

THE ELECTRIC VEHICLE SCENARIO: DOES IT GET US INTO THE RIGHT LANE AND CAN WE AFFORD IT?

Barry Zondag, Hans Nijland, Anco Hoen, Daniëlle Snellen
PBL Netherlands Environmental Assessment Agency

1. INTRODUCTION

To achieve EU climate ambitions and to reduce oil dependency, the European Commission aims for CO₂ emission reductions of 80% from all sectors and 60% from the transport sector, by 2050, compared to 1990 levels (EC, 2011a, b). By 2050, inner-city traffic should be carbon-free. The European Commission stresses that the decarbonisation of the transport sector firstly depends on technology development towards clean and efficient vehicles based on conventional internal combustion engines, and, secondly, on the deployment of breakthrough technologies in ultra-low-carbon vehicles. Currently, battery electric vehicles (BEVs¹) are widely seen as a promising breakthrough technology for decarbonising transport (see e.g. Barkenbus, 2009; McKinsey, 2009). Nevertheless, the market share of BEVs in new vehicle sales in Europe in 2011 was a modest 0.07% (EEA, 2012), despite the high ambitions of many European countries for a large-scale deployment of electric vehicles for the medium term ranging from 200 thousand vehicles in Norway and Portugal up to 2 million vehicles in France.

In order to realise these ambitions many countries have adopted supporting measures, like fiscal measures (e.g. tax exemptions or reductions for EVs) or parking facilities, to stimulate consumers to buy EVs. Substantial research focuses on the process of a transition towards fully electric driving. However, very few studies deal with the environmental and financial implications once the transition is completed. This paper focuses explicitly on this question and explores the pro's and con's of such a future. The study applies a scenario approach to explore these impacts applying a what-if scenario in which all passenger cars are fully electric by 2050. In addition the scenario assumes full electric urban freight distribution in 2050. A wide scope has been taken to get an overview of the potential impacts.

In section 2 the methodology and main assumptions are described in more detail. The impacts of electric passenger transport and electric urban distribution are presented in section 3 and 4. In Section 5 we discuss the sensitivity of the results for some crucial assumptions we made. The paper finalises with a discussion on the findings.

2. A WHAT IF EXPLORATION

A specific feature of this study is that we have taken a rather bold approach by exploring the long term impacts of a ‘what-if’ scenario. The what if question analysed in this study is: what are the consequences on mobility, the environment and the financial position of consumers and the government if the majority of transport is fully electric by 2050. It avoids the complexity of how to get there and simply assumes that such a change has been realised in 2050. We followed this approach to gain insights on the impacts of a fully electric scenario. The study presents findings on a wide set of impacts including transport, spatial, financial and environmental impacts and, where possible, we have quantified these impacts to get an impression of their magnitude.

The quantitative data and tools applied in this research are the Dynamo car ownership model, the National Model System as transport model and a base year matrix for road freight transport. The Dynamo car ownership model has been applied to explore the impacts of changes in fixed and variable car costs on car ownership. These changes in car ownership were input to the National Transport Model, together with changes in the variable costs of driving. The National Model System is a disaggregated choice model which is generally applied for transport studies at the national level in the Netherlands. In this study it was applied to quantify the impacts on vehicle miles travelled, infrastructure network usage and congestion.

For freight transport a proper forecasting tool for the Netherlands was missing in the time period of this study. Therefore a base year matrix for road freight transport by commodity type and vehicle type has been used to explore the potential effects of electric urban distribution. The ‘what-if’ scenario that has been tested, assumes that only light-duty trucks can operate within urban boundaries. The base year matrix was used to get an insight on the market size and composition, by vehicle and product type, of the urban freight transport included in this study. This information on the current market composition was used to explore the impacts by truck type in the number of trips, vehicle kilometres, ton kilometres and transport costs. The main driver of changes is the switch from heavy duty vehicles to light duty vehicles to/from and in urban areas.

As part of the nature of such explorative work we have made many assumptions about future technological conditions and price developments.

The main assumptions are described below and they are more thoroughly documented in the original report and background documentation (PBL 2012). To test the robustness of our findings we have performed a sensitivity analysis on two critical assumptions: the speed of technological progress and the future oil prices. This sensitivity analysis is reported in a separate section in this paper.

3. MAIN ASSUMPTIONS

3.1. Policy and taxes

We assumed a continuation of current policies and taxes in the Netherlands. This includes an EV tax exemption for registration tax but not for annual road taxes (the current EV exemption for annual road tax ends in 2015). Further taxes comprises of around 50% of the petrol fuel price at the pump, around 40% for diesel and 50% of the price of electricity for households.

3.2. Energy prices

We have assumed an oil price of USD 100 per barrel (2010 prices). This is slightly lower than some other recent scenario assumptions. For example, IEA (2011) assumes oil price of USD 125 dollar in 2035 in their reference scenario and of USD 135 in the New Policies scenario. Regarding electricity prices, based upon fully renewable sources, we assume a 50% increase by 2050. This percentage is in between that of studies by PBL (2009) assuming a 20% increases of electricity prices (without taxes) and ECF (2011) who assumed, in case of fully renewable sources, an increase in electricity prices of respectively 80% by 2030. In its world energy outlook the IEA study assumes electricity prices to remain more or less constant, however this does not include the conversion to fully renewable sources.

3.3. Efficiency improvement

Driven by increasingly stringent CO₂ standards we expect conventional internal combustion engine vehicles (ICEVs) to become some 40% more energy efficient. EVs will become more energy efficient as well. Estimates range from 20% (CE, 2011) to 80% (ElementEnergy, 2011). Combining efficiency improvements with fuel/energy prices as described above results in costs per kilometre. Table 3 shows the costs per kilometre driven for ICEVs and EVs, assuming high and low efficiency improvement for ICEVs.

Table 3 Fuel costs per kilometre in 2050 (index electric = 100), assuming high and low efficiency improvement for ICEVs.

Fuel cost per km (index electric = 100)	High efficiency improvement	Low efficiency improvement
petrol	130	150
diesel	100	135
electric	100	100

3.4. Battery costs

The cost of the battery is a big part of the price of an electric vehicle. Assumptions on the development of battery costs are therefore crucial for the cost of electric driving. A literature review (Anderman, et al., 2000; EPRI, 2001; Simpson, 2006; Kalhammer et al., 2007; BERR, 2008; Nemry & Brons, 2010; CE, 2011) shows that current cost estimates range between USD 200 and 1000 per kWh. Estimates on future costs are substantially lower. This may be an indication of trust in technology development and/or in economies of scale. Economies of scale are particularly important in the automotive industry (see e.g. Thomas, 2009; Thiel et al., 2010). Most studies estimate long term costs for a kWh between USD 200 and 300.

Range: The range of an EV is determined by the installed kW, the weight of the vehicle and the driving style of the user. Current EVs have a theoretical range of about 200 kilometres. However, the range under real-world driving conditions is 85 – 100 kilometres (see Kievit et al., 2012). We assumed a real-world range of 250 kilometres in 2050, a tripling of the current range. Furthermore, we assumed that the current lifetime of batteries (4 – 10 years, see e.g. CE, 2011; ElementEnergy, 2011) will be extended to 12 – 14 years, comparable with the lifetime of an ICEV. Currently, there are three ways to recharge the battery: by slow charging, by fast charging and by battery swapping. We have assumed that slow charging of batteries, complemented with some fast charging possibilities, is the leading technology in 2050. Firstly, because it requires less investments, and secondly because fast charging may affect battery lifetime (CE, 2011).

4. IMPACTS OF ELECTRIC PASSENGER VEHICLES

4.1. Car ownership and usage

Our model outcomes indicate a 10% to 20% lower degree of vehicle ownership (compared to the 2050 situation with only ICEVs) due to the higher purchase price of EVs. The number of households with more than one vehicle drastically decreases (more than 50%); the number of households without a vehicle increases by 10% to 15%. Despite the lower number of vehicles,

modelled total mileage remains more or less constant (-5% to +10%). This is mainly the result of the low driving costs of EVs.

4.2. Financial impacts consumer

To compare the costs of driving for different vehicles, we use the concept of total cost of ownership (TCO) which includes the total cost of acquisition and the operating costs. From a TCO perspective, EVs probably will remain more expensive than conventional vehicles running on petrol, diesel or gas. The average total additional costs of an EV in comparison to an ICEV are estimated at about 15,000 to 20,000 euros, based on the assumptions described in section 3. Table 5 shows the increase in TCO of EV's compared to ICEV's for various fuel types, vehicle mileages and vehicle weights. We have assumed a 'horizontal' switch (e.g. people switch from a light, medium or heavy weight ICEV to respectively a light, medium or heavy weight EV). The results show that only people who drive more than 20,000 km per year on petrol are likely to be cheaper off driving electric vehicles, especially if they are driving light vehicles. However, precisely for this group, the limited range of the electric vehicle and the long battery charging times create a relatively high resistance to switching to electric vehicles (see e.g. Hoen en Koetse, 2012). The TCO for diesel-fuelled vehicles is expected to be lower than for electric vehicles under almost all circumstances.

Table 5 Total costs of ownership of EVs compared to ICEVs, according to various fuel types, mileage and vehicle weight

	Petrol			Diesel		
	Annual mileage			Annual mileage		
	10,000	20,000	30,000	10,000	20,000	30,000
Light	+5%	-5%	-10%	+10%	+10%	+5%
Medium	+11%	0%	-5%	+20%	+15%	+10%
Heavy	+15%	+5%	-5%	+30%	+25%	+20%

4.3. Tax income government

Table 6 shows that, under an unchanged tax regime, the government will receive 5 to 7 billion euros less annual revenues (a 2% to 3% cut of a total annual government tax revenue). This loss of revenues is the result of three mechanisms: 1) electric vehicles are currently exempt from purchase tax, 2) annual road tax revenues are lower, as vehicle ownership is expected to decrease due to higher acquisition prices of EVs and 3) energy tax on electricity is proportionately lower than the excise duty on petrol and diesel.

If the government continues to aim for electrification of the passenger vehicle fleet, the government will need to apply a dynamic taxation policy to maintain the current level of revenues. Considering the figures in table 5 it is likely that these taxes need to be collected in other sectors, if governments do not want electric driving to become very unattractive for consumers.

Table 6 Comparison of government revenues (in billions of euros) for ICEVs and EVs in 2050

Revenues	Acquisition tax	Annual road tax	Levies + VAT	Total
2010	2	5	5.5	12.5
2050 ICEV	2.5-3	5.5-7.5	6.5-8.5	14.5-18.5
2050 EV	-	4.5-6.5	4-5.5	8-12
difference	-2.5 to -3	-0.5 to -1	-3	-6.5

4.4. Environmental impacts

The main result for the environment of the switch towards electric vehicles, is that the CO₂ emissions from the transport sector (excluding international shipping and aviation) would be halved, at the very least. This is under the assumption that the power supply is based upon sustainable sources. If we confront this potential with the high national and international targets we find that this scenario has high potential to meet the CO₂ targets in the transport sector, or vice versa without such a change (either electric or fuel cells) it would be very difficult to achieve the desired targets.

Other environmental impacts of electric vehicles are expected to be much smaller. Regarding air pollution the expected impacts are only marginal as conventional vehicles are expected to become much cleaner in the future as well. Electric vehicles are much less noisier at a low speed than conventional ones and noise annoyance caused by traffic in cities is predicted to decrease by about a third (Verheijen and Jabben, 2010). This means that potentially savings can be made with regard to noise measures that are no longer necessary and less urban land need to be restricted in its opportunities for development. At moderate speeds (from approximately 40 kph) the noise production of the tires is dominant and the difference between electric vehicles and conventional vehicles disappears.

4.5. Safety

The safety of electric cars in urban areas is disputed due to their low level of noise production. However, so far, most data analysis of traffic accidents with

hybrid vehicles involved in the Netherlands and in Japan did not show significantly higher risks for hybrid vehicles compared to conventional ones (Schoon and Huiskens, 2011). Nevertheless, since 2009 the Japanese government, the US Congress and the European Commission are exploring legislation to establish a minimum level of sound for EVs and hybrid electric vehicles when operating in electric mode.

5. IMPACTS OF ELECTRIC URBAN FREIGHT DISTRIBUTION

The aim of the European Commission of a carbon free inner-city transport in 2050 accounts for urban freight transport as well. In accordance with the section on passenger car transport we have explored a what-if scenario in which almost all urban freight distribution is electric by 2050. Almost refers to the fact that for specific types of transport with a very high energy demand, e.g. related to construction work, a switch towards electric vehicles is considered to be unrealistic.

Electrification of freight transport is not feasible for long distance freight transport. Other strategies, like a switch to biofuels or hydrogen, are considered to have more potential for this segment (PBL 2009). Our scenario therefore only assumes electrification of inner-city freight distribution.

Regarding urban freight distribution we have focused on the aspects of:

- Freight transport trips and kilometres by vehicle type;
- Use and location of logistic distribution centres;
- Land use impacts;
- Environment and safety;
- Government revenue.

The freight transport impacts have been explored by analysing a base year matrix for road freight transport by commodity type and vehicle type. We do recognise that future freight matrices are scenario dependent and might differ substantially from the existing matrix, however a proper freight transport forecasting tool was missing at the time of the study. The quantitative analyses on the existing base matrix was therefore a fall back option to provide us with insight on the order of magnitude of potential changes. Following the 'what if' scenario, of electric urban freight distribution, a consequence is that only light-duty trucks can operate within urban boundaries. Furthermore, we assume a real-world driving range of the trucks (3-10 tons) of 200 km which is less than the 250 km for smaller trucks and

vans. These driving ranges assume technological developments as described in section 3.

Overall the operating costs of vans and light-duty trucks are not expected to vary largely between conventional and electric engines. The vans and light duty trucks drive on average more kilometres annually than passenger cars. Therefore, the higher acquisition costs for the battery are better compensated with the lower energy costs. However, additional costs can occur if travel distances to and from the urban areas exceed the driving range of the electric vehicles. In that case an additional transshipment is needed. On average the daily use of light duty trucks and vans appears to be within the driving range distance of electric vehicles. Processed data from the National Bureau of Statistics indicates daily distances of on average around 100 km for trucks under 7 tons and 170 km for trucks between 7 and 12 tons.

5.1. Changes in freight transport

The main changes in freight transport are summarised in table 7. These changes have been calculated by decomposing the base year matrix in different market segments by commodity type, distance, urban relationship and number of shipments (Significance 2012). Furthermore, the changes are calculated by applying the differences in average load factors between light and heavy vehicles and the need for transshipment for long distance trips in and out of urban areas (outside driving range of electric vehicles).

The table shows that the main change is the increased number of trips with light duty vehicles due to a switch from heavy to light vehicles. The need for transshipment for long distance trips with light vehicles also results in an increase in light vehicle trips but has only a small effect on vehicle and ton kilometres. The overall effect is that the number of vehicle kilometres slightly increases and that the ton kilometres slightly decreases. The decrease in ton kilometres results from the lower load factor of light vehicles compared to the more heavy ones. The overall impacts on the costs of freight transport are rather small compared to the size of the underlying changes.

Table 7 Main changes in freight transport

	Light duty vehicles (between 3 and 10 tons)	Heavy duty vehicles (above 10 tons)	Total
Number of trips	+194%	-19%	+51%
Total vehicle kilometres	+61%	-14%	+7%
Total ton kilometres	+40%	-11%	-5%

Average trip length	-45%	+6%	-29%
Costs	+63%	-14%	+4%

5.2. Urban consolidation centres and spatial impacts

The electric light duty vehicle scenario gives a strong incentive to use urban consolidation centres to transfer the long distance transport by heavy duty vehicles into light duty vehicles. Such transshipment results in additional costs but also gives the opportunity to consolidate flows and save costs by increasing the utilization factor of vehicles. The overall effect of the use of urban consolidation centres is hard to estimate, more theoretical exercises result in overall benefits but in practice we do not see many successful examples yet. The growing demand for urban distribution centres will result in a spatial claim to accommodate these centres. Furthermore, the attractiveness of urban fringe locations for the retail sector will potentially increase due to the restrictions for conventional vehicles within urban areas.

5.3. CO2 emissions

The most important environmental impact is the reduction in CO2 emissions estimated between 1 and 2 megatons, depending on the scenario assumptions for the growth in freight transport. This is relatively modest compared to the reduction of 14 to 27 megatons for the transition towards electric passenger car transport. For the freight transport sector the overall CO2 emission reduction goal of -60% therefore also requires policy measures to reduce CO2 emissions from long distance freight transport.

5.4. Tax income government

Due to the fact that the taxes for freight vehicles, both fixed taxes and fuel taxes, are much lower than the taxes for private cars, the impact of the switch towards electric urban distribution on the tax income of the government is estimated to be zero or slightly positive (see table 8). In contrast with the passenger transport this will likely not be an obstacle.

Table 8 Comparison of government revenues (in billions of euros) for ICEVs and EVs in 2050 for electric urban distribution

Revenues	Acquisition tax	Annual road tax	Levies + VAT	Total
2010	<0.5	0.5	1.5-2	2.5-3
2050 ICEV	<0.5	0.5-1	1.5-2	3
2050 EV	<0.5	0.5-1	2	3-3.5
difference	0	0	<0.5	<0.5

6. SENSITIVITY ANALYSIS

As the long term future is highly uncertain, the results of this study depend on many assumptions. Two crucial assumptions deal with important drivers of fixed and variable costs, the technological development of batteries and the oil price development respectively. In this section, we explore the sensitivity of our outcome for these assumptions.

6.1. Technology development

We assumed in our electric scenario that in 2050, batteries will be three times cheaper than they are now (see section 3). This is somewhere in the middle of current estimates. Current batteries have a life-time of 4 - 10 years. We assumed an extended life-time for batteries of 10 -14 years. If this does not come true, and life-time remains unchanged, TCO of EVs increases a lot (see table 9, life-time of 8 years, in comparison with table 5, life-time of 12 years) .

Table 9 Total costs of ownership of EVs compared to ICEVs, according to fuel type, life-time of batteries of 8 years (instead of 12 years)

	Petrol			Diesel		
	Annual mileage			Annual mileage		
	10,000	20,000	30,000	10,000	20,000	30,000
Light	+30%	+15%	+5%	+40%	+30%	+25%
Medium	+45%	+30%	+15%	+55%	+45%	+35%
Heavy	+55%	+35%	+25%	+80%	+70%	+60%

If, on the other hand, batteries would become much cheaper, TCO of EVs would decrease a lot. The TCO for EVs would be the same as for ICEVs for the average consumer if battery-costs would decrease by a factor 4 - 5 (i.e. around 1.5 times cheaper than we assumed). High-mileage drivers would be cheaper off, while low-mileage drivers would still pay more than they would with an ICEV). In that case, the government would still lose 5 - 7 billion euros yearly (due to loss of acquisition tax and fuel levies mainly). Only if battery-costs would decrease by at least a factor 20 (i.e. 7 times more than we assumed), losses for consumers and government together would be compensated, as TCO for EVs would in that case be much lower than TCO of an ICEV (ceteris paribus). If the huge consumer benefits of 5 - 7 billion euros would be redirected towards the treasury, neither consumers nor the government would in that case lose money by electric driving.

6.2. Oil price development

In this study we compared the electric scenario with the conventional scenario. The electric scenario would become more attractive if electric driving became cheaper (by swift technological development) or if driving an ICEV became more expensive. In the conventional scenario we assumed oil prices of \$₂₀₁₀100/barrel. With prices of around \$₂₀₁₀200/barrel (and unchanged tax rates), from a consumers point of view of petrol cars, the break-even point is reached (table 10). With oil prices that high, for all consumers together TCO of an ICEV becomes as high as TCO of an EV. Government would still lose 5 - 7 billion euros annually (mainly due to loss of acquisition tax and fuel levies). Only when oil prices reach around \$₂₀₁₀400/barrel, losses for consumers and government together would be compensated, as electric driving would in that case become extremely cheap compared to driving an ICEV. Again, if the consumer benefits of 5 - 7 billion euros would be redirected towards the treasury, neither consumers nor the government would lose money by electric driving.

Table 10 Total costs of ownership of EVs compared to ICEVs, according to fuel type, mileage and vehicle weight with oil price \$₂₀₁₀200/barrel

	Petrol			Diesel		
	Annual mileage			Annual mileage		
	10,000	20,000	30,000	10,000	20,000	30,000
Light	0%	-10%	-15%	+10%	+5%	0%
Medium	+5%	-5%	-10%	+15%	+10%	+5%
Heavy	+10%	-5%	-10%	+30%	+20%	+15%

6.3. Lessons learned

A drastic increase in oil prices or a swift technological development could eventually turn the picture in favour of the electric car. However under most circumstances government and consumers should expect that an electric scenario is substantially more expensive than the conventional scenario. Most researchers looking at TCO of EV and ICEVs come to similar conclusions as we did. Prud'homme (2010) calculated the 'private additional cost' of an EV (compared to an equivalent ICEV) to be around 12,000 euros on a lifetime basis (for a 2010 EV in France). Crist (2012) extends this exercise to a comparison of three EV types with their ICEV counterparts, using recent price figures for EVs available on the market (data from Renault). Taking into account a subsidy of 5,000 euro and depending on the vehicle segment considered, the EV's additional costs amount to 4,000 to 5,000 euro over the vehicle's lifetime. With a higher daily mileage (e.g. 90 km/day), the financial benefit would be 4,000 euro. The latter often relates to very specific niches (a

high daily mileage, frequent deliveries, frequent charging opportunities). Prud'homme and Koning (2012) conclude that 'the 100% electric car appears as a gamble on the part of producers and governments. Until massive cost and deficiency improvements are achieved, it will require enormous subsidies. If they are achieved, and achieved rapidly, this gamble might pay off. If not, a lot of resources will have been wasted. On the other hand, Offer et al. (2010) conducted such an exercise and concluded that EVs will probably be the cheapest vehicles (on a lifetime basis) by 2030.

7. CONCLUSIONS

The attention for electric transport is not new and in the beginning of the 20th century many people expected the car to become an electric one. Even Henry Ford invested in an electric vehicle company in the early nineteenth hundreds (Dennis & Urry 2009). The electric car however, lost the battle from the internal combustion engines mainly due to availability of better infrastructure which made longer trips possible and therefore required longer-range vehicles. Also the discovery of oil in Texas, the invention of the electric starter and the initiation of mass-production by Henry Ford made ICEVs much more affordable than electric cars. Looking at the future of electric transport we can conclude that the disadvantages of high costs and limited range still exist and it is very uncertain if the speed of technological development is fast enough to solve these issues in the coming decades. If we look at the speed of technological development over the last two decades we must conclude that it has not been sufficient and more radical breakthroughs will be needed to give electric transport a truly competitive position.

In this study we found that, under our set of assumptions, in a world where all cars are electrical ones, car ownership will be significantly lower due to the higher purchase prices of EV's. Car mileage will be roughly the same, since driving an EV is cheaper than a traditional car. Less cars are therefore driven for more kilometres per car. The lower car ownership means that more people and also more households depend on other forms of transport. An increase in demand for public transport might well occur.

Under the current tax regime most of the financial consequences of the electric vehicle scenario are for the government facing a much lower tax income for passenger transport. Even though the consumer pays much less car related taxes the overall financial impact for the consumer as an aggregated group is expected to be negative. If we allow for heterogeneity in consumer behaviour it gives a more mixed picture with a more positive outcome for people driving many miles compared to people with a modest car

usage. Please note that the outcome of the financial impacts depends both on the speed of technological progress as well as the future oil prices as explained in section 6. For urban freight transport we do not see similar large financial consequences in comparison to passenger transport. The reason for this is that freight transport pays less taxes under the current tax regime and that freight vehicles drive, on average, many more kilometres per year than a passenger vehicle.

The biggest environmental impact is that the switch to electric transport will seriously reduce the CO₂ emissions from the transport sector by a factor 2. This is under the assumption of green power production.

The study has also results in the following recommendations:

- Focus equally on other options (fuel cells, biofuels) as the electric car has so far not proven to be the superior solution. This means that the current focus and target setting for electric vehicles needs to be broadened with other alternatives. In the case of the Netherlands we like to emphasize the use of supply side incentives to support technological developments, currently the Netherlands focuses strongly on consumer incentives;
- Raise awareness that if we like to meet CO₂ targets for transport this does not only call for a costly transition but most likely for higher costs for transport at a structural basis. If this is acceptable governments should improve their capability to apply dynamic taxation policies to ensure their revenue;
- The driving range of a car will become an important competitive factor in an electric world and cars will be differentiated by battery costs and driving range. A better match between consumer preferences for driving ranges and the battery costs of the car can help to reduce the existing financial barrier.
- Potential early adopters of electric vehicles are drivers with many trips over relative short distances, such as vans for last mile delivery, taxi's or consumers with such patterns (like city drivers). Further multi-modal options can be explored to overcome the barriers of electric transport.

BIBLIOGRAPHY

Anderman, M., F. Kalhammer & D. MacArthur (2000), Advanced batteries for electric vehicles: An assessment of performance, cost, and availability, California Air Resources Board.

Barkenbus, J. (2009), Our electric automotive future: CO2 savings through disruptive technology, *Policy and Society*, 27, 399-410.

BERR (2008), Investigation into the scope for the transport sector to switch to electric vehicles and plug-in hybrid vehicles, Dep. for transport, United Kingdom.

CE (2011), Impacts of electric vehicles, Deliverable 1 (An overview of electric vehicles on the market and in development) 2 (Assessment of electric vehicle and battery technology) en 3 (Assessment of the future electricity sector), CE, Delft.

Crist, P. (2012), Electric Vehicles Revisited - Costs, Subsidies and Prospects, OECD, Paris.

Dennis, K. & J. Urry (2009) *After the car*. Cambridge: Polity Press.

ECF (2011), Power Perspectives 2030, On the road to a decarbonised power sector, The Hague.

EEA (2012), Monitoring CO2 emissions from new passenger cars in the EU:summary of data for 2011, Copenhagen.

ElementEnergy (2011), Influences on the Low Carbon Car Market from 2020–2030. Final report, Cambridge: Element Energy Limited.

EPRI (2001), Comparing the benefits and impacts of hybrid electric vehicle options, Electric Power Research Institute (EPRI), Palo Alto, California.

European Commission (2011a), A Roadmap for moving to a competitive low carbon economy in 2050, COM(2011) 112 final, Brussels: European Commission.

European Commission (2011b), White paper, Roadmap to a single European Transport Area, Towards a competitive and resource efficient transport system, COM(2011) 144 final, Brussels: European Commission, 2011

IEA (2011), World Energy Outlook, 2011, Paris: IEA.

Hoën A. & M.J. Koetse (2012), A Choice Experiment on AFV Preferences of Private Car Owners in The Netherlands, PBL Working Paper 3, PBL Netherlands Environmental Assessment Agency, Den Haag, 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, USA.

Kievit O., van de Kieft, J., van Wezel, R., Koffrie, R., van Goethem, S., Bolech M. (2012), Afsluitende rapportage praktijkproef elektrisch rijden RWS , TNO 2012 R10624, Delft.

McKinsey & Company (2009), Roads toward a low carbon future: reducing CO2 emissions from passenger vehicles in the global road transportation system.

Nemry, F. & M. Brons (2010), Plug-in hybrid and battery electric vehicles. Market penetration scenarios of electric drive vehicles, EC, JRC, IPTS.

Offer, G.J., D. Howey, M. Contestabile, R. Clague and N.P. Brandon (2010), Comparative Analysis of Battery Electric, Hydrogen Fuel Cell and Hybrid Vehicles in a Future Sustainable Road Transport System, *Energy Policy* ,38 (1), 24-29.

PBL (2009), *Getting into the right lane for 2050*, The Hague:PBL.

PBL (2012), Nijland, H.A., A. Hoën, B. Zondag, D. Snellen, Elektrisch rijden in 2050: gevolgen voor de leefomgeving, Den Haag: Planbureau voor de Leefomgeving.

Prud'homme, R. (2010), Electric Vehicles: A Tentative Economic and Environmental Evaluation, Discussion Paper 2010-22.

Prud'homme R. and Koning M. (2012), Electric vehicles: a tentative economic and environmental evaluation, *Transport Policy* 23, 60-69.

Schoon, C.C. & C.G. Huijskens (2011), Verkeersveiligheidsconsequenties elektrisch aangedreven voertuigen, SWOV-rapport R-2011-11, Leidschendam.

Significance (2012), Memo verkenning duurzaam goederenvervoer 2050, De Haag

Simpson (2006), Cost-benefit analysis of plug-in hybrid electric vehicle technology, Paper presented at the 22nd International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition (EVS-22) Yokohama, Japan.

Thiel C., Perujo, A., Mercier, A. (2010), Cost and CO2 aspects of future vehicle options in Europe under new energy policy scenarios, *Energy Policy* 38, 7142-7151.

Thomas, C.E. (2009), Fuel cell and battery electric vehicles compared, *International Journal of Hydrogen Energy* 34, 2065-2074.

Verheijen, E. & J. Jabben (2010), Effect of electric cars on traffic noise and safety, Bilthoven: RIVM.

NOTES

¹ Main concepts of electric vehicles are:

- *Battery Electrical Vehicle (BEV)*: BEVs contain a large battery which is the only available power source in the vehicle. BEVs are driven by one or several electric motors.
- *Hybrid Electrical Vehicle (HEV)*: besides an electric motor, an HEV also contains a combustion engine which can often operate either separately or together, depending on the architecture chosen by the manufacturer.
- *Plug-in Hybrid Electrical Vehicle (PHEV)*: a PHEV is an HEV that adds a plug, a charger and a larger battery so it can be charged with electricity from the grid. As with HEVs, different kinds of motor architectures are possible (serial, parallel or combined line-up of electric motor vs. combustion engine).
- *Fuel Cell Electrical Vehicle (FCEV)*: a FCEV uses an electric motor for its propulsion. The electricity is generated on-board in the fuel cell which uses hydrogen that is stored in a pressurised tank within the car.

This article focuses on Battery Electric Vehicles.