy data Figure B.4. Because most equipment is used on different locations, and sometimes for a limited number of hours per day, hydrogen is not an option. There is a small potential for electricity but the main low-carbon fuel will be biofuels.

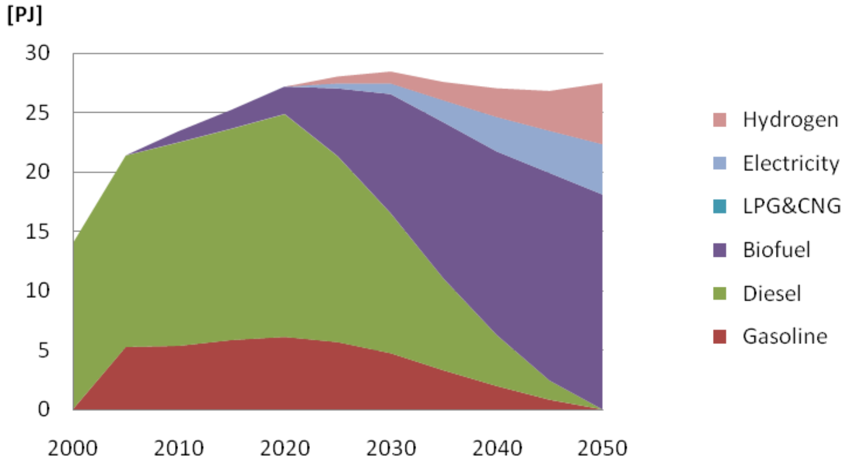

Figure B.1 *Energy consumption of other road transport [PJ] ‘Mean-route’*

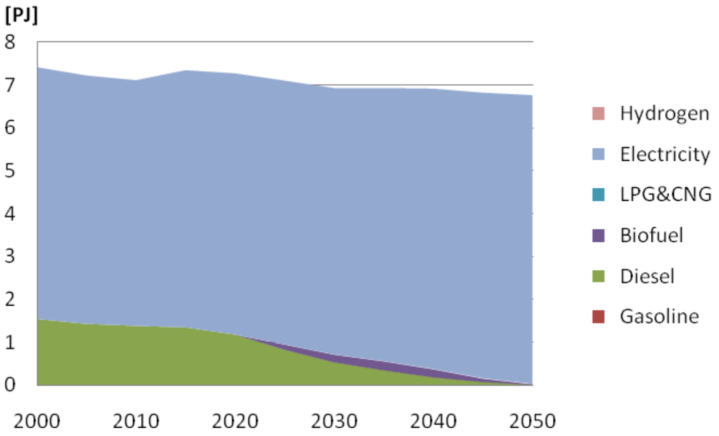

Figure B.2 *Energy consumption of rail transport [PJ] 'Mean-route'*

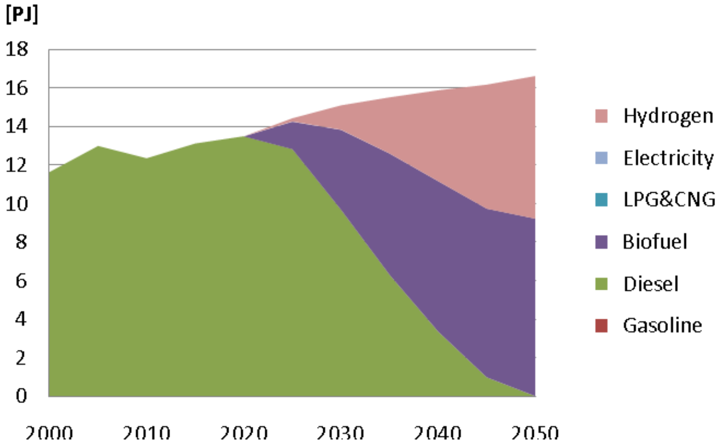

Figure B.3 *Energy consumption of inland shipping [PJ] 'Mean-route'*

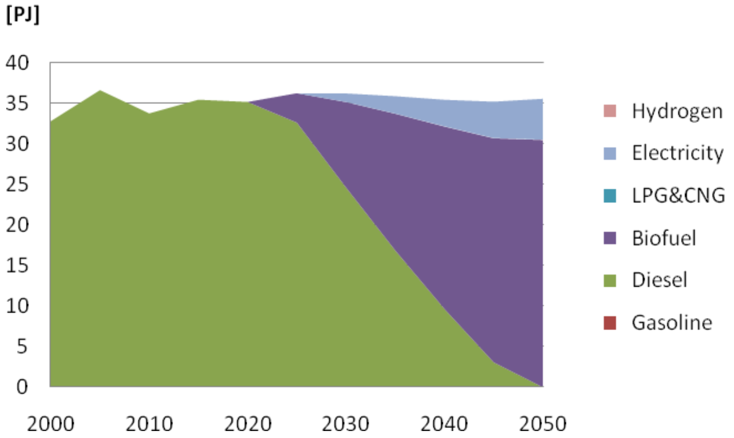

Figure B.4 *Energy consumption of mobile equipment [PJ] 'Mean-route'*

Appendix C Additional visions on future transport

For comparison two additional visions on the future developments in the transport sector are included below. On main aspects both visions are in line with the vision presented in our study, but both studies do not focus as much on the timing of technology roll-out as in our study.

C.1 2050 vision on low-carbon transport by Skinner et al.

Skinner et al. (2010) present a basic vision on options to reduce transport's GHG emissions.
By 2050, it is projected that vehicles, particularly in road transport, will have become more specialised, e.g. different cars designed for urban and inter-urban uses, heavy duty vehicles designed differently for short- and long-distance travel with vehicle build-ups that may enable new logistic concepts, and will make use of different energy carriers and alternative fuels in doing so.
By mode, the use of the alternative fuels and energy carriers could be differentiated as follows:

- *Biofuels*: Virtually carbon-neutral biofuels are likely to be used in aviation and for long-distance heavy duty road vehicles (due to lack of alternatives), as well as possibly in inland waterway vessels. The use in light duty road transport modes will probably have peaked, as other technologies have the potential to reduce GHG emissions from these modes.
- *Electricity*: All main rail lines are likely to be electrified (the majority are already), while there is likely to be significant use of light duty, electric vehicles on roads.
- *Fuel cells/hydrogen*: These are likely to be used in selected rail applications (e.g. shunting) and specialised road applications (e.g. fleets and urban buses).
- *Natural gas*: Liquefied natural gas (LNG) is likely to be used in inland waterway and maritime vessels, while compressed natural gas (CNG) could be used, in short to medium term, in road transport.

C.2 2050 vision on low-carbon transport by PBL

The vision on low-carbon transport by PBL (2009) focuses on Europe in the global perspective including all transport modes. Low-carbon means 80% reduction, compared to 1990 levels, of total CO_2 emissions (well-to-wheel) from European transport, by 2050, based on the EU target of restricting temperature increase to 2 °C, compared to pre-industrial levels. The potential emission reduction of technological measures is primarily taken from the OECD/IEA BLUE Map scenario (OECD/IEA, 2008). Under business-as-usual policies, CO_2 emissions are expected to more than double. To reduce transport emissions by 80%, relative to 1990 levels, emissions in 2050 need to be reduced almost by a factor of 12 compared to the baseline scenario.

Range of low-carbon technologies

The vision includes all transport modes - road and rail passenger travel, aviation, road freight and shipping. The reduction target is achieved by:

- Using low-carbon fuels, such as hydrogen, electric traction and biofuels.
- Improving vehicle energy and logistic efficiency.
- Reducing traffic volumes and shifting to more energy efficient modes, such as rail transport.

The vision for low-carbon transport, based on 80% reduction in CO_2 emissions, is presented in Figure C.1. It includes emissions outside the EU territory from aircraft and ships fuelled in the EU.

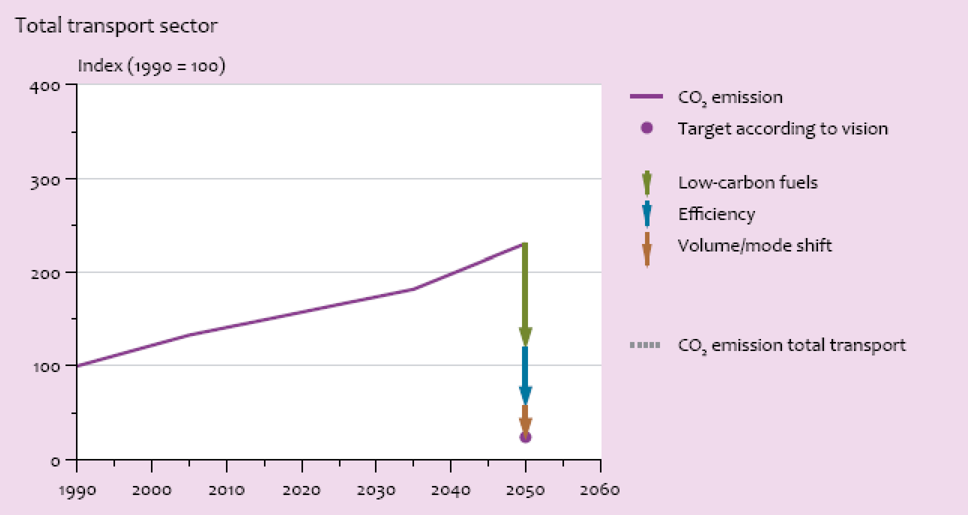

Figure C.1 *Reduction of emissions according to PBL study (PBL, 2009)*

Differential emission reduction for transport modes

In achieving the 80% reduction target by 2050, reduction of CO_2 emissions is not the same in all transport modes. Passenger transport contributes most to the overall target. Road freight, aviation, inland shipping and maritime transport contribute less to the overall reduction target because fewer cost-effective technologies are available.

Zero-carbon road passenger vehicles

Road passenger transport reduces CO_2 emissions by 95%, relative to the baseline scenario in 2050 (by a factor of 20 to 25), largely by using near-zero emission vehicles and fuels. Current cars are replaced by electric vehicles and/or fuel-cell vehicles with hydrogen produced through electrolysis.

Biofuels and improved efficiency in road freight transport

Road freight transport reduces carbon dioxide emissions by about a factor of 6, relative to the baseline scenario, by 2050, resulting from a complete shift to advanced bio-diesels and maximum improvement in vehicle energy and logistic efficiency, and, to a small extent, from mode shifts to rail freight and shipping.

Gradual change to biofuels accompanied by modal shift

Emissions from maritime transport and aviation are reduced by a factor of 6 and 10, respectively, relative to the baseline scenario, by 2050. This is achieved by a 50 to 75% share of advanced biofuels and by a combination of technological, logistic and operational measures, including speed reductions (which results in 50 to 60% reduction in carbon dioxide emissions per vehicle km. Further emission reductions in aviation result from changes in travel behaviour.