Electric driving
Evaluating transitions based on system options

Policy Studies

Netherlands Environmental Assessment Agency

Electric driving

Evaluating transitions based on system options

D. Nagelhout, J.P.M. Ros

Netherlands Environmental Assessment Agency

Electric driving – Evaluating transitions based on system options

PBL publication number 500083013

Corresponding Author: Dick.Nagelhout@pbl.nl

This publication can be downloaded from our website: www.pbl.nl/en and is also available in Dutch.

The Netherlands Environmental Assessment Agency (PBL) is the national institute for strategic policy analysis in the field of environment, nature and spatial planning. We contribute to improving the quality of political and administrative decision-making by conducting outlook studies, analyses and evaluations in which an integrated approach is considered paramount. Policy relevance is the prime concern in all our studies. We conduct solicited and unsolicited research that is both independent and scientifically sound.

Office Bilthoven
PO Box 303
3720 AH Bilthoven
The Netherlands
Telephone: +31 (0) 30 274 274 5
Fax: +31 (0) 30 274 44 79

Office The Hague
PO Box 30314
2500 GH The Hague
The Netherlands
Telephone: +31 (0) 70 328 8700
Fax: +31 (0) 70 328 8799

E-mail: info@pbl.nl
Website: www.pbl.nl/en

Abstract

Electric driving; an attractive challenge

Over the past years, electric driving has become more and more attractive because of the development of better batteries. Driving electric vehicles could drastically reduce CO_2 emissions, especially if more electricity would be generated by using sustainable energy. As most passenger cars are not used at night, this is the ideal time for charging their batteries. This would be cost-effective because, at that time, there is a surplus of generating capacity, and wind energy could also be used more effectively. Moreover, consumers will be able to drive clean and quiet vehicles at costs that seem surmountable in the future.

At least two obstacles still need to be overcome. The first of which is the current maximum range of electric vehicles of around a few hundred kilometres. Battery producers and universities are working hard on the development of batteries that could be charged within 5 to 10 minutes at EV fast-charge stations. This limited range would not be a drawback for the so-called plug-in hybrid electric vehicles (PHEVs), which can run on both fossil fuel and electric power, and are expected to come onto the market in the near future. However, these plug-in hybrids reduce less CO_2 and carry slightly higher costs. The second obstacle is the need for a standardised European network of charging stations, and electrical outlets near residences and at commercial and public parking facilities.

This report shows the challenges facing the government and the business community of utilising the benefits of electric driving and of overcoming the obstacles.

Key words: electric vehicle; plug-in hybrid; transport; transition; battery

Contents

Summary

Electric vehicles combined with electricity production based on renewable sources and clean fossil fuel, potentially, could reduce CO_2 emissions from passenger cars and other light-duty vehicles by 80 to 90%, in the long term. Electric transport would also substantially reduce traffic noise within cities. Costs do not appear to become an issue, as batteries are expected to become substantially cheaper. With respect to user friendliness, the most important short-term disadvantages of electric vehicles are their limited ranges, the lack of available recharging points, and battery charging times.

Despite any improvements that still could be made to vehicles' current propulsion systems, it is unlikely that these will enable the transport sector to achieve its long-term greenhouse gas reduction targets. Achieving these targets would require large-scale transition towards alternative fuels and advanced vehicle technology. Apart from electrically propelled vehicles, alternatives also include fuel-cell vehicles and the use of biofuels, all of which have both advantages and disadvantages. Fuel-cell vehicles on hydrogen would require a complex hydrogen infrastructure, and the fuel cell itself would need to become a good deal more affordable for it to compete successfully with conventional vehicles. Moreover, the costs of the necessary steps for such an energy conversion, cause the performance of this alternative to be low. For biofuels, the disadvantage would be the large areas of land required to grow biofuel crops, creating possible conflict with food crops and biodiversity. This causes the availability of biomass to be limited. Other reports have been published on both of these alternatives; this report looks specifically at the option of the electric driving system.

The advantages: clean, quiet, and less dependent on oil and gas

Electric driving is no obvious choice for heavy freight traffic. For private vehicles and other light-duty transport, however, it is considered a viable option; in the long term (around the second half of this century), looking at the characteristics of average car use, up to 90% of all kilometres driven could be electric. Per kilometre, the emission could even be nil, depending on the future technology of energy production per kilowatt hour. Renewable sources and clean fossil fuels would enable very low emission levels; with costs of production and transport, by 2050, roughly estimated only 2 or 3 euro cents per kWh more than today. Like fuel-cell vehicles, electric driving would also create advantages for the quality of the city living environment. Air pollution could be brought down even further than with future clean conventional cars or hybrids, and noise pollution within cities – especially from acceleration – could decrease. Electric driving could also be an alternative for mopeds, scooters and motorcycles, which cause major noise annoyance (around 20% from scooters) to over 10% of city populations. Moreover, electric-vehicle users, themselves, could also enjoy the quieter mode of transport.

Another advantage would be a decreasing dependence on oil and gas. Independence from the latter has to do with the charging systems, and requires some explaining. Electric driving could cause an increase in the demand for electricity; around 10% on a national scale, and up to 50% or more in urban areas. In our present situation, electricity supply during the night outweighs demand, and this would be the time during which most batteries of electric vehicles would require charging. In an ideal situation, cars (which are not used for up to 23 hours a day) would be plugged into the grid, as much as possible. This would create a better balance between supply and demand, with both a central and local management system, monitoring network capacity, user's individual wishes regarding the fuel price, and when they would need a fully charged battery. Automated management systems would be able to make better use of wind energy, with its fluctuating level of supply, thus, decreasing the dependency on gas power stations which are currently being used for enlarging flexibility in energy supply.

The disadvantages: less flexible in use

The disadvantages of electric driving have to do with the limited range of electric vehicles and practical problems around charging. The energy density of batteries is such, that a sizeable and expensive battery system (the aim is for 1 kg/km) would be needed to achieve a range of a few hundred kilometres, and it takes several hours to recharge. Although most daily distances could be driven on one fully charged battery, the need to recharge would be a handicap for longer trips. Solutions are being sought for solving this problem, and a workable alternative will become commercially available in the short term: the so-called plug-in hybrid. This vehicle could, for example, drive electrically for 50 kilometres, after which a switch is made to conventional fuel combustion. In this way, a CO_2 emission reduction of over 50% is achieved. However, these two propulsion systems make this type of vehicle relatively expensive. Other solutions could be found by expanding the options for sharing or renting vehicles for longer journeys. Currently, a system is being developed for fast-charging electric vehicles at specific charging stations. Technically, today's batteries could not cope with such a

system, however, the industry and researchers are aiming for charging times of five to ten minutes. In addition, developers are also working on battery-swapping stations where flat batteries could be swapped for fully charged ones, within minutes. However, this would require standardisation, and it would limit car manufacturers' options for fitting a sizeable battery packet into the vehicle where it would take up the least possible room.

The price tag in the long term: dependent on user-friendliness

The costs of electric driving are expected to be lower than those of conventional or hybrid vehicles, by between 2020 and 2040 – even if there would be no difference in taxation per kilometre. It is the battery price that largely determines the price of electric vehicles. According to the literature, battery prices could drop to between 150 and 300 euros per kWh storage capacity, on the assumption that, in the future, there will be enough lithium available – an important element in the most promising types of batteries. As increased battery capacity would mean an increased range, this would make electric driving not only more user-friendly, but also more expensive. The same applies to plug-in hybrids. However, once fast charging at acceptable prices in under five minutes becomes a reality, with a system that is available throughout Europe, not much will stop electric driving.

Short-term barriers: the charging facilities

Looking at production costs and fuel prices, electric driving in the next ten years could be expected to become more expensive than driving conventional vehicles. However, from a consumer point of view, this is not necessarily true; taxation on fuel is higher than on electricity. Moreover, several policy instruments also apply to electric vehicles: no tax on private vehicles and motorcycles, and no VRT (Vehicle Registration Tax) or road tax. Therefore, the costs to consumers are about the same as for driving conventional vehicles (at a petrol price of 1.60 euros per litre). In addition, certain companies are developing a system for leasing batteries, which removes the investment barrier, and places certain battery lifespan risks elsewhere (for there is no vehicle at the moment that drives around for fifteen years with the same battery). However, one of the conditions would have to be that consumers can recharge their batteries at home, as well as at various other locations. Today, less than half of all vehicles are being parked at or near peoples homes; if motorists have no guarantee that they can either charge their cars near their homes, near their workplace or elsewhere convenient, than this could become a major barrier to electric-vehicle sales.

European policy impulses are aimed at the automotive industry

The barriers for consumers also largely determine the choices made by the automotive industry to market electric vehicles. European regulation provides few impulses; although electric vehicles could help to achieve the expected CO_2 standards and the 10% target for renewable energy in transport, they are not essential for achieving this. Without specific rules and regulations on the subject, the industry will be less motivated to develop and manufacture electric vehicles. The design of battery lease plans will cause vehicle manufacturers, battery manufacturers, electricity companies and the companies that supply the charging facilities to enter into certain agreements. For consumers, leasing these batteries would require specific attention to how the risks are covered regarding lifespan of the batteries, a situation for which there is no practical experience to draw on.

1 Introduction

1.1 Progress of transition

In 2001, the fourth National Environmental Policy Plan (NMP4: VROM, 2001) gave a policy impulse towards changing systems, in the long term, to overcome persisting, environmental problems. The policy plan also instigated various policy actions, which have shaped the term transition management within the context of sustainable development. In 2005, an interdepartmental directorate for energy transition was set up, enabling an improved management of the transition process across the various government departments. In consultation with all the ministries involved, the Netherlands Environmental Assessment Agency published a first evaluation in 2006, of the progress of the transition process, and of the role of policy, based on an analysis of six system options. In addition, in 2008, a report was published on solar energy in domestic housing.

The seven system options and the summarising reports are:
- Liquid biofuels (Ros and Montfoort, 2006);
- 'Green' services in agriculture (Reudink *et al.*, 2006);
- 'Green' bio-feedstocks (Van den Born and Ros, 2006);
- Fish feed for aquaculture (Rood *et al.*, 2006);
- Fuel-cell vehicles on hydrogen derived from concentrating solar power (Nagelhout and Ros, 2006);
- Micro co-generation and the virtual power station (Elzenga *et al.*, 2006);
- Transition processes in connection with the role of policy (Ros *et al.*, 2006b);
- Solar energy in the living environment (Montfoort and Ros, 2008).

In this report, we present an analysis of eight system options built around electric driving.

The development of a better system for the long term, has received extra attention through the fourth National Environmental Policy Plan (NMP4), but the NMP4 was not the start of it. Numerous research programmes were already underway, and there were many ideas on new institutional design, as well as many policies influencing them, directly or indirectly. Looking at developments of the last years would be pointless without considering this context. Moreover, there are many relevant international developments. Therefore, starting point for the evaluations was the actual progress of these processes. This included an indication of the incentives presented by Dutch policy, and their effectiveness. In their pre-developmental phase, transitions are target-seeking processes.

Without any clear targets, it is hard to determine what should be monitored and evaluated. We searched for an approach in which the evaluation could be narrowed down to concrete elements in the transition process. This led to a choice of system options as a starting point for determining any progress. A system option shows how part of a future system could look; it forms a potential target. The evaluation focuses on the process of realising a particular system option, and on the conditions required to cash in on its potential. This gives the evaluation a somewhat *backcasting* character. In the formulation of end conclusions, one has to consider that alternatives – supplementary or competitive – within the broad transition process, are also being developed.

This report focuses on three elements:
- an estimation of the potential of the new technological system – that is, the highest achievable application, within reason, for the long term (around 2050);
- an assessment of the effects of the implementation of the system option, compared to those of the existing, fully developed, system;
- an analysis of the current process of realising the system option, and the role of policy within this process.

1.2 The system option of electric driving

This report describes the system option of electric driving, and evaluates the activities and policy around it. Electric driving, in this report, encompasses not only the all-electric vehicle, but also the plug-in hybrid. The latter charges its battery from the power grid, with which then tens of kilometres could be driven before an internal combustion engine would take over. Hybrid vehicles that are currently on the road – which have a battery supporting the internal combustion engine – are only mentioned indirectly. The same applies to the fuel-cell vehicle which was discussed in an earlier publication (Nagelhout en Ros, 2006). Our current report describes not only the developments of the vehicle, but also the set up of the entire system around it. The data in this report were based on literature research and interviews with actors who were working on batteries, electric vehicles and the power grid.

1.3 Work method and reader

For this report, the evaluation method for transitions were used, together with the indicated building blocks, as set up by the Netherlands Environmental Assessment Agency (Ros *et al.,* 2006a; Ros *et al.,* 2009).

First, it is important to have a description and, especially, a definition of the regarded system option, which together form the picture of the possible future, provided in Chapter 2. This entails the coherent combination of techniques, processes, institutions and structures. The attitudes of the various actors are partly determined by the potential and possible effects of the system option. Therefore, Chapter 3 focuses on the highest achievable application, within reason, and its effects, especially on CO_2, local air pollution, safety, noise, feedstock supplies, and costs.

Evaluations of environmental policy are mostly based on monitoring of emissions, environmental quality, and where possible, the effects on nature and human health. However, in the case of running transitional processes, the intended changes in these areas are achieved only in the long term. Therefore, policy should focus, first, on the pre-development of such a process of change, in which the following activities are assumed:

- the development of a sense of urgency, based on the perception of the problem;
- the development of a joint vision for the future;
- researching and developing new technologies and institutions;
- carrying out practical experiments for parts of the new system, or for the set up of certain niches.

Chapter 4 lists the actual developments in the pre-development phase of the transition over the past years. It states the activities in this area and the corresponding policy actions, and discusses the coherence between the developments. Special attention is given to the correspondence between the cycle of ‘creating vision⍰Research & Development⍰experiments’, aimed at the long term, and the cycle of ‘action orientation⍰creation of markets and niches’, which is aimed at the short term.

Chapter 5 discusses the degree of motivation that is generated by the activities in the pre-development phase and by government policy, and whether these fulfil the needed preconditions for implementation of the actual system change. To research this, crucial actions were identified which could lead to investments in production capacity. Subsequently, all factors were combined in a force field analysis. Chapter 6 contains conclusions on the possible effects, the progress, and the influence of Dutch policy.

The appendix presents a list of the people who were interviewed for this study. We appreciate them providing their time and expertise.

2

Description of the system option: outlining the future

2.1 Short outline of the basic idea

This chapter provides a look into the future. What could a system of electric driving look like, around 2050? The exact year is unimportant, it just needs to be far enough into the future so that a substantial system innovation would seem possible, without it being too far away, becoming more like science fiction. We have not attempted to provide a detailed blue print of the future system, because there simply would be too many possible variations on such an optimised system. It is an outline, indicating the many things involved in a possible realisation of the system.

Contrary to conventional vehicles, which have internal combustion engines running on petrol, diesel or gas, electric vehicles operate electric motors which run on electricity provided by a battery. Electric vehicles have the advantage of causing considerably less stress on the local environment, and of being more energy efficient than vehicles with internal combustion engines. That makes this system option interesting – even without considering how the electricity would be generated. This system option assumes that, in the long term (by around 2050), an important number of today's conventional vehicle drivers, will be driving all-electric vehicles. Another part of the motoring population is expected to be driving plug-in hybrids, vehicles which drive part of the journey on electricity. Local freight traffic would mostly be covered by electric vehicles such as vans and small trucks, quietly and cleanly driving around town. This study did not consider heavy freight trucks, as these are thought to be less suitable for driving on batteries, because of the weight and size of the required battery.

This system option also includes the charging system used by motorists, and the anticipation of possibilities of future electricity supply. For instance, batteries could be recharged mostly during the night, using the overcapacity in electricity generated by wind turbines. Another possibility would be a link with locally generated electricity (solar PV), or to have solar energy from the Sahara Desert transported through a *High-Voltage Direct Current* (HVDC) system. In addition, there would be fast-charging points/battery swapping stations, especially along motorways, charging facilities near public car parks, and near domestic parking areas reserved for motorists without a garage or other charging option at their homes.

Electric vehicles appear to be most suited for short and medium-range distances, because of the weight and purchasing price of the batteries. Assuming that users will travel longer distances, too, means that any future system would need to include either fast-charging and battery-swapping facilities, or offer an easily accessible, readily available, pool of rental or shared vehicles, for instance, based on hybrid technology. Advantages to the local living environment, of electric vehicles of all variants between bicycles and cars, could lead to a relatively large accessibility of inner cities for electric traffic.

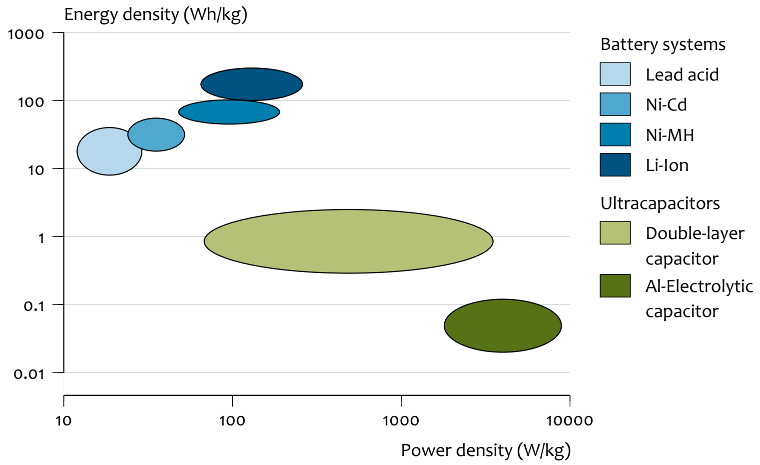
2.2 Changes in the structure of production

The automotive industry is characterised by a limited number of factories that produce the vehicles, and a large number of companies that supply them – some of which in alliances with the vehicle manufacturers. However, parts which are needed for conventional vehicles, such as combustion engines, petrol tanks, exhaust systems, catalysts, starting motors, and transmissions, are all not needed in electric vehicles. Instead, they need electric motors, chargers, and of course batteries for the power supply to the vehicle. In short, this means that the structure of the production in and around the automotive industry would need to change. Moreover, besides the existing infrastructure for the distribution of liquid or gaseous fuels, there would also be a need for coupling facilities for connecting vehicles to the grid. Furthermore, additional electricity would have to be produced, and that in a clean manner, to prevent transferring part of the emissions elsewhere.

2.2.1 The passenger car

For a proper understanding of the subject, a few words on the passenger car are necessary. The hybrid vehicle which entered the market over ten years ago ('Prius'), and for which sales figures are currently growing, has a battery that is charged through the combustion engine. This battery

Characteristics of some battery systems and ultracapacitors **Figure 2.1**



enables the vehicle to use fuel in the most efficient way. Also, because of the battery application, the vehicle's motor can be lighter (more economical). However, this hybrid can only run on electricity for a few kilometres. There are also certain hybrids – already on the market, and in development – with only one particular feature, such as a stop-start system that saves energy by turning off the motor when the vehicle is stationary, or regenerative braking, a system through which electricity is fed back into the battery.

The plug-in hybrid, however, is much more advanced. It has a large battery which is charged from the power grid. Depending on the size of its battery and some other aspects, this vehicle can drive tens of kilometres on electric power, and then switch to fossil fuel. It is also possible to use part of the remaining battery capacity in the same efficient way as regular hybrid vehicles do. Plug-in hybrids also come in several types; there are vehicles with two complete propulsion systems, and hybrids with a small, constantly running combustion engine that, when required, functions as a generator supplying electricity to the battery and the electric motor that drives the vehicle (the *extended range electric vehicle*, such as the future Chevrolet Volt). Another future option could be an electric hybrid with not only a battery, but also a fuel cell and a hydrogen tank.

An all-electric vehicle only has a battery and one or more electric motors, and relies fully on electricity from the power point. A comprehensive overview is provided by Passier *et al.*, 2008.

2.2.2 The battery

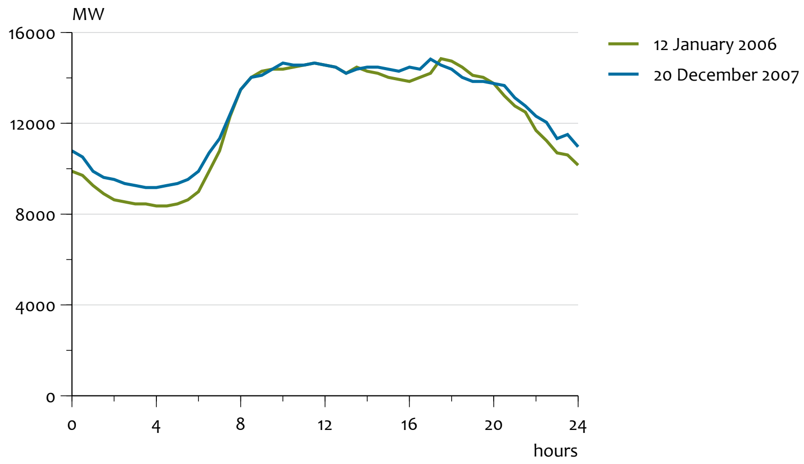
The success of electric driving depends on the improvement of the battery, because this determines the price and user-friendliness of the vehicle. As early as around 1900, there were vehicles on the road that were partly or fully driven by electricity. Their demise was caused by a range and top speed that were too low (and they made too little noise!).

A battery consists of one or more cells; a cell is formed by two different electrodes – an anode and a cathode – electrolyte and a separator in the electrolyte. This chemically stores the energy. The combination of anode, cathode and electrolyte varies per battery type. Batteries are often named for their main combination of chemical elements, such as lead, nickel, cadmium, cobalt, hydrogen and lithium. Batteries have to meet various requirements; the ideal battery has a high energy density (low weight and small size), can deliver a lot of power, be charged quickly, has a long lifespan, and is safe and cheap. The importance of the various requirement depends on the intended use of the battery. For hybrid vehicles, the emphasis is on delivering a (short) strong burst of power. For electric vehicles or plug-in hybrids, the energy density is of major importance (the amount of energy that can be stored per kg).

The balance between energy density and power density can vary slightly, through the choice of cell size and the set up of the total battery system. Figure 2.1 shows the characteristics of a number of battery types (Mulder and Wagemaker, 2008).

Currently, hybrid vehicles use NiMH (nickel metal hydride) batteries (H ions flow between anode and cathode), and the market is expanding. For the coming decades, batteries containing lithium (Li-ion batteries) are generally seen as the most promising choice for electric driving. The current Li-ion battery has a much higher energy density than the NiMH battery. However, Li-ion batteries are susceptible to overcharging; to expand its lifespan, a battery management system is required, which constantly monitors the condition of the cells (Notten, 2006). There are several other battery types containing lithium, such as the *Li-ion polymer* battery, which is flexible and even lighter than the Li-ion battery; and the *lithium iron phosphate* ($LiFePO_4$) battery, which is cheaper than the conventional Li-ion battery, but also has a lower energy density. The latter has a longer lifespan, because the $LiFePO_4$ is more stable than other electro materials. This enables frequent charging and discharging of the battery. The average lifespan of a passenger car is fifteen years, and, ideally, this should also apply to its battery – especially seeing the current and future battery prices. A battery which delivers the energy for 250 kilometres of driving per charging cycle, with a lifespan of 2000 charging cycles, would enable 500,000 kilometres of travel. A speculative option for used batteries, once they loose too much of their charging capacity to be used in vehicles, would be to use them for electricity storage.

Load curve of the power grid in the Netherlands (TenneT) **Figure 2.2**



For new generation Li-ion batteries, there is the important aspect of their improved safety, which has removed the major bottleneck of their previous inflammability.

Apart from the battery, which chemically stores energy, there is also the so-called *ultracapacitor* (or *electrochemical double layer capacitor*) for physical storage of electricity. It has a relatively low energy density, which makes this technology less suitable for storage in vehicles. The advantage of ultracapacitors, however, is that they can be fast-charged and can release their power quickly, which could enhance a system's performance.

2.2.3 The electricity supply

For the Netherlands, the electricity demand of all mostly electric vehicles, in the future, could go up to between 10 and 15 TWh per year, or 10% of the total electricity demand. This means not only that the supply of electricity will have to be attuned to this demand, but also that this offers opportunities for improving the balance between supply and demand. In winter, the greatest demand for electricity is during the daytime and early evening, see Figure 2.2 (TenneT, 2008).

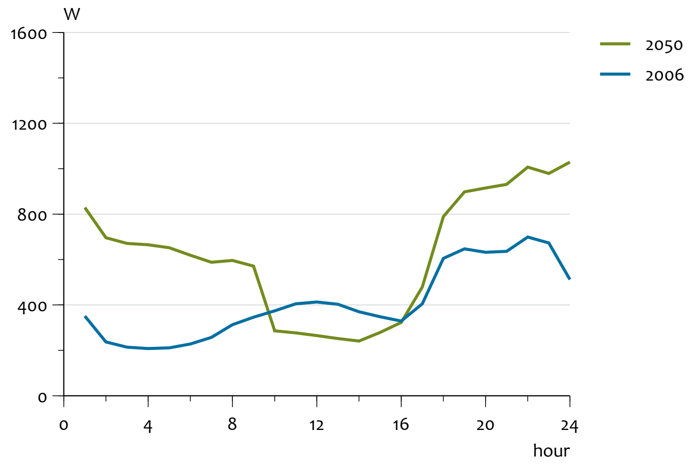
If, in a manner of speaking, everyone would purchase an electric vehicle tomorrow and charge it only during the night, a large part of the needed electricity could be supplied by the existing installations. For there is a large difference between the demand during the day and during the night, the so-called peak hours and off-peak hours. However, the low-voltage network is not geared to situations of everyone charging a battery at the same time. Using several scenarios, KEMA (electrical safety testing and certification company) estimated the daytime and nighttime electrical activities of the average household, in a few suburban districts, differentiating between summer and winter. Activities ranged from the use of air conditioning, heat pumps, micro cogeneration, to solar energy, but also to upcoming electric driving activities (De Boer and In 't Groen, 2009). Figure 2.3 shows an example of these calculations, indicating the current daytime electricity use for an average household, in an average suburb, compared to their expected use by 2050. In this comparison, a future penetration is assumed of 50% for heat pumps, 10% for air conditioning, and 40% for electric vehicle use (being 60 to 75% of all households). In this figure, it is assumed that electric vehicles are being charged between 23:00 hrs and 05:00 hrs. By 2050, in this example, nearly 40% of the suburban electricity demand would be spent on electric driving.

If, in today's suburban areas, nighttime charging would be managed to spread charging over time, the low-voltage network would be able to cope, in the medium term. This would require an automated central management system. However, by 2050, when every vehicle requires charging, extra investments would be needed. This moment of extra investment could be delayed by offering attractive options, such as charging points in car parks, so that vehicles can remain plugged into the grid anytime they are not driving. Building a new, low-voltage network in an existing urban area is very expensive. This is different for new urban areas, where such facilities could be built in from the start.

At night, relatively cheap coal and nuclear power stations currently cover basic power needs. During the daytime, more expensive, gas-fired power stations chip in. In the near future, much capacity will be added in the form of wind energy; wind turbines also work at night, when demand is low. Wind energy could be used more efficiently, if electric vehicles were charged during the night. Moreover, for electricity companies, electric driving also offers the advantage of being manageable. For balancing supply and demand, this means that the dependence on gas-fired power stations could decrease. Electricity companies could communicate with their customers through a specific communications system, to come to an agreement on the specific time whereby a vehicle would need to be recharged to a certain capacity, and at which price (Postma, 2008a and 2008b; Better Place, 2008; Lowenthal, 2008). Also, for plug-in hybrids, deals could be made, for instance, about not fully recharging when the station's capacity is low or when the price is too high; in which case the vehicle's combustion engine would be used more (Kintner-Meyer *et al.*, 2007).

And then there is the option for charged batteries to supply electricity to the grid at peak hours during the daytime (*vehicle to grid*), or the even cheaper alternative of using surplus energy in the home. Opinions vary on whether this would be

Average electricity demand per household **Figure 2.3**



a viable option, because of the home adjustments that would need to be made.

Charging options are various; around 30% of Dutch citizens have a garage (though not often used for parking vehicles), or carport, and some motorists can park their vehicle on private property. Apart from these options, a network of charging points would be required: along streets, in car parks, and at the workplace. In the long term, current filling stations would convert to offering electricity from fast-charging points.

Table 2.1 provides an overview of the charging options, the conditions, and the advantages and disadvantages.

General conditions would consist of standardisation and a solid *privacy-proof* gauging and payment system.

2.3 Adjustments to mobility behaviour

Batteries take up space within vehicles. However, it is assumed that, in the future, the space available to passengers and luggage will remain at today's level, because batteries (flexible in shape) can be positioned anywhere in the vehicle, and – in all-electric vehicles – some conventional motor parts will be left out. Limitations could only arise if robotic battery-swapping systems were used. The vehicle would still be as reliable as it is today, the comfort would be enhanced by the quiet motor, the acceleration would be faster than that of vehicles using petrol, and the safety of the battery would be no different from that of the current ones used in conventional petrol systems.

The electric vehicle would be attractive to consumers if, just like today, there is sufficient choice between small and large vehicles. Looking at the pricing of the batteries, it seems likely that consumers will be able to choose between vehicles which have either short or long ranges, or which perhaps are customised. Electric driving could be fitted in various ways, to meet people's mobility behaviour. As ranges of at least 300 kilometres would need to be covered, and the battery packs that meet this demand will remain expensive, it is reasonable to assume that – for longer (business) trips and holidays – fast-charging options will be a practical option (most sources speak of five to ten minutes per charge, which is a little slower than conventional fuel fill-ups). Research has shown that many people want to arrive at their destinations as quickly as possible, and that they ignore the advice to take two-hourly breaks (Belvilla, 2008). On this point, therefore, users of all-electric vehicles could feel limited.

Instead of owning long-range vehicles, a suitable alternative could be an advanced and easy-to-use system of renting or sharing such vehicles (hybrids or plug-in hybrids). Having to get used to another vehicle, could be a disadvantage of such a system; however, an advantage would be that, even into the far and distant future, batteries could be recharged anywhere. It is possible to tow a caravan or trailer with an electric vehicle (using a high torsion bar), if the electric motor was designed to prevent overheating. It would, of course, shorten its range, but this also applies to vehicles that operate combustion engines, and there are other transport options to use, such as bording a car train.

In 2050, just like today, the choice of vehicle will depend on several things: family composition, income, vehicle price, commuting distance, local amenities, and required space within the vehicle (for extra passengers, holidays or transporting goods). When households use two or more vehicles, it stands to reason that one of them is electric. For single households or one-car households, the choice for an electric vehicle seems less certain, as they would also, occasionally, wish to travel longer distances.

Table 2.2 provides an overview of the main options.

According to CBS (*Statistics Netherlands*), the Netherlands has 5.3 million commuters per day, covering an average distance of 17 kilometres. Of these commuters, 2.8 million travel by car, over an average distance of 22 kilometres (one-way trip) (CBS, Statline). Please note that these are averages; the apportionment is unknown. Worldwide, most commuter trips appear to stay under 50 kilometres, as do a large parts of daily trips (Kendall, 2008). Vehicles are also used for study travel, business, shopping, visits, and holidays. The usual pattern is that of occasional longer trips, combined with mostly short trips,

Charging options in a future system — Table 2.1

Charging principle	Conditions	Advantages and disadvantages
Power point at home	Own garage, or carport, or parking space on private property	Possible at night
Charging point in suburb	Right to a parking space with charging point close to home; Suited to low-voltage network; Vandal-proof	Possible at night
Charging point in car parks, also at the workplace		Decreases the needed range; Mostly during the daytime
Fast-charging points at charging stations	Specific facilities for high energy density	Relative short recharging times; Possible en route; Mostly during the daytime; Fast charging produces much heat, which is bad for the battery; Cooling advisable
Changing battery packs at swapping stations	Charging capacity at swapping stations; Standardised packs and standard fitting in vehicles, needed for robotic swapping method; Robotic system for swapping, storage and recharging	Recharging takes a relatively short time; Storage and charging takes up much space; Decreases space in smaller vehicles that use small batteries
Charging lanes along roads	System for safe coupling of vehicles to charging cables	Charging en route saves time (benefit dependent on actual charging speed); (too?) high investments

Some options for private use of electric vehicles — Table 2.2

<table>
<tr><th>Situation</th><th>Short distances</th><th>Medium-range distances</th><th>Long distances</th></tr>
<tr><td rowspan="5">Households: two vehicles</td><td>Small electric vehicle</td><td colspan="2">Plug-in hybrid</td></tr>
<tr><td>Small electric vehicle</td><td colspan="2">Hybrid</td></tr>
<tr><td colspan="2">Large electric vehicle</td><td>Hybrid</td></tr>
<tr><td colspan="2">Plug-in hybrid</td><td>Hybrid</td></tr>
<tr><td colspan="3">Two plug-in hybrids (possibly with different ranges)</td></tr>
<tr><td rowspan="3">Households: one vehicle</td><td>Small electric vehicle</td><td colspan="2">Sharing or renting system, or public transport</td></tr>
<tr><td colspan="2">Large electric vehicle</td><td>Sharing or renting system, or public transport</td></tr>
<tr><td colspan="3">Plug-in hybrid</td></tr>
</table>

including on weekends (CBS, Statline). It is thought that more than 99% of passenger cars cover less than 300 kilometres per day (Goodspeed, 2009).

Electric driving is especially suited to short-distance travel, such as within cities. This travel does not have to be by car; methods of transport change constantly – think of the options that already exist, such as electric bicycles, Segways and scooters.

2.4 Institutional changes

This system option requires some technological and institutional changes. Some of these changes are highlighted below.

- Much in the way of batteries is still under development. Grid management requires a certain amount of standardisation, essential to the charging of batteries. In the future, charging a battery (fast or not) and paying for the amount of electricity should become possible throughout Europe, which requires a standardised system.
- With the introduction of electric driving and nightly charging, power companies will have less overcapacity during the night (and summer), which will lead to different work routines (e.g., maintenance schedules).
- Ultimately, taxation imposed on traffic participation is expected to be the same for everyone; if revenues from fuel taxes decrease, this could lead to higher electricity prices for motorists (and not for households without electric vehicles).
- Vehicle manufacturers, garages, and emergency services, all will have to adjust their areas of expertise; working on an electric vehicle requires other and extra skills in the field of electronics. This would not only apply to vehicle-repair shops, but also to ambulance workers, the police and fire brigade.
- Garages would work less on all-electric vehicles as these have less wear and tear on parts and, therefore, require less maintenance and repair.
- For owners of small electric vehicles who infrequently need a larger vehicle, existing rental systems would have to be expanded. This also applies to vehicle-sharing systems.
- The current battery recycle system would also need to expand to include Li-ion car batteries.

2.5 Spatial planning

Within cities, there would be fewer fast-charge station than there are now filling stations, because recharging would be done mainly at home, during the night. As not everyone has private parking next to their home, other charging facilities would have to be set up, such as along streets or in car parks, with safe and vandal-proof systems. The charging stations along motorways would need to be larger than they are now (charging a battery takes more time than filling up with petrol), and for battery-swapping stations, this need is even greater. Another aspect would be that, within urban environments, from a safety point of view and compared to conventional petrol stations, charging stations probably would be easier to build. Vehicles could also be recharged in car parks at people's workplace or in public car parks. To improve the quality of the environment, electric vehicles could receive preferential treatment regarding access to the inner city (easy access to parking facilities, such as in London and Oslo). Such preferential treatment, however, would only be needed in the transitionary phase; at full implementation of electric driving this would no longer be necessary.

2.6 Important actors

Several parties will be involved in the realisation of the system option. For some, their positions will be strengthened, while others will experience a weakening or will have to change their role. And then there are parties specifically needed to achieve the transition. A brief impression:

- The automotive industry will need to make adjustments; first to one model, later to more. Running investments, such as in conventional combustion engines, may need to be written off sooner than expected. Opportunities will arise for new participants from the world of electronics.
- Battery manufacturers will experience a fast growing market.
- Power companies and grid managers can also expect an expansion in their field of work.
- IT companies will supply knowledge, needed to manage electricity supply and data communications.
- Garages will do less of their current work, and do another type of work.
- For universities, often in collaboration with commercial companies, there is much fundamental and applied research to be done.
- Oil companies will lose part of their market share.
- District councils will facilitate the realisation of charging points.
- Consumers have to start purchasing.
- Central government can ease the transitional process by removing obstacles.

The following chapters will elaborate on most of these actors.

2.7 Relation with other researched system options

Electric driving is one of the alternatives to current – fossil fuel driven – vehicles, for achieving substantially cleaner modes of transport. In addition, there is also the use of biofuels and fuel-cell vehicles on hydrogen. These modes of transport can be partly supplementary and partly competitive. The related system options are given in the overview in Section 1.1. For local electricity generation (solar PV or micro cogeneration), the unused electricity could be stored in batteries, instead of fed back into the grid. Another report on local energy systems is due to be published (Faber en Ros, 2009).

Judging potential effects of this system option

3

A system option becomes more interesting if it harbours solutions to large, social problems. However, changes at system level can be so far-reaching, that any possible effects could only be judged by using a wide approach. Therefore, this chapter starts with a general, qualitative discussion, using an assessment scheme that was taken from the sustainability matrix (VROM/NSDO, 2002), before carrying out a qualitative analysis on certain specific issues. To judge something as being 'better' or 'worse', a reference is needed – in this case, we took the system currently dominating road transport: that of the combustion engine running on fossil fuels. We also took into account a future, further improvement of existing vehicles on petrol and diesel. The aspects of safety, noise, climate effects, air pollution, costs, and raw materials, will be discussed in separate sections.

3.1 Safety

Without specific built-in modifications, electric driving would create diminished road safety for cyclists, pedestrians, the blind, and children, because these road users rely partly on sound as a warning system of approaching traffic. They would hear the approach of quieter electric vehicles at a much later stage. According to the *Gezondheidsraad* (the Dutch Health Council), however, this problem would not eventuate, as there are indications that 'when road-traffic changes occur, the risk of accidents goes down, at least temporarily'. (Gezondheidsraad, 2008). Nevertheless, research has shown that quieter trams and the use of mp3 players both lead to a slight increase in road accidents (Stoop, 2008). Moreover, practical research by Mitsubishi in cooperation with *TNT post* also indicated that lack of noise leads to dangerous situations. There are suggestions for installing small loudspeakers on the exterior of electrical vehicles, producing a swishing sound or other identifiable sound (such as ringtones of mobile

Electric driving sustainability test **Table 3.1**

	Social		Economical		Ecological	
The Netherlands	Noise	better	Energy security[1]	better	Local air pollution	slightly better
	Safety	neutral		slightly better–better	Acidification	slightly better
	Landscape[3]	neutral		neutral		
	User-friendliness	slightly worse	GDP[2]			
	Purchasing power	neutral				
Elsewhere	Food security	neutral–slightly better	Natural resources	slightly better	Land use[4]	neutral–slightly better
					Nature value/biodiversity	slightly better–better
					Climate effects	better

Legend: worse (red) · slightly worse (yellow) · neutral (grey) · slightly better (light green) · better (dark green)

[1] Security of supply has increased by a decreasing dependence on oil. After all, electricity can be generated from various sources. The dependence on gas in electricity production is also decreasing, as gas is specifically used for additional generation of electricity when demand peaks, and these peaks in demand are expected to level off. Another aspect of security of supply is the risk of power failure – which is not such a hot item in the Netherlands – and is less acute because of the possibility of storing electricity in batteries (V2G).
[2] Refineries are becoming less important. Batteries will probably be manufactured mostly in the Far East, but there are opportunities for the Dutch automotive industry to manufacture parts for electric vehicles (analogous to CENEX-ARUP, 2008), as is also the case in the current automotive industry.
[3] At night, much electricity could be supplied through the existing power grid. Once electric driving would be fully implemented, an expansion of the grid could possibly be needed, with accompanying adverse effects on landscape. However, it is assumed that much of the future demand for electricity will be generated locally, so that an expansion of the grid might not be necessary.
[4] A large application of electric driving could cause a decrease in the use of biofuels. Applying biomass in electricity generation would be much more efficient as it would lead to decreased land use (less biomass per kilometre).

phones). However, emitting a less-than-modest sound would create a trade-off with the subject of the following section.

As indicated earlier, it is assumed that another potential safety aspect – the inflammability of certain Li-ion batteries – could be solved by technical management measures and inherently safer combinations of materials. In addition, emergency services are also expected to know how to handle electric vehicles.

3.2 Noise

Surveys show that road traffic is the most important source of serious noise nuisance. The number of people affected has remained constant over the period from 1993 to 2003. Scooters cause most of the noise (19%), followed by motorcycles (11%), and trucks (10%). With only 6%, passenger cars score below nuisance from neighbours or neighbourhood activities. The percentage of people affected by noise nuisance from passenger cars has decreased (Franssen *et al.,* 2004). Depending on noise level and duration, noise nuisance can lead to sleep disturbance, bad school results, high blood pressure, and cardiovascular disease (Berglund *et al.,* 1999). In the Netherlands, an assumed 12 percent of the adult population is believed to suffer from serious sleep disturbance caused by road-traffic noise. Up to 270,000 people suffer from high blood pressure caused by traffic noise (Knol and Staatsen, 2005), leading to cardiovascular disease. Please note that *traffic noise* is a broader category than *road-traffic noise*.

Measuring noise according to road type shows that 50 km/h zones score the highest (Franssen *et al.*, 2004). Noise from traffic is determined by the vehicle engine, its tyres and the road surface. For passenger cars, their tyres start to cause noise nuisance at speeds from 40 km/h; at lower speeds, it is the engines which cause noise nuisance, especially during acceleration and changing gears. A shift towards electric passenger cars and plug-in hybrids (when driving electrically), and especially also electric mopeds, scooters and motorcycles, could mean that noise nuisance within cities largely disappears. In addition, adverse health effects would decrease substantially, although noise nuisance from motorways would diminish only partly.

3.3 Energy and climate

With 25 Mt CO_2 eq/y, Dutch road traffic covered in this system option, currently adds around 12% to greenhouse gas emissions. Passenger cars currently on the road emit an average of 170 g CO_2/km. Although traffic is expected to increase further, the emission factor for conventional petrol and diesel vehicles is expected to drop. This could happen relatively soon, because of improvements to tyres, aerodynamics, lighting, material reductions and substitutions. In addition, changes could be made to engines, such as a large-scale introduction of variable valves, turbos, and compressors. All together, this could mean an average efficiency improvement for all vehicles, of over 30% (OECD/IEA, 2008a; King, 2007; Heywood, 2008). Since 2002, vehicles have become around 1.5% heavier, because of added safety precautions and increased comfort demands, and this trend is expected to continue at least up to 2012 (Smokers *et al.,* 2006). In addition, since 1998, Dutch motorists have scaled their class of vehicles up a notch (KiM, 2007), and it is unclear if this trend will continue. Such a development will greatly influence the total in CO_2 emissions, but in the comparison of vehicle types it is less important, as the development probably also would apply to electric vehicles and hybrids. A number of expected improvements, such as those in aerodynamics, tyres and lighting, will also apply to plug-in hybrids and electric vehicles. The hybrid, with a battery that is charged through its combustion engine which optimises fuel use, has an additional reduction in CO_2 emissions of around 15% (OECD/IEA, 2008a).

Please note that, by 2050, conventional oil will have been partly replaced by non-conventional oil from tar sands, and gas or coal. On a *well-to-wheel* basis, these fuels are over twice as carbon intensive as current fuels (OECD/IEA, 2008a). Greene estimated a market share of 10% in a reference scenario for 2030, and a share of 20% in a high oil-price scenario (OECD/ITF, 2007). In addition, the market share of biofuels may increase further.

Energy efficiency is higher in a system of electric driving, than in a system that uses petrol or diesel. Although the efficiency of a power station is less than that of a refinery, this is amply compensated by the electric motor's more efficient conversion to kinetic energy, compared to the combustion engine. This difference increases even further for processes of liquid fuel production (including biofuels) that require more energy, as is the case with feedstocks such as coal or biomass (Eickhout *et al.,* 2008).

The direct greenhouse gas emission factor for electric vehicles is nil. Any greenhouse gas emissions, across the entire chain, depend strongly on the efficiency of the battery, and on the CO_2 emission from the production of electricity needed for charging it. With current electricity production within the Netherlands, greenhouse gas emissions of less than 100 g CO_2 eq/km from electric vehicles are considerably lower than those from conventional vehicles.

What will electricity supply be like, around 2050? Although they are an important part of this system option, this report does not explicitly discuss the technological variants. Assuming that a global emission reduction of 25 to 60% is needed, compared to 1990 levels, for reaching climate targets (Van Vuuren *et al.,* 2006; OECD/IEA, 2008a), then an emission factor would be needed of certainly less than 100 g CO_2 eq/kWh. This could even go down to zero or be negative (by application of biomass and CO_2 storage), if measures in other sectors (such as transport) turn out relatively expensive, causing electricity production to be taken a step further. This could also be necessary, if the demand for electricity rises, substantially. In the case of stringent CO_2 reduction in electricity production, the emission per kilometre would end up to be 80 to 100% below that from the future, economical hybrid. For plug-in hybrids, CO_2 emissions depend on the distance that is driven on electricity, instead of on fossil fuel (part biofuel). Determinants are battery capacity, number of kilometres per trip or day, and charging frequency. It is assumed that around 60 to 70% of kilometres are driven electrically, with batteries that

Estimation of CO2 emissions from certain types of vehicles, now and in 2050

Table 3.2

		Electricity mix[1]		
		2050 NL	2004 NL	2005 EU15
Current conventional vehicle	170			
Conventional vehicle 2050	120[2]			
Hybrid 2050	95[2]			
Plug-in hybrid 2050		50[2]	90	85
Electric vehicle 2050		10	75	60

[1] Emission factor for electricity production (in CO_2 eq/kWh) in the Netherlands; in 2004, according to the Energy report of the Dutch Ministry of Economic Affairs: 468 (EZ, 2008); in 2005, in de EU15: 389 (De Visser *et al.*, 2006); and in 2050, based on assumptions used for creating Table 3.4
[2] Without taking into account the application of non-conventional, fossil fuels or biofuels

Estimation of CO_2 emissions from certain types of vehicles, now and in 2050, at the electricity mix of around 2005, and a possible future mix (in g CO_2/km).

Estimation of the maximum imaginable application of electric driving, around 2050

Table 3.3

Situation	Maximum % of vehicles	Maximum % of electrically driven kilometres
EV with range of < 100 km	30-50	20-40
EV with range of < 100 km, plus PHEV with range of < 50 km	30-50 supplemented to 100	50-70
EV with range of < 250 km	70-90	60-80
EV with fast-charging or swapping stations	95	90

Possible spread of an energy mix for electricity production between day and night, in 2050

Table 3.4

	Share (%) day	Share (%) night
Coal (largely with CCS)	26	29
Nuclear energy	20	25
Biomass (partly with CCS)	9	8
Wind	25	30
Solar	3	
Gas (largely with CCS)	12	3
Cogeneration gas (partly central)	5	5
Total	100	100

allow for 50 kilometre trips (OECD/IEA, 2008a; Kromer and Heywood, 2007).

What could be the share of electric vehicles in total road traffic of light vehicles? Table 3.3 provides some indication. The starting point was an estimation of the number of vehicles that currently travel less than 100 km/day and 250 km/day, and their share in the total kilometres driven. For plug-in hybrids, there would be no limitation on the number of vehicles – not even for holidays – just on the number of kilometres. When, occasionally, longer distances would be covered, we assumed the use of fast-charging stations or battery-swapping stations, or rental vehicles or sharing vehicles. This would concern only a small number of vehicles, but – relatively speaking – more kilometres. The increasing lifespan of vehicles was also taken into account.

A large demand for electricity to charge electric vehicles could change the balance between supply and demand over the course of twenty-four hours. Batteries could be charged mostly during the night, especially if home-charging would be the norm. This depends on the possibilities of home-charging, vehicle price differences between the various ranges, and any differences in tariffs. A predominately nighttime demand for electricity could influence the choice of the optimum technology package for electricity generation. For example, the option of using wind energy more efficiently, with its relatively large nighttime supply, is often mentioned. Thus, electric driving offers the possibility of using both wind energy and running coal-fired power stations, during the night, five percentage points more efficiently (CENEX-ARUP, 2008) Table 3.4 shows an estimation for a possible technology package, dividing night and day.

3.4 Local and large-scale air pollution

With a switch to electric (or hydrogen) vehicles, exhaust emissions from road traffic would go down to zero. This would cause $PM_{2.5}$ concentrations in the Netherlands, by 2050, to drop by an average of 0.6 µg/m³ compared to 2030, and in busy streets this could even go down to 1.5-3 µg/m³. It would mean a reduction of 10% in the contribution from anthropogenic sources to average $PM_{2.5}$ concentrations in the Netherlands; and in busy streets this could even be between 15 and 30%. Compared to the expected reduction for the period between 1990 and 2030, this reduction is relatively small, because vehicles that meet Euro 6 standards already have low

Some important parameters for determining the additional costs of electric driving

Table 3.5

Cost aspect	Costs or additional costs, with respect to the reference case	Explanation
Production and transport costs of electricity[1]	€ 0.105 per kWh	For 2050 (PBL analysis of greenhouse gas emission reduction of 60% between 1990 and 2050)
Production costs of petrol	€ 0.92 per litre of petrol/diesel (excluding taxes/surcharges)	Oil price in 2050: $ 120 /barrel (OECD/IEA, 2008b)
Battery price[2]	Module costs € 230-310 per kWh PHEV[3] € 200-230 per kWh city EV[3] € 135-140 per kWh EV battery system management including plug € 1900 EV € 1600-2000 PHEV	Costs per unit of energy capacity. This is dependent on battery design, which needs to be tuned to desired output (e.g. Kalhammer *et al.*, 2007)
Additional costs vehicle (excluding batteries)	City car EV - € 2000 Family car PHEV circa + € 1000 Family car EV - € 3500	For EV, saving on costs of combustion engine and accompanying parts
Additional annual costs of maintenance	Small city car EV - € 75-100 Family car PHEV + € 25-50 Family car EV - € 120-150 Depending on amount of kilometres driven, annually	Very rough estimate: electric vehicle has fewer moving parts, therefore, less wear and tear, which means it needs less maintenance and repair than conventional vehicles
Depreciation period	At 5,000 km/y: 20 years At 15,000 km/y: 15 years At 40,000 km/y: 8 years	

1) Assuming that costs of setting up charging points will be paid out of the extra electricity sales. Additional costs for fast-charging or swapping stations have not been taken into account.
2) Once an older battery is no longer suitable for use in vehicles, it can be used within the network for temporary storage of electricity. Any remaining value has not been included.
3) (Plug-in Hybrid) Electric Vehicle

emissions. Particulate matter emissions from wear and tear of tyres and road surfaces, however, will not alter with a switch to electric vehicles. Although the reduction in concentrations is limited, it is relevant to human health. Moreover, an emission reduction will take place at the production of fuels (from refineries, among other things), and – although this is partly countered by an increase in emissions from the electricity sector – in real terms, the application of electric vehicles will mean an improvement in urban air quality.

Health benefits from emission reduction measures are calculated in studies on the reform of EU directives (see, for example, AEAT, 2005). Using the same methods, health benefits from a change-over to electric vehicles could also be calculated. Estimations of health benefits can be translated in around 0.5 to 1 billion euros per year.

3.5 Long-term costs

To many, the costs of transport and energy are an important part of overall costs. How much do the costs of electric driving vary from those of driving conventional vehicles? This section discusses the long-term costs (for short-term costs, see Chapter 5), for the time when technologies that are needed in the new system are much further along in their development. The learning curve will have been largely or fully completed. The costs include those of vehicles, batteries, renewed electricity facilities, and liquid fuels – excluding taxes, deductions and surcharges. In this comparison with the conventional system, the emphasis is on the additional costs. The conventional system concerns diesel and petrol, and fully developed passenger vehicles.

Such a cost estimate for some decades into the future could only be indicative. However, an attempt has been made to offer some insight. Table 3.5 presents the aspects that determined the cost estimate.

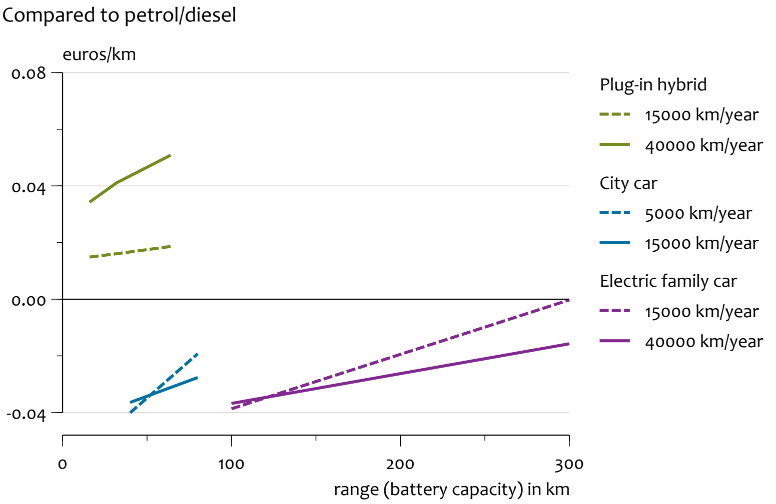
Table 3.5 Some important parameters for determining the additional costs of electric driving

The price of the battery largely determines the price of the vehicle, and as such, also the depreciation costs. In turn, the battery price is dependent on the required vehicle capacity. Buyers have to weigh the benefit of having a larger range (without having to recharge), against a higher purchasing price. Figure 3.1 shows the additional costs per kilometre driven, related to the vehicle range. Total costs of battery systems vary per type of vehicle, but costs of battery management systems are of the same order for all vehicles. Module costs, however, depend on type of vehicle and required output (Kalhammer *et al.*, 2007). Moreover, the costs per kilometre are determined by the distance travelled (for annual averages, see Figure 3.1). Figure 3.1 shows the additional costs, which indicate that electric vehicles are cheaper than petrol or diesel vehicles, in the long term. Plug-in hybrids remain slightly more expensive, especially for large distances.

Calculating costs over such a long period of time can be no more than an indication. Since there are many assumptions influencing the outcome, a sensitivity analysis was performed, with varying parameters. Starting point for this analysis was an electric vehicle with a range of 300 kilometres, because this type of vehicle – together with the chosen parameters – has no additional costs. Figure 3.2 shows the influence of the varying parameters.

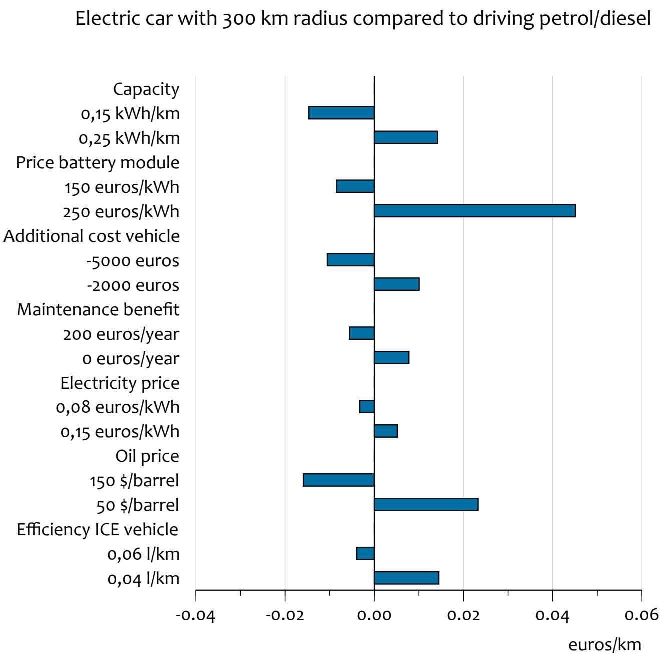
In conclusion, it can be said that the costs of achieving cleaner air might decrease, as it could prove to be cheaper to apply central flue gas cleaning at power stations than for each vehicle, individually.

Additional costs of electric driving in 2050 **Figure 3.1**



Indication of additional costs of electric driving, compared to diesel or petrol, for various vehicle types and battery capacities, in the long term

Sensitivity analysis of additional costs of electric driving in 2050 **Figure 3.2**



Influence of varying parameters on the estimated additional costs of electric driving, in the long term, compared to driving on petrol or diesel

3.6 Natural resources

Electric driving will slow down the oil stocks depletion. Various sources can be used for electricity generation, of which smaller (gas) or larger (coal) stocks are available. In addition, renewable energy could be used, and dependency on gas for a more flexible electricity supply is becoming smaller.

Experts consider several variants of the Li-ion battery the most likely choice for the coming decades. However, one battery contains approximately 1.75% lithium (CENEX-ARUP, 2008), and the availability and purity of lithium is being called into question, as the titles of some publications also show: *The Trouble with Lithium*, *Peak Lithium* (a variant of the Peak Oil discussion), *An Abundance of Lithium*, *The Saudi Arabia of Lithium* (Bolivia), and *Bolivia holds key to electric car future* (Tahil, 2007; Meridian International Research, 2008; Evans, 2008; Forbes, 2008; BBC, 2008; and www.evworld.com, November 2008).

Lithium is not only used in batteries; over half of today's production is being used for making glass, ceramics and aluminium, and it is also used in synthetic rubber and lubricants. For this last category, alternatives to lithium do exist. Lithium is relatively easy to extract from beneath the salt flats in Chile, Argentina, Bolivia, the United States, Australia, Russia and China. Rapid introduction of plug-in hybrids and electric vehicles would lead to a much higher production and increase the search for possible extraction areas. In addition, the price of lithium is likely to increase, in the long term. However, it appears that there would be enough lithium available to supply all future vehicles with a lithium-ion battery. In the EU, waste batteries have to be collected, and lithium could also be recycled, although to which percentage and quality is yet unknown (CENEX-ARUP, 2008; ICMM, 2008).

4

Results from activities in the pre-development phase

4.1 Development in problem perception

Over the last years, climate change and security of supply have risen sharply on the list of social issues. Worrisome conclusions, drawn from monitoring, and better insights into climate through expanding scientific knowledge (IPCC), have all added to this rise, but this is certainly also true for the way in which it has been communicated (think of Al Gore). In addition, several incidents in relation to energy security (e.g. when Russia cut off gas supplies to the Ukraine, in January 2009) have also played an important role. The system option considered in this report could be of great benefit to the issue of climate change, as well as that of security of supply.

Over recent years, biofuels have often been labelled as being an important part of the solution to both these problems, and application of biofuels has become a fact. The application, however, has been coupled with ever-increasing concern about the sustainability of this solution (loss of biodiversity, additional greenhouse gas emissions from land conversions, and possibly a negative influence on food prices). Therefore, the search for other transport options was stepped up, bringing electric driving more to the forefront.

The quality of the local living environment will benefit from cleaner and quieter vehicles. Problems concerning air pollution, such as particulate matter, have gained much attention. The European standards for air pollution caused much commotion, not because of its effects, but more so because of its consequences for building activities. The implementation of the electric vehicle will not be in time to solve these problems; it could only make a limited contribution. However, conventional vehicles will also become substantially cleaner than they are today.

Road traffic is major source of noise nuisance, and the calls for quieter vehicles are increasing. Here, electric propulsion could be a great improvement, especially at acceleration and low speeds, not only for passenger cars, but also for mopeds and scooters. The noise nuisance from motorways, however, will hardly go down, as this is mainly caused by tyre noise – although certain improvements in this area are also possible.

This report does not address the explanation behind the increasing problem perception, nor will it discuss the policy initiatives to influence this perception, such as monitoring, research programmes and communication.

4.2 Vision for the future (for vehicles and electricity)

John German, manager of Environmental and Energy Analysis at American Honda, made the following acknowledging statement: ‘Twenty-five years ago, methanol was the hot solution to energy problems; fifteen years ago, it was electric vehicles; ten years ago, hybrid-electric; five years ago, fuel cells; two years ago, ethanol; and today, it’s the plug-in hybrid. Throughout this period, gasoline has remained the primary transportation fuel in the US’ (Ritter, 2008). His statement puts things into perspective, and shows that it is not easy to find a long-lasting vision for the future.

In the fourth Dutch National Environmental Policy Plan (NMP4), three alternatives (from Energy Research Centre of the Netherlands (ECN)) were presented in the form of feasible (energy technological) future images: status quo, the Netherlands as hydrogen country, and the Netherlands as electricity country (VROM, 2001). All three are still current. Looking at traffic, specifically, the entire automotive industry is convinced that conventional vehicles could still become much more efficient, as well as cleaner and quieter – although, up to a certain point. Many are of the opinion that electric driving could be implemented sooner than fuel-cell vehicles on hydrogen. The reasons for this are the cost differences, the energy losses in the production of hydrogen, and the building of a hydrogen infrastructure (Rishi *et al.*, 2008; OECD/ITF, 2008; Valentine-Urbschat and Bernhart, 2008). Many manufacturers have already announced (plug-in) hybrids or electric vehicles. In Europe, meeting the CO_2 emission standards will also play a role (the focus being on vehicle exhaust emissions, not emissions from fuel production, or those leaving the flues of power stations). Large manufacturers in the United States have to catch up and produce more efficient vehicles, to withstand the competition from Asian producers.

Fuel-cell vehicles have not been written off, yet; Honda, for example, believes in them more than in electric vehicles, and this also applies to Shell (Shell, 2008). In 2007, both ECN and the Nuclear Research & consultancy Group (NRG) had more faith in hydrogen, for the long term (ECN, 2007), but in 2008 they reported to also see possibilities for the electric vehicle (Uyterlinde *et al.,* 2008). The International Energy Agency (IEA) kept both options open for the long term, in its Energy Technology Perspectives (OECD/IEA, 2008a). The same applies to a number of vehicle manufacturers. Combining a large battery with a hydrogen fuel cell could, in due course, also be an efficient option for managing energy and maintaining an unlimited range.

Recently, IBM did extensive research among 125 managers in the international automotive industry (Rishi *et al.,* 2008). Looking at the options for electric driving around 2020, they realised that new developments in batteries are promising. In addition, they assumed that consumers would be prepared to invest in plug-in hybrids and electric vehicles. They expected that, by 2020, consumers would be more open to flexible access to transport. People may want to purchase a small, efficient passenger car, with a certain access to alternative transport facilities included in the price (such as public transport or larger rental vehicles). Furthermore, the industry considered that leasing batteries may also become a way of avoiding the high costs for the first owner (Rishi *et al*., 2008). Currently, companies are working on such a concept (Better Place; Essent in the Netherlands).

According to research commissioned by Essent, the majority of Dutch people have a positive attitude towards electric driving, although performance and costs are still unclear (Essent, 2008).

With regard to costs, the vision for the future can be said to give too little attention to the question of how dwindling tax incomes for the government (from road tax and other levies) will be compensated in the future.

Electricity producers envisage a larger market, an improved way of factoring in basic costs during off-peak hours, a more complete use of wind energy, and a large managing ability for better balancing demand and supply. Grid managers could encounter problems of overloading of the low-voltage system, and play a large part in preventing this from happening.

The system option actively involves at least four departments: the Dutch Ministry of Transport, Public Works and Water Management (V&W), the Dutch Ministry of Economic Affairs (EZ), the Dutch Ministry of Finance, and the Dutch Ministry of Housing, Spatial Planning and the Environment (VROM). There are two platforms which are relevant to energy transition: that on sustainable mobility and on sustainable electricity supply; these platforms have both strategic groups and working groups. Information gathered from various parties leads to visions, focuses on yet to perform R&D, experiments, and subsequently (re)adjustment of such visions.

Until recently, within the platform on sustainable mobility, there appeared to be a preference for biofuels and hydrogen. In the past years, not much attention has been paid to electric driving, compared with the period around 2000; however, this is changing rapidly. The name of the working group on hybridism was recently expanded to hybridism and electric driving. According to the Action Plan on Local Infrastructure of the platform on sustainable mobility, there will be around 500,000 plug-in hybrids on the Dutch market, by 2020. (Energy transition (*Energietransitie*), 2008). From the various strategic groups and working groups of the platform on Sustainable Electricity Supply, a number of points of action and initiatives were brought together to incorporate local applications into the energy supply system.

4.3 Research & Development

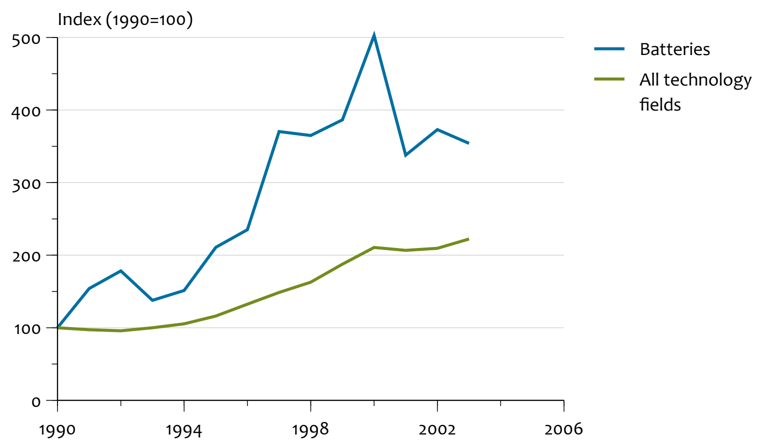
Research and development could lead to strong improvements in the design of plug-in hybrids and electric vehicles, but in the field of batteries it is dominant. Battery developers and manufacturers aim to develop a battery with which an average passenger car can drive one kilometre per kilogram of battery. Vehicle manufacturers are forming alliances with battery suppliers, or start manufacturing batteries themselves. Therefore, much research is performed on alternative materials for the electrodes and the electrolyte and their structures, to produce batteries that are light, small, safe, cheap, can provide a lot of capacity, and can be recharged fast. Between 1990 and 2003, the number of patent applications for batteries grew twice as fast as before, see Figure 4.1 (Tans, 2006).

Eventually, the required battery space within vehicles will become less of a problem, as battery cells can be positioned in various places. Much research is also being done to enable fast-charging of batteries (within five minutes), but this puts high demands on batteries. Currently, in a laboratory environment, batteries can be charged to half their capacity within ten minutes (Notten, 2006). Fast-charging cannot be done from a domestic power point, because it requires more voltage. Although there is much research being done around Li-ion batteries, Toyota, for example, expects to launch a successor to the Li-ion battery (metal air?), by 2030.

Superconductors cannot store much energy (although more than conventional conductors), but they can deliver and be charged much faster than batteries. Having a combination of a battery and conductor in a vehicle could be useful at times of acceleration, when much energy is required, or during braking, when much energy could be stored. The costs of such a combination have dropped considerably over the last decade, but would still need to come down by a factor of 10 or even 20, for it to become an attractive option. (OECD/IEA, 2008a). Kromer and Heywood (2007) are not optimistic about the prospects, but in Germany, a research programme is being initiated that will span several years, researching the battery–conductor combination.

Plug-in hybrids carry the disadvantage of needing two propulsion systems. Energy Technology Perspectives (OECD/IEA, 2008a) states, that the plug-in hybrid's combustion engine would need to be more powerful to enable this heavier vehicle to equal the performance of conventional vehicles.

Worldwide and European patent applications **Figure 4.1**



Development of patent applications for batteries worldwide and in Europe (Tans, 2006)

An alternative, however, could be to fit this vehicle with a lighter generator, which runs at a constant speed of rotation, supplying power to the battery: the so-called Extended-Range Electric Vehicle.

Research is also being carried out at system level. At the moment, a company called Better Place is working on plans, together with Renault-Nissan and several governments, for constructing fast-charging stations and swapping stations in Israel, Denmark, the United States (California and Hawaii), Canada (Ontario), Portugal and Australia. The plan is set up around the idea that consumers rent batteries, which they can charge both at home and along motorways, or have them (robotically) swapped. A problem with this system would be that, in the short term, it would require much standardisation of the battery location within the vehicles. German vehicle manufacturers, therefore, are sceptical.

In the Netherlands, several parties have combined forces in the project Intelligent E-Transport management. In this context, power company Essent is starting the Mobile Smart Grid system, in which cars are charged at home or elsewhere, and consumers feed information into the system, stating how much energy they would like, when they would like it, and at which price. The Mobile Smart Grid collects these data, carries out the consumers requests, and sends them an invoice – regardless of where the battery was charged. This system could be instrumental in preventing a grid overload, and make use of the availability of wind energy during the nighttime. The Essent system will start with 100 to 200 own vehicles, but other Dutch grid managers are also interested in this development. Similar plans exist in France, Ireland and Germany, some also in collaboration with Better Place.

4.4 Practical experiments

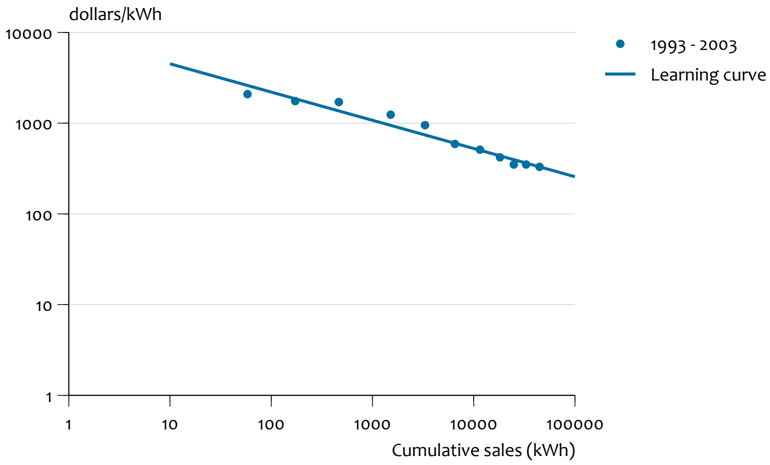
Hybrid vehicles are beyond the point of experimentation. Plug-in hybrids have recently entered the Chinese market, but are elsewhere only available as kit cars. Several manufacturers are hoping to market plug-in hybrids, in the coming years. The same holds for all-electric vehicles; in the short term, manufacturers see a market for small city vehicles and, especially, delivery vans. There are also plans for luxury sports cars, such as the (already available) Tesla. Soon, BMW will put 500 Minis on the German and US markets, in a test programme, which also focuses on charging batteries at home. In central London, much experience is being gained, with car parks that have already been fitted with charging points for electric vehicles. In Rotterdam, charging points for electric scooters have been placed at strategic locations within the city. It appears that every manufacturer is active in the field of hybrids and electric driving, and – for further development – is waiting to see what the market and government will do next.

4.5 Learning curves

Research and experiences from experiments in niche markets result in improvements in the price–performance ratio. This shows the developments in the learning process. The price–performance development in batteries dominates the prospects for electric driving. It is generally expected that variants of Li-ion cells will be used in electric driving. Figure 4.2 shows its learning curve. There is no historic knowledge on batteries used in electric driving, and up to now, developments have been driven by applications in portable electric equipment, where the focus mostly was on energy density, and not so much on battery lifespan.

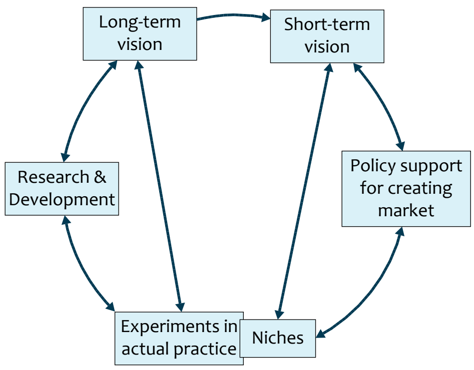
Between 1991 and 2005, the price of Li-ion batteries per unit of stored energy (Wh) decreased by a factor of ten. With information on prices and sales from 1993 to 2003 (Battery University, 2008) a *progress ratio (PR)* of 0.83 can be calculated (PR: factor for the decrease in costs at a doubling of cumulative production). It should be noted that this development did not take place in applications for vehicles, but, for example, in laptops. These batteries are mass produced, but their battery cells are much smaller. Today, Li-ion batteries cost around $ 300 per kWh (see Figure 4.2). If vehicle batteries would be assembled on the basis of these cells, batteries would become rather expensive, because of the high costs involved

Learning curve Li-ion cells **Figure 4.2**



Learning curve for production of small Li-ion-cells.

Relationship between activities in the pre-development phase **Figure 4.3**



Relationship between activities in the pre-development phase.

in creating the modules and batteries. From the literature, it is hard to get a clear picture of the costs involved, as it is often unclear whether prices concern cells (and which size of cells), modules, or complete systems. According to IEA, in the short term, costs would vary between 650 and 800 euros/kWh for complete battery systems (circa 240 euros/kWh, in the long term) (OECD/IEA, 2008a). The cost level for Li-ion batteries for laptops suggests that scaling up specific batteries for vehicles rapidly could lead to a reduction in costs. This could lead to a lower PR over the coming years. It is unclear whether application of Li-ion batteries in vehicles would also require any specific development of cells, other than in current applications.

Following the learning curve is a way of monitoring the integral developments in research and in actual practice. Disadvantage of this indicator, however, is that short-term price changes are strongly influenced by factors other than costs. During a process of expansion, supply and demand continually have to be attuned to each other, involving temporary under- or overcapacity. Therefore, it would take a period of at least ten years before a useful estimation of the PR value could be given (Junginger *et al.*, 2008).

4.6 Relationship between activities

To analyse the relationship between the various activities, the long-term and short-term cycles are assessed for their development and mutual connections. This was done according to the scheme in Figure 4.3.

Since a few decades, electric driving has been considered an option for cleaner road traffic, in the long term. However, the ideas about the most feasible option vary; the most important alternatives are fuel-cell vehicles on hydrogen and biofuels. This has had its influence on R&D and on practical experiments. A certainly powerful element of the vision for the long term has been the necessity for cleaner and more efficient vehicles, which has been addressed in the short-term cycle. This also led to the hybrid vehicle, the success of which (especially the 'Prius') is instigating much R&D in batteries for hybrids, which has favourable consequences for further development of both the plug-in hybrid and the electric vehicle. For biofuels, the situation is different; negative publicity around its side effects has led to technology being scaled down for the long term vision, while at the same time providing an extra impulse for efficiency improvements to batteries. Currently, a number of vehicle manufacturers are developing different versions of electric vehicles and plug-in hybrids, on a modest scale. These products could be seen, above all, as practical experiments.

Developments in the short term have been accelerated by the need for security of supply, the drying up of oil stocks, and especially the high oil prices (the currently low oil price is seen as a temporary phenomenon, caused by the economic crisis). Moreover, the existing electricity infrastructure would be suitable for setting up charging facilities relatively quickly, and could cover a large area if municipalities and grid managers combine forces. Such developments would bring mass production one step closer.

5 Motive for system change

The preparatory phase of a transition towards electric driving, ultimately, should provide motivation for the actual realisation; a process which involves various actors. The first actors are the vehicle manufacturers; this chapter discusses their decisions to invest in mass production of electric vehicles and plug-in hybrids. But there is also another actor's viewpoint, that of the consumer; what are the considerations for buying such vehicles? Electricity production is regarded as the third actor; producers could act as lease companies for battery systems. For all these actors, the developments have been analysed, and how they influence each other.

The learning curve of R&D, together with the first applications, lead to an improved price–performance ratio, and more efficient production processes. Practical experience shows how risky or complex certain technologies are. Society's problem perception is reflected through direct (NGOs and action groups) or indirect stimuli to act on these problems. The process of creating a vision for the future strengthens the belief that a system option is (or is not) likely to become important, and provides the stimulus to participate, in a variety of ways.

In addition, government can motivate actors even more by setting targets and applying policy instruments that influence other areas; instruments such as financial stimuli or persuasive means of communication.

Table 5.1 shows the analysis of the force field for vehicle manufacturers, which also shows that these fields cannot be seen separately from those involving other actors. On the forefront are the vehicle purchasing prices and the cost of electric driving, although things such as CO_2 standards for vehicles also play a role, and are likely to become more stringent in the future, while other standards might be lowered. This also applies to currently increasing social pressures on action against climate change. With the growing confidence in electric vehicles as the technology of the future, vehicle manufacturers appear to be lining up, ready to storm the market.

To manufacturers, countries equal groups of motorists; a country is as influential as the size of its population and their purchasing power. Dutch policy aimed at changes within the Netherlands, therefore, is much less influential than Europe as a whole.

Table 5.2 shows the considerations for private vehicle purchase. 'The' motorist does not exist. Households vary in size (in 2002, 34% of households in the Netherlands were one-person households, and this percentage is expected to grow in the future (CPB/MNP/RPB, 2006)). In addition, there are other differences, such as in income, degree of urbanisation, and in availability of public transport, which all lead to a diversity in supply. Moreover, people have different world views, causing differences in their consideration of environmental aspects. Nevertheless, a number of barriers will definitively have to be removed before electric driving could soar. For a wider consumer acceptance, charging a battery would need to be at least as simple as filling the petrol tank. On top of that, not everyone can be certain of having a charging point both at or near their home and at their travel destinations. Grid managers' ideal situation is that of vehicles being plugged into the grid when they are not driving, which would mean plugging and unplugging several times a day, instead of filling the tank perhaps once a week. Apart from which, it certainly would be equally important for electric driving not to be more expensive than driving conventional vehicles, also taking into account the difference between purchasing costs and annual running costs. Furthermore, a distinction has to be made between costs and prices; to illustrate this, a calculation was done for a vehicle in the compact class, at a battery purchase price of 800 euros/kWh, an electricity price of 0.17 euros/kWh, and a petrol price of 1.30 euros/litre. This showed that annual expenses for driving an electric vehicle would be 20% higher than for driving a conventional car. This is partly caused by the low vehicle purchase tax on efficient petrol cars. At a battery price of 600 euros/kWh and a petrol price of 1.60 euros, the expenses for driving either vehicle would be the same.

Batteries make the vehicles expensive; when buying a vehicle, consumers first and foremost look at purchase price and not so much at annual costs (e.g., see King, 2007). Several companies are looking at battery leasing as a solution (Essent, Better Place). This concept would offer other actors the opportunity to enter this market. A third, crucial factor is the ease with which one could travel further, in one day, than the range of one battery charge (which is dependent on battery capacity). At the moment, this is not easy enough.

Force field analysis of vehicle manufacturers' investment in mass production of the electric family vehicle — Table 5.1

Force	Features and developments 2000-2008	Policy stimuli within the EU
Price– performance ratio	Although the costs of electricity are lower than those of petrol and diesel, the electric vehicle's purchasing price is high, and the first thing that consumers look at. Batteries have improved in performance, but their price remains high. Electric driving is still more expensive, per kilometre, but this is generally expected to change rapidly Developments around oil prices (which are higher and less stable than for electricity) The advantages of home charging might outweigh the disadvantage of a small range; however, this disadvantage must be regarded a drawback. Overcoming this drawback, in the form of the plug-in hybrid, has a considerable price tag	Subsidy schemes for vehicle and battery research Fiscal instruments, such as tax exemptions – varying per country
Investment barriers	The set up of a production line for electric vehicles is probably not more expensive than for a new line of vehicles with adjusted combustion engines, it may even be slightly cheaper	
Complexity	The previously existing risk of explosion of Li-ion batteries has gone down dramatically, because of technical measures and adjustments So far, there is little experience regarding battery lifespans	
Government objectives	The Netherlands has no role in the deliberations; The EU, Japan and the United States do. CO_2 emissions have to be brought down, however, this could also be achieved with improved conventional vehicles	Electric vehicles have zero emissions, which fact is taken into account in setting the vehicle CO_2 standards for the EU The Renewables Directive obliges countries to set a 10% target for renewable energy in 2020, for the transport sector
Social attitudes	Increased importance of climate control, and decreased dependence on oil Increased concern about sustainability of biofuels as an alternative	Instruments of communication
Vision within the chain	There is the shared and growing view of electric vehicles achieving an important market share. The matter of how this market will be divided, is becoming more and more relevant Initiatives of setting up large-scale projects in some countries, form the start of collaborations between crucial players	

Force field analysis of the consumer purchase of an electric city vehicle — Table 5.2

Force	Features and developments 2000-2008	Policy stimuli
Price– performance ratio	Energy expenses for electric driving are low, as electricity costs less per kilometre than petrol or diesel	Levies on petrol and diesel, currently, are higher than tax on electricity
Investment barriers	The purchase price of electric vehicles is substantially higher than that of similar conventional vehicles on petrol or diesel; battery prices have come down, but the developments in electric vehicles are still insufficient to provide the full advantage of savings effects (cheaper propulsion system). Battery leasing systems could emerge	Financial instruments (other than vehicle purchasing tax and road tax) make electric driving relatively attractive and interesting, if provided with slightly larger range
Complexity	Home charging is simple, however, not everyone has access to private parking. There are no charging points available elsewhere Maintenance and repairs of electric vehicles is expected to be low (far less moving parts) Battery lifespans are still uncertain, therefore, warranties are important	
Government objectives		Relevant government objectives are not aimed specifically at consumers
Social attitudes	Increased concern about climate and security of supply, and much discussion on biofuels as an alternative. Electric driving is reasonably well-known as a clean alternative for city-driving	Financing of research and monitoring around climate and biofuels. Government support in communications on climate problems (IPCC, and bringing Al Gore to the Netherlands)

Table 5.3 shows the force field analysis for energy producers that consider branching out to leasing. Their reasons are not only to create additional demand for electricity because of increased electric vehicle use (50% per household, for one vehicle), but also that it would create an improved balance between the supply and demand of sustainable energy. For the Netherlands, this would mean a more efficient application of wind energy, which could be used for charging batteries during the nighttime.

Currently, the economic advantages of electric driving are receiving much attention, with the emphasis on the large

Force field analysis for the leasing of batteries for electric vehicles by energy producers and grid managers **Table 5.3**

Force	Features and developments 2000-2008	Policy stimuli
Price– performance ratio	Electricity sales go up More efficient use of the existing grid Wind energy may be able to compete with other alternatives if the price of nighttime charging is right	
Investment barriers	Leasing batteries to consumers provides the possibility to influence their charging behaviour. This could lead to a more even use of electricity, and lower or postponed investments in production units and grid	
Complexity	Standardisation is needed. Agreements are set up between vehicle manufacturers and grid managers	ITM project
Government objectives	More sustainable energy can be achieved more easily	Sustainable energy: 20% (cabinet) or 14% (EC proposal) by 2020
Social attitudes	In a liberalised market, investments in sustainable energy make useful arguments for attracting customers and retaining them	
Vision within the chain	Essent's plans are viewed with interest. Those interested in new coal-fired power stations are not into wind energy. However, energy from coal could also be applied in electric driving	

price differences per kilometre between fuel and electricity. At the filling station, over half of the price of petrol is made up of fuel tax. Although this also applies to electricity, electric driving is still significantly cheaper per kilometre driven. On balance, motorists would pay less tax, and at large-scale application of electric driving, the government would suffer a substantial loss. In 2008, government income from fuel sales totalled around 10 billion euros. If the government would want to maintain current tax levels from road traffic, it will search for alternative ways to tax motorists. Therefore, it is thought likely that this would be achieved by increasing electricity prices.

6 Conclusions

Greenhouse gas emission from electric driving could be very low – substantially lower than from the most efficient, future combustion engines. This would depend on the greenhouse gas emissions from electricity production, in the long term, but there would be enough technological options for an electricity production with very low emission factors, by 2050. The overall effect would partly be determined by the scale of electric driving; if the barrier of the limited range of 100 kilometres (for many smaller vehicles, city vans, and second cars) cannot be overcome, then the share of electrically driven kilometres is estimated to stay between 20 to 40%. Should this barrier be removed, then a share of 90% would be possible, in the long term.

At large-scale application, electric driving could have a large share in future electricity demand; up to 10% by 2050. At neighbourhood level, the electricity demand from electric vehicles could be 50% or more. Balancing supply and demand could be substantially improved, because charging could take place during off-peak hours. This could be an enormous stimulus for investment in wind energy, which could be applied during the nighttime when demand for electricity is traditionally low. This would also apply to power stations with a continuous supply, such as coal-fired power stations (with CCS) and nuclear power stations. At the same time, the dependency on gas, often in flexible application, would decrease.

Electric driving would have a continuing and positive influence on the urban living environment. Air quality would improve because of the zero emissions from electric vehicles, although improvements to combustion engines are also expected to add to this improvement. Noise nuisance could decrease, certainly if mopeds, scooters and motorcycles also become electric. Although this would only happen if electric vehicles were not fitted with very loud, extra sound-producing devices to warn other road users of their approach.

Electric motors are very efficient; across the board, electric vehicles can be said to be twice as efficient. Bio-electricity is more efficient than liquid biofuel, in the sense that with the same amount of biomass (from wood or woody materials), one could drive two to four times the number of kilometres on bio-electricity. This is part of the reason why fuel costs are low.

In the long term – depending on its success, this could be somewhere between 2020 and 2040 – the total costs of driving an electric vehicle (not including road tax or levies) with a range of up to 300 kilometres, could be the same or even lower than driving on petrol or diesel. Uncertain elements in this statement are, for instance, oil prices and battery prices with possible other savings. Opposite the extra costs of the battery are the cheaper propulsion system, lower maintenance costs, and lower energy costs. In the short term, the expenses would be lower for city motorists who would not need a large range yet drive many kilometres, because the taxation on energy per kilometre would be lower, and because they would not pay road tax or vehicle purchasing tax.

The limited range is an important barrier to the introduction of electric vehicles. This is not only connected to the expensive batteries, but also to weight. The aim is to drive one kilometre per kilogram of battery. There are four possibilities for removing the range-related barrier:

- Battery-swapping stations: within a few minutes, the entire battery pack could be robotically swapped. This would happen at the expense of flexibility, regarding to how and where the battery is placed inside the vehicle. Battery-swapping stations could be combined with fast-charging stations.
- Fast-charging stations: fast-charging could be on offer wherever there is great power density. Fast-charging current batteries would mean shortening their lifespan.
- Plug-in hybrids: in principle, fast-charging and battery swapping would also be possible, but the greatest advantage of this vehicle is the option of switching to liquid fuel when the battery is empty, and refuelling is simple. A disadvantage would be the need for two propulsion systems, making the vehicle more expensive than a comparable vehicle with only a combustion engine or electric motor.
- Rental or sharing vehicles: if large (hybrid) vehicles would be used more widely and, therefore, would be available at relatively low prices, consumers could choose to rent or share one when they plan long-distance trips. Disadvantages of such a system (the importance attached to them varies per person) are the effort it would take to reserve the vehicle, not having personal items already on board, and having to get used to different types of vehicles.

A second important barrier is the need for assurance that batteries could be charged – always and everywhere. A widely spread system should be set up, with safe and permanently available charging points; not just near peoples homes, but also at public parking facilities along roads, in car parks, and near work locations.

For grid management, it is important that vehicles are plugged in, as often as possible, so that the grid system is not overloaded, and to make efficient use of, for instance, wind energy. Municipalities will play a large role in organising the charging point system. Essentially, installing the charging points should not be a problem, as the electricity sector has a vested interest in the success of electric driving (increase in sales, and more efficient management, caused by off-peak charging and more widespread use of the electricity network). Furthermore, society as a whole will benefit from an optimal use of wind energy. Availability of personal parking spaces near homes, in those areas that currently have only public parking, has to be arranged with the help of local government, which could create some obstacles.

A third barrier is the investment barrier connected to electric vehicles, because of the costs of batteries and their uncertain performances and lifespans. Leasing would be an option; lease companies (this can be grid managers, or other companies) could spread the risks of failure over a large number of users.

Plug-in hybrids are more expensive than electric vehicles or those with combustion engines. The advantage of introducing these hybrids on the market would be their limited dependence on a charging point system. This type of vehicle could make a considerable contribution to the reduction of CO_2, as over half of its kilometres are expected to be driven on electricity.

Bad experiences with electric vehicles in the 1990s have caused Dutch policymakers to pay little attention to electric driving, over the last decade. Fuel-cell vehicles were thought by many to fit better within the long-term vision, and biofuels have been dominating the debate over the last five years and are still subject of research programmes running today. However, electric vehicles have come back into view, as fuel-cell vehicles are not expected in the coming years, there are doubts about the sustainability of biofuels, and climate and energy supply problems are only growing. This is partly due to the fact that battery technology has improved (thanks to the rise of mobile electronics), and oil prices have been rising over the past years. The success of the hybrid vehicle (with its icon, the *Prius*) has provided an extra stimulus for research in vehicle batteries. In the Netherlands, government has strongly financially supported the promotion of the hybrid vehicle (no vehicle purchasing tax, no road tax, and lower added income tax for leasing).

There are learning costs involved in the further development of electric vehicles and plug-in hybrids. The battery, especially, needs to become more efficient to enable large-scale application. To reach a reasonable purchase price, the development of the battery with the most favourable outlook, the Li-ion battery, over the coming years, will total two to three billion euros in additional costs (learning costs), based on the costs of the development up until now, with an estimated progress ratio of around 0.83. This amount can be considered modest, seeing the amounts spent each year on driving (around 30 trillion euros).

Appendix 1 Interview round

A. Brouwer, SenterNovem
M. Wagemaker, TUDelft
P.H.L. Notten, TUEindhoven
P. de Boer- Meulman, KEMA
J. van Baalen, TNO
G. Passier, TNO
A. Postma, Essent
R.J.F. Hoogma, SenterNovem

Literature

AEAT (2005). Cost-Benefit Analysis of the Thematic Strategy on Air Pollution, Service Contract for carrying out cost-benefit analyses of air quality related issues, in particular in the clean air for Europe (CAFE) programme, report number AEAT/ ED48763001/Thematic Strategy, AEA Technology, Didcot, United Kingdom.

Battery University (2008). www.batteryuniversity.com

BBC (2008). Bolivia holds key to electric car future, BBC News, 9 November 2008.

Belvilla (2008). Online research.

Berglund B., T. Lindvall, D.H. Schwela (eds) (1999). Guidelines for community noise. World Health Organization, Geneva, Switzerland.

Better Place Introduction. Power Point Presentation, October 2008.

Boer, P. de en B. In 't Groen (2009). Prediction of domestic electricity demand en supply on neighbourhood level (*Wijkniveau-voorspelling van elektriciteitsvraag en -aanbod van woningen)*. KEMA, Arnhem, The Netherlands.

Born, G.J. van den en J.P.M. Ros (2006). Bio- feed stocks for the chemical industry, evaluation of transitions based on system options (*Biogrondstoffen voor de chemische industrie, Evaluatie van transities op basis van systeemopties)*. Netherlands Environmental Assessment Agency (MNP), Report 500083005, Bilthoven, The Netherlands.

CENEX-ARUP (2008). Investigation into the Scope for the Transport Sector to Switch to Electric Vehicles and Plug-in Hybrid Vehicles. Study for the United Kingdom Department for Business Enterprise & Regulatory Reform, and the Department of Transport.

CPB/MNP/RPB (2006). Welfare, Prosperity and Quality of the Living Environment – A scenario study for the Netherlands in 2040 (*Welvaart en Leefomgeving – een scenariostudie voor Nederland in 2040)*. CPB/MNP/RPB, The Hague/Bilthoven/The Hague, The Netherlands.

ECN (2007). The promise of sustainable European energy management. Energy vision of ECN and NRG (*De belofte van een Duurzame Europese Energiehuishouding. Energievisie van ECN en NRG)*. Energy Research Centre of the Netherlands, Petten, The Netherlands.

Eickhout, B., G.J. van den Born, J. Notenboom, M. Van Oorschot, J.P.M. Ros, D.P. van Vuuren, H.J. Westhoek (2008). Local and global consequences of the EU renewable directive for biofuels, Testing the sustainability criteria. Netherlands Environmental Assessment Agency (MNP), Report 500143001, Bilthoven, The Netherlands.

Elzenga, H.E., J.A. Montfoort, J.P.M. Ros (2006). Evaluating transitions: the micro co-generation systems option and the virtual power plant (*Micro-warmtekracht en de virtuele centrale, Evaluatie van transities op basis van systeemopties)*. Netherlands Environmental Assessment Agency (MNP), Report 500083003, Bilthoven, The Netherlands.

Energy transition (2008) (*Energietransitie)*. Action plan local infrastructure, action items and initiatives by grid managers to integrate local applications into the energy supply system (*Actieplan decentrale infrastructuur, actiepunten en initiatieven vanuit de netbeheerders om decentrale toepassingen in te passen in de energievoorziening*). SenterNovem, Utrecht, The Netherlands.

Essent (2008). www.essentelektrischrijden.nl, November 2008.

Evans, K. (2008) An Abundance of Lithium (Part One and Two). www.worldlithium.com.

EZ (2008). Energy report 2008 (*Energierapport*). Ministry of Economic Affairs, The Hague, The Netherlands.

Faber, A. en J.P.M. Ros (2009). Distributed electricity production in the built environment, Evaluation of transitions based on system options (*Decentrale elektriciteitsvoorziening in de gebouwde omgeving, Evaluatie van transities op basisvan systeemopties)*. Netherlands Environmental Assessment Agency (PBL), Report 500083011, Bilthoven, The Netherlands.

Forbes (2008). The Saudi Arabia of Lithium. www.forbes.com, 24 November 2008.

Franssen, E.A.M., J.E.F. Dongen, J.M.H. Ruysbroek, H. Vos, R.K. Stellato (2004). Annoyance from environmental factors and the assessment of the living environment in the Netherlands (*Hinder door milieufactoren en de beoordeling van de leefomgeving in Nederland, Inventarisatie verstoringen)* 2003. TNO, Report 2004-34, The Hague, National Institute for Public Health and the Environment (RIVM), Report 815120001, Bilthoven, The Netherlands.

Health Council (2008). Hydrogen in road traffic – a new fuel's advantages and disadvantages to health (*Waterstof in het wegverkeer – voor- en nadelen voor de gezondheid van een nieuwe vorm van brandstof*). The Hague, The Netherlands.

Goodspeed, R. (2009). Will Electric Cars Fuel Urban Sprawl? The Energy Collective, 13 January 2009.

Heywood, J.B. (2008). More Sustainable Transportation: The Role of Energy Efficient Vehicle Technologies. Report prepared for the OECD International Transport Forum, Leipzig, Germany, 28-30 May 2008.

ICMM (2008). Zero Waste Recycling of Metals – Case Study.

Junginger, M, P. Lako, S. Lensink, W. van Sark, M. Weiss (2008). Technological learning in the energy sector. Report 500102017. Utrecht University/ ECN, The Netherlands.

Kalhammer, F.R., B.M. Kopf, D.H. Swan, V.P. Roan, M.P. Walsch (2007). Status and Prospects for Zero Emissions Vehicle Technology, Report for the ARB Independent Expert Panel 2007. State of California Air Resources Board, Sacramento, California, United States.

Kendall, G. (2008). Plugged in – The end of the oil age. WWF-World Wide Fund for Nature, Brussels, Belgium.

KiM (2007). Mobility Balance (*Mobiliteitsbalans*). Netherlands Institute for Transport Policy Analysis (*Kennisinstituut voor Mobiliteitsbeleid)*. The Hague, The Netherlands.

King (2007). The King Review of low carbon cars, Part 1: the potential for CO_2 reduction. HM Treasury, London, United Kingdom.

Kintner-Meyer, M., K. Schneider, R. Pratt (2007). Impacts assessment of plug-in hybrid vehicles on electric utilities and regional U.S. Power Grids. Pacific Northwest National Laboratory, Richland, WA, United States.

Knol, A.B. en B.A.M. Staatsen (2005). Trends in the environmental burden of disease in the Nederlands 1980-2020. National Institute for Public Health and the Environment (RIVM) (*Rijksinstituut voor Volksgezondheid en Milieu*), Report 500029001, Bilthoven, The Netherlands.

Kromer, M.A. en J.B. Heywood (2007). Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet. Sloan Automotive Laboratory; Laboratory for Energy and the Environment. MIT. Cambridge. United States.

Lowenthal, R. (2008). Networked Charging Stations. '08 Conference Electric Drive Transportation Association, 2-4 Dec. Washington (DC), United States.

Meridian International Research (2008). The Trouble with Lithium 2 – Under the Microscope. Martainville, France.

Montfoort, J.A. en J.P.M. Ros (2008). Solar energy in the living environment, Evaluating transitions based on system options (*Zonne-energie in woningen, Evaluatie van transities op basis van systeemopties*). Netherlands Environmental Assessment Agency (MNP), Report 500083009, Bilthoven, The Netherlands.

Mulder, F.M. en M. Wagemaker (2008). Hydrogen and Electrical Energy Storage. Syllabus. TU Delft, The Netherlands.

Nagelhout, D. en J.P.M. Ros (2006). Fuel cell vehicles running on hydrogen derived from Concentrating Solar Power (*Brandstofcelauto op waterstof verkregen uit zonthermische krachtcentrales (CSP), Evaluatie van transities op basis van systeemopties)*, Netherlands Environmental Assessment Agency (MNP), Report 500083007, Bilthoven, The Netherlands.

Notten, P.H.L. (2006). Battery modelling & Battery Management – Management report. EETK99124. Philips Research, TU Eindhoven, Eurandom. Eindhoven, The Netherlands.

OECD/IEA (2008a). Energy Technology Perspectives, Scenario's & Strategies to 2050. Paris, France.

OECD/IEA (2008b). World Energy Outlook. OECD, Paris, France.

OECD/ITF (2007). Future Prices and Availability of Transport Fuels. Discussion Paper No. 2007-15. International Transport Forum.

OECD/ITF (2008). Transport and Energy – The Challenge of Climate Change. Research Findings. International Transport Forum. 28-30 May 2008. Leipzig, Germany.

Passier, G., F.V. Conte, S. Smets, F. Badin, A. Brouwer, M. Alaküla, D. Santini (2007). Status Overview of Hybrid and Electrical Vehicle Technology 2007; Final report of Phase III, Annex VII, IEA. TNO, Delft, The Netherlands.

Postma, A. (2008a). The meaning of sustainable mobility to grid managers (*Wat betekent duurzame mobiliteit voor de netbeheerders?*) Presentation at meeting on Building smart energy grids for a sustainable energy supply, organised by the platform for Sustainable electricity supply and the Platform New Gas, 3 October 2008. SenterNovem, Utrecht, The Netherlands.
Postma, A. (2008b). Mobile Smart Grid, (*de infrastructuur voor elektrisch rijden. Bijdrage voor het Nationaal Congres Mobiliteit & Milieu*), 21 November 2008, 's-Hertogenbosch, The Netherlands.
Reudink, M.A., H. van Zeijts, J.P.M. Ros (2006). Market for 'green services' option:
evaluation of transitions in nature conservation in the Netherlands (*Markt voor groene diensten, Evaluatie van transities op basis van systeemopties*), Netherlands Environmental Assessment Agency (MNP), Report 500083004, Bilthoven, The Netherlands.
Rishi, S., B. Stanley en K. Gyimesi (2008). Automotive 2020 – Clarity beyond the chaos, IBM Institute for Business Value. New York, United States.
Ritter, S.K. (2008). Biofuels, Batteries, and Solar Cells: The Future Of Driving. Chemical & Engineering News, Volume 86, Number 33, August 18, 2008.
Rood, G.A., D. Nagelhout, J.P.M. Ros, H.C. Wilting (2006). Future fish supply dependent of alternatives for fish oil and fishmeal (*Duurzame viskweek voor behoud van de visvoorraad, Evaluatie van transities op basis van systeemopties)*, Netherlands Environmental Assessment Agency (MNP), Report 500083006, Bilthoven, The Netherlands.
Ros, J.P.M. en J.A. Montfoort (2006). Evaluation of transitions in fuel systems: the liquid biofuel option (*Evaluatie van transities: systeemoptie vloeibare biobrandstoffen*), Netherlands Environmental Assessment Agency (MNP), Report 500083002, Bilthoven, The Netherlands.
Ros, J.P.M., J.C.M. Farla, J.A. Montfoort, D. Nagelhout, M.A. Reudink, G.A. Rood, H. van Zeijts (2006a). Evaluation method for National Environmental Policy Plan 4 (*Evaluatiemethodiek voor NMP4-transities, Bouwtekening voor de evaluatie van het beleid ter ondersteuning van systeeminnovatie op de lange termijn*). Netherlands Environmental Assessment Agency (MNP), Report 500083001, Bilthoven, The Netherlands.
Ros. J.P.M., G.J. van den Born, H.E. Elzenga, J.A. Montfoort, D. Nagelhout, M.A. Reudink, G.A. Rood, H. van Zeijts (2006b). Gradual transition in realising a long-term policy (*Transitieprocessen en de rol van het beleid – Evaluatie op basis van zes systeemopties*), Netherlands Environmental Assessment Agency (MNP), Report 500083008, Bilthoven, The Netherlands.
Ros, J.P.M., D. Nagelhout, J.A. Montfoort (2009). New environmental policy for system innovation: Casus alternatives for fossil motor fuels. Applied Energy, Volume 86, Issue2, February 2009, Pages 243-250. IGEC III – Special Conference (IGEC-III), June 18-20, 2007 Västerås, Sweden.
Shell (2008). Shell energy scenarios to 2050. Shell International BV.
Smokers, R., R. Vermeulen, R. van Mieghem, R. Gense, I. Skinner, M. Fergusson, E. MacKay, P. ten Brink, G. Fontaras, Z. Samaras (2006). Review and analysis of the reduction potential and costs of technological and other measures to reduce CO_2 emissions from passenger cars. TNO/IEEP/AUT, Delft, The Netherlands.
Stoop, J.A.A.M. (2008). Research and interviews on the safety of city trams. (*Rapportage Onderzoek en Interviews Veiligheid Stadstrams*). Kindunos Veiligheidskundig Adviesbureau B.V, Gorinchem, The Netherlands.
Tahil, W. (2007). The Trouble with Lithium – Implications of Future PHEV Production for Lithium Demand. Meridian International Research, France.
Tans, N. (2006). Patent applications in electricity storage (*Octrooiaanvragen in de elektriciteitsopslag*). The Netherlands Patent Office (*Octrooicentrum*), Rijswijk, The Netherlands.
TenneT (2008). Transport Balance (*Transportbalans*) 2007. TenneT TSO B.V. Arnhem, The Netherlands.
Uyterlinde, M.A., C.B. Hanschke, P. Kroon (2008). Effects and costs of sustainable innovation in road traffic (*Effecten en kosten van duurzame innovatie in het wegverkeer – Een verkenning voor het programma 'De auto van de toekomst gaat rijden'*). ECN, Petten, The Netherlands.
Valentine-Urbschat, M. en W. Bernhart (2008). Power train 2020. Automotive inSIGHTS. No.2-2008. Roland Berger Strategy Consultants, Munich, Germany.
Visser E. de, R. van den Hoed, H. Barten (2006). Concentrating solar power for fuel cell vehicles. Ecofys, Utrecht, The Netherlands.
VROM (2001). Fourth National Environmental Policy Plan (*Nationaal Milieubeleidsplan 4. Een wereld en een wil, werken aan duurzaamheid*). Ministery of VROM, The Hague, The Netherlands.
VROM/NSDO (2002). National Strategy for Sustainable Development (*Nationale Strategie voor Duurzame Ontwikkeling – Verkenning van het rijksoverheidsbeleid*). Ministery of VROM, The Hague, The Netherlands.
Vuuren, D.P. van, M.G.J. den Elzen, P.L. Lucas, B. Eickhout, B.J. Strengers, B. van Ruijven, M.M. Berk, H.J.M. de Vries, M. Hoogwijk. M. Meinshausen, S.J. Wonink, R. van den Houdt, R. Oostenrijk (2006). Stabilising greenhouse gas concentration levels: an assessment of options and costs. Netherlands Environmental Assessment Agency, Report 500114002, Bilthoven, The Netherlands.

Colophon

Responsibility
Netherlands Environmental Assessment Agency

Coordination and editors
D. Nagelhout, J.P.M. Ros

Graphics
M. Abels, F.S de Blois

Design and layout
Uitgeverij RIVM

Corresponding Author
D. Nagelhout; dick.nagelhout@pbl.nl

Electric driving; an attractive challenge

Over the past years, electric driving has become more and more attractive because of the development of better batteries. Driving electric vehicles could drastically reduce CO_2 emissions, especially if more electricity would be generated by using sustainable energy. As most passenger cars are not used at night, this is the ideal time for charging their batteries. This would be cost-effective because, at that time, there is a surplus of generating capacity, and wind energy could also be used more effectively. Moreover, consumers will be able to drive clean and quiet vehicles at costs that seem surmountable in the future.

At least two obstacles still need to be overcome. The first of which is the current maximum range of electric vehicles of around a hundred kilometres. Battery producers and universities are working hard on the development of batteries that could be charged within 5 to 10 minutes at EV fast-charge stations. This limited range would not be a drawback for the so-called plug-in hybrid electric vehicles (PHEVs), which can run on both fossil fuel and electric power, and are expected to come onto the market in the near future. However, these hybrids reduce less CO_2 and carry slightly higher costs. The second obstacle is the need for a standardised European network of charging stations, and electrical outlets near residences and at commercial and public parking facilities.

This report shows the challenges facing the government and the business community of utilising the benefits of electric driving and of overcoming the obstacles.