Electric vehicles – the future of passenger transport?

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Abstract

This paper evaluates the market and environmental performance of all-electric and plug-in hybrid vehicles. We briefly discuss the technical state of the art and current activities of various market actors. Next, we show how electric vehicles compare to their (obvious) competitors, particularly hydrogen fuel cell vehicles and improved ICE vehicles. Furthermore, based on market penetration scenarios for the Dutch road transport sector, we show the impact of a large scale shift towards electric vehicles on CO_2 emissions, local air quality, and costs. A well-to-wheel assessment of climate benefits shows that the method of electricity generation is the predominant factor determining CO_2 emissions. Finally, we discuss which policy instruments are suited for stimulating electric vehicles.

Introduction

BACKGROUND AND CLIMATE GOALS

At a time of steeply rising atmospheric CO_2 emissions, volatile oil prices, and increasing transport demand, the transport sector receives a lot of attention. Not only policy makers are concerned with how to deal with global warming and a possible future oil scarcity, but also society is engaged in discussions on future alternatives to present cars with internal combustion engines (ICE). One of these alternatives, the (plug-in) electric vehicle, is increasingly receiving attention.

In Europe (EU-27) the share of transport in total greenhouse gas emissions is approximately 22% (EEA, 2008). Road transport accounts for 72% of all transport-related CO_2 emissions, a fraction that has increased by 32% between 1990 and 2005 (DG TREN, 2008). The Stern Review on the Economics of Climate Change (Stern, 2006) indicates that the developed world needs to achieve emissions reductions of 60-80% by 2050 in order to prevent excessive climate change. This reduction target is relative to the year 2000. As economies continue to grow, the demand for transportation tends to increase correspondingly. Therefore the transport volume is expected to double until approximately 2050. Consequently, if the required CO_2 reduction is to be divided equally across all sectors, and taking sector growth into account, the transport sector has to cut CO_2 emissions by about 70-90% compared to 2000. Several European governments have already announced plans to electrify their road transport sector.

This paper evaluates the market and environmental performance of all-electric and plug-in hybrid vehicles. We briefly discuss the technical state of the art and current activities of various market actors. Next, we show how electric vehicles compare to their (obvious) competitors, particularly hydrogen fuel cell vehicles and improved ICE vehicles. Furthermore, based on market penetration scenarios for the Dutch road transport sector, we show the impact of a large scale shift towards electric vehicles on CO_2 emissions, local air quality, and costs. A well-to-wheel assessment of climate benefits shows that the method of electricity generation is the predominant factor determining CO_2 emissions. Finally, we discuss which policy instruments are best suited for the stimulation electric vehicles.

The electric vehicle

VEHICLE TYPES

Cars with electric engines on board can be divided into hybrids, plug-in hybrids, and all-electric vehicles. Hybrid vehicles, like the well known Toyota Prius, power their electric engine only with 'on board' generated electricity, by their ICE engine, and recovery of braking energy. In contrast, plug-in hybrids, and all-electric vehicles (also) store energy from the national electricity grid in on board batteries.

Hybrid vehicles

A hybrid vehicle is powered by an electric motor and a (relatively small) battery in combination with an internal combustion engine that also drives a generator that can load the battery. The hybrid technology allows the internal combustion engine to be run close to its optimum efficiency point. When the car is being driven at lower speeds and under low loads, stored electrical energy in the battery is used to power the car. At higher speeds and under hard acceleration power is supplied by the internal combustion engine. This type of hybrid is called a parallel hybrid, because the internal combustion engine and the electric motor are both directly connected to the drive train and wheels. Parallel hybrids are most commonly produced at present (e.g. Toyota Prius). In contrast, in a so called series hybrid, the combustion engine only drives an electric generator instead of directly driving the wheels. The greatest efficiency gains compared with a conventional car are made in town driving with frequent acceleration, braking and stops. On highway trips hybrids are hardly more efficient than conventional vehicles (King, 2007).

Plug-in hybrids

For the greatest CO_2 and efficiency benefits to be gained from hybrid technology, the battery will need to be charged by electricity from the grid rather than the internal combustion engine. These "plug-in" hybrids are vehicles that can be plugged into an external charging point to extend their electric drive range. This requires a much greater battery capacity than 'normal' hybrids. When their battery is depleted, plug in hybrids can switch to power generated by their on board internal combustion engine, thereby offering a much larger driving range compared to an all electric vehicle. However, plug-in hybrids are inevitably more expensive, due to the additional ICE engine. In practice, plug -in hybrids are able to drive a large percentage of the time powered entirely by the electricity grid since most car trips, including home to work commuting, are relatively short.

All electric vehicles

Fully electric, battery-powered vehicles, are only loaded by electricity from the grid. Currently the compromise between battery weight and capacity on the one hand and battery price, on the other hand, results in a broad range of driving ranges. At the low end of the market, the relatively small batteries result in driving ranges of less than 100 km. At the high end price range, the large batteries enable driving ranges of 300 km and more. Recent developments in battery technology raise the expectation that, in the longer term, batteries could offer better driving range, performance and recharging time at lower costs.

ENVIRONMENTAL PERFORMANCE

CO_2 emission reduction is predominantly determined by the energy generation chain. Based on the present electricity mix, and associated CO_2 emission, the climate benefits of electric transport are still modest. The future potential, however, is very substantial. Basic well to wheel calculations for electricity generation combined with carbon capture and storage (CCS) show that a large overall CO_2 reduction is possible. Future coal power plants, with 85% CCS, are expected to reach an efficiency up to 40-45%, equalling about 135 g CO_2/kWh, whereas future gas plants, with 85% CCS, are expected to reach an efficiency of 50-55%, equalling about 70 g CO_2/kWh (Eurelectric, 2007). Additional energy losses, and associated CO_2 emissions, are low since the overall energy chain of electric transport is rather efficient. The energy chain of electric transport from the production plant to the car, battery charge, discharge, on board power electronics and electric engine, can reach an overall efficiency of up to 85%. Consequently, the total potential CO_2 reduction of electric transport – also compared to advanced future ICE technologies - can be very substantial. See also the more detailed example in the section on environmental impact.

Low carbon electricity sources

Low CO_2 electricity production of fossil fuel burning with CCS can be supplemented or supported by alternative CO_2 free production electricity production from renewable sources, including wind, hydro, geothermal, photo-voltaic. Furthermore electricity from electric vehicles could be produced by nuclear power plants.

CO_2 extensive electricity production from fossil sources does critically depend on large scale implementation of Carbon Capture and Storage technology (CCS). The full potential of the CCS technology is however not yet unequivocally quantified. According to a recent study by Clingendael (van den Heuvel, 2008) the CO_2 storage in the Netherlands will have to rely on the portfolio of depleted gas fields. In a realistic case, the Dutch subsurface could technically store approximately 35-40 Mton/year of CO_2 for a period of 40 years (equal to the typical lifetime of a power station). Currently the technology is in the demonstration phase.

TECHNOLOGICAL DEVELOPMENTS

Batteries

Batteries are the crucial technology for electric vehicles. Key battery requirements include: (1) a high energy density (sufficiently small per kWh) and physically manageable, (2) acceptable price and lifetime, (3) safe and (4) recyclable. Currently, lithium ion phosphate batteries, are regarded as the best solution. The energy density of these type of batteries is around 150-200 Wh/kg, but is expected to be 250-275 Wh/kg, and reach 400 Wh/kg in 10 years (Hansen, 2008), thereby also doubling the driving range compared to the present generation of batteries. Furthermore it is important to realize that hybrids require batteries with different characteristics compared to batteries in plug-in hybrids and all electric vehicles. Batteries in hybrids are usually operated in a narrow segment of the charge-

Table 1 Scenario overview

Reference: Clean and Efficient policy scenario with moderate EU policy	Scenario: specific innovation (electric vehicles) in the Netherlands and the EU
Policy as announced in the Dutch programme 'Clean and Efficient': • Road pricing • European CO_2 regulation for passenger cars at 130 g/km in 2015, moderate CO_2 regulation for vans • Fiscal measures, e.g. for drivers of company cars and registration tax differentiation • Promotion of ecodriving	This scenario includes the following, on top of the 'Clean and Efficient policy': • Quick market penetration of the all electric car: 300.000 all-electric vehicles in 2020; 1 mln in 2025, 1.8 mln in 2030, 3.5 mln in 2040 • Buses: hybrid or on hydrogen; • 85% of newly sold cars is hybrid in 2020, 25% of these is plug-in hybrid. • Heavy duty vehicles: 15% hybrids
Biofuels[1]: 10% in 2020 and beyond	15% in 2020, 20% in 2030
Efficient tyres: 25% at passenger cars	Complete penetration of efficient tyres in 2030, high penetration of energy saving ICT (90% in 2030)

[1] *Expressed as share of total gasoline and diesel volume including biofuels (i.e. excluding other alternative fuels).*

discharge curve, to optimize energy efficiency and battery life. In contrast, batteries in plug-in hybrids and all electric vehicles require batteries that can be discharged as deep as possible, in order to increase the driving range. Batteries with suitable capacities for electric cars (Li-Ion) are currently mass-produced by two suppliers, AESC (joint venture of NEC and Nissan) in Japan and A123 an American company producing in East Asia. These type of batteries need to be charged slowly (e.g. overnight). Batteries that can be charged fast in combination with a long lifetime are not expected to become available within the next three years. Global availability of lithium, is not a fundamental critical issue (Hanschke et al, 2009).

Infrastructure

Electric vehicles need a dedicated infrastructure both for charging at home and elsewhere. This can be relatively simple, since an average car can be charged overnight from a single household electricity group (220V, 16 Amps). In the Netherlands, however, many people do not have a garage or private parking place on their own territory. Only about 1,5 million households out of 7 million have the possibility to install home charging facilities where they can charge the car at their own territory. Consequently many 'charging spots' will need to be constructed in public locations as well as at locations where people work. Charging points, like water and power distribution networks and telecommunications networks, could be designated as regulated assets, typically enabling the service provider to cover installation and operating costs and achieve an adequate return on their investment. This could be an incentive for utility firms to install them. (BERR, 2008). Most likely, providers will develop and implement 'smart' solutions for billing the electricity. Finally some electric vehicle concepts rely on the installation of battery exchange stations, as a solution to extend the initially limited driving range of electric vehicles. Therefore large-scale implementation of the electric vehicle infrastructure will take time. An additional possibility to extend the driving range of electric vehicles is the development of fully automated battery exchange stations. This model, however, would require a high level of standardisation of the battery, which may hamper an optimal distribution of the battery weight in the bottom of the car.

Market penetration scenarios

In the context of the Dutch road transport sector, several innovation scenarios have been developed to illustrate the prospects of technical innovations in drive trains and alternative fuels (Hanschke et al, 2009). This paper will focus on one of these scenarios where electric transport has a key role. The scenarios have each been based on an ambitious, but considered to be realistic and coherent vision of the future road transport sector in which innovation will be one of the key elements to further reduce CO_2 emissions. Therefore, the scenario contains a combination of different innovations in drive trains and fuels, e.g. electric transport and (plug-in) hybrids, biofuels, efficient tyres, energy saving ICT. The other scenarios, not discussed in this paper, respectively focus on hydrogen and on a continuing dominance of the ICE, with large contributions of hybrids, biofuels, and CNG/biogas.

The EV scenario is compared to a Reference scenario, representing the implementation of the most important measures from a Dutch policy strategy called Clean & Efficient, as displayed in Table 1. The energy use and CO_2 emissions of road transport have been calculated with a simulation model (TEMPO; Transport Emission Model for POlicy evaluation) for the years 2020, 2030 and 2040. The model includes the vehicle stock and indicates what penetration rates could be achieved. The market penetration scenario for electric vehicles and plug-in hybrids assumes market shares as depicted in Figure 1.

These market shares have been based on the following assumptions, visualized in Figure 1. The emergence of electric transportation is preceded by a strong emergence of hybrid vehicles. Around 2015 half of all newly sold passenger vehicles will be hybrid. 10% of those will be plug-in, increasing the share of (plug-in) hybrids from 85% of newly sold cars in 2020 to 100% in 2040. Assuming a sufficiently available charging infrastructure, improving technology with decreasing additional costs and satisfied users, after 2020 more and more hybrid vehicle owners will switch to the plug-in hybrid. With an electric range of approximately 30-60 km, an average user can drive approximately half the distance using electricity. This results in a rapid increase in the share of plug-in hybrids. In 2030, 4 out of 10 hybrids will be produced as plug-ins. A comparable de-

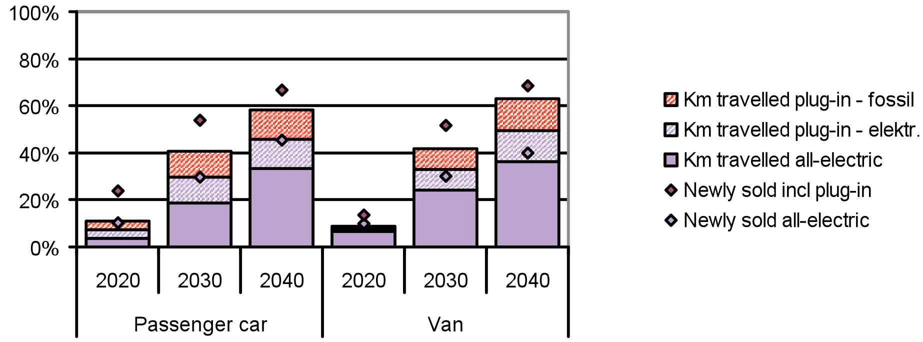

Figure 1. Market shares electric vehicles and plug-in hybrids

velopment is foreseen for delivery vans; however this may take some more time.

Meanwhile, the technology for all-electric vehicles has been further developed and become available commercially. Around 2015 this technology will gradually start penetrating the vehicle fleet. The early adopters will likely be either in the low mileage segments or in the high mileage segments. In the low mileage segments such as second cars, the small battery size will result in an attractive vehicle price, enabling a larger group of consumers to buy the vehicle. In the high mileage segments, particularly business cars, the substantial additional cost of a large battery is no barrier since the investment is counterbalanced by low mileage costs. In addition, this market segment benefits from the green image of electric driving. Moreover the development of this market segment will be facilitated by solutions such as battery swapping or fast charging. By 2020 the charging infrastructure will be readily available, costs will decrease and the range will gradually increase.

After 2020 the new group of all-electric drivers will mainly consist of people who have already gained experience with electric driving through a plug-in hybrid. These users prefer the financial advantage of all-electric compared to plug-ins (only one drive train). At the other end of the market there are users who transfer from hybrid to plug-in hybrid. The number of newly sold electric passenger cars increases from around 10% in 2020 to an approximate 45% in 2040. The market share can continue to increase after 2040. However, for some segments electric transportation could be a less attractive option, such as for long distance driving, 4 WDs and caravan pulling. These applications will eventually not go beyond plug-in hybrids (unless the action radius issue is solved by e.g. fast-chargers). A comparable development is expected for delivery vans.

Environmental impact

CO_2 EMISSIONS

Calculations using the TEMPO model (see Annex 1) show considerable reductions in CO_2 emissions in the EV scenario compared to the reference, as shown in Figure 2. The rapid increase in emission reduction is due to a combination of the increasing market share and an improving CO_2 emission factor. Despite comparable market shares (see Figure 1), the reduction from plug-in hybrids is smaller, because the vehicles are still partly driven on fossil fuels.

The key factor in the emission reduction potential of electric transport is the method in which the electricity is generated. In this analysis, the basic assumption was based on the average emission factor of the Dutch electricity generation mix, and the expected improvement of this in line with government ambitions. Due to an increase in the share of renewable electricity and the application of CCS (CO_2 capture and storage) in a number of electricity plants, the emission factor is assumed to decrease from 500 g/kWh in 2020 to 300 g/kWh in 2040.

There is however another level of complexity in the choice of the emissions factor, because the actual emissions also depend on when the car is charged. Large scale charging at night might make use of baseload coal-based power with corresponding high emissions. It can also make use of renewable power when other demand is low, obviating the need for additional storage. Moreover, it can be discussed whether the generating mix average is a good measure of the emissions to be attributed to electric driving. A more accurate approach would be to determine the marginal emission factors, based on the mix of additional power plants (or those with increased production) required meet the extra demand of the transport sector. This is a complex matter with many uncertainties, which deserves a separate study[1]. As a sensitivity analysis, in this study two alternative emission factor trajectories were considered, based on two alternative production routes for the power use of the transport sector:

- Low: electricity from a mix of new coal and gas plants equipped with CCS, and/or a high share of renewables.
- High: electricity from new coal plants without CCS.

An emission factor of 0 g/kWh is theoretically possible, but is, however, unlikely before 2040, unless it can be regulated, for instance with certificates showing that the electricity used to charge a car is from (additional) renewable sources. Table 2 summarizes the above principles for the sensitivity analysis. The direct emissions are not included (amount always 0).

Figure 3 presents the resulting CO_2 emissions, and clearly illustrates the sensitivity to the electricity generation mix. Given the fact that the EV scenario also contains a substantial share of innovations not dependent on the emission factor of electricity, such as biofuels, energy saving ICT, and efficient tyres, there is still a large emission reduction even in the 'high' scenario. It turns out that the reduction specifically attributable to electric vehicles and plug-in hybrids ranges from 2,3 Mton

1. See e.g. www.itm-project.nl.

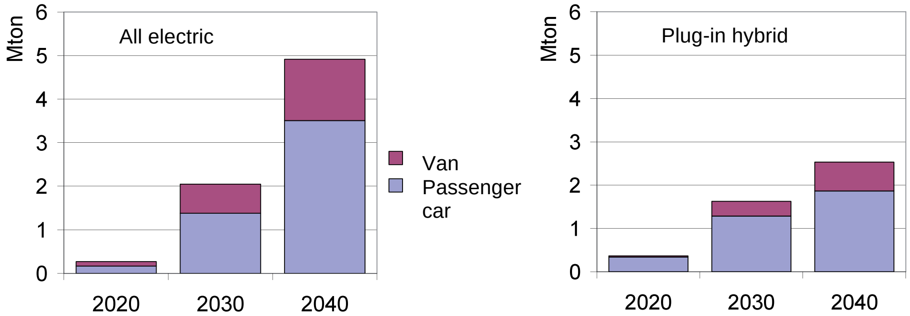

Figure 2. CO_2 emission chain reduction potential electric transportation and plug-in hybrid

Table 2. Principles sensitivity analysis emission chain factors electricity

CO_2 emission chain factor [g/kWh]		2020	2030	2040
Basic	–	500	400	300
Low	–	100	100	100
High	–	600	600	600

(high scenario) to 10,9 Mton (low scenario) in the year 2040, corresponding to range of 5-25% reduction compared to the reference scenario.

OTHER EMISSIONS

Driving electrically is also beneficial for local air quality. Figure 4 shows the impact of the EV scenario on the emissions of NO_x and PM_{10} (particles). The reference scenario already shows a significant reduction, particularly between 2010 and 2025, as a result of the tightened European standards. Because of this, the remaining emissions in 2040 have already decreased by 70% to 75% compared to 2010, and the main problem regarding these emissions will already be solved independently of the introduction of electric vehicles.

Costs

CURRENT COSTS AND OPPORTUNITIES FOR COST REDUCTION

The key factor for market introduction of electric vehicles is to overcome the 'chicken and egg dilemma', of producing initially expensive cars and a challenging infrastructure, before mass production will reduce the battery and car price and customers start to pay for the infrastructure. The price of electric vehicles is dominated by the battery costs. At present, a battery price of 10,000-15,000 Euro and a corresponding battery capacity of 20-30 kWh, depending on vehicle size and weight, corresponds to a driving range to about 150-200 km. There is a realistic prospect that battery prices will go down in the future and that the energy density will increase; especially when mass production starts. Battery research for other purposes (laptops, mobile phones) has already contributed to better batteries, and will continue to do so in the future. The calculations in this study are based on a scenario where present battery prices, as mentioned above will decrease rapidly towards about 5,000 Euro in 2020 and 3000 Euro in 2040.

COST EFFECTIVENESS IN THE EV SCENARIO

Table 3 shows the cost effectiveness from a national perspective[2] for all electric transport and plug-in hybrids. The costs are based on assumptions regarding decreasing battery costs as documented in (Hanschke et al, 2009). Around 2030 the cost effectiveness of electric transport is expected to be approximately 300 Euro per ton avoided CO_2. Up to 2040 the cost effectiveness will further improve to approximately 150 Euro per ton. This decrease is the result of decreasing additional costs per vehicle and decreasing fuel cost. Due to the extra cost of a double drivetrain, it will take until 2040 for plug-in hybrids to reach a cost effectiveness of roughly 300 Euro per ton avoided CO_2.

The analysis is based on crude oil prices around 9 Euro/GJ in 2030; this corresponds to some 70 USD/barrel. A sensitivity analysis where fossil fuel prices are 50% higher shows that the cost effectiveness of electric transport in 2020 and 2040 will improve with 75-100 Euro per ton, via roughly 175 Euro per ton in 2030 to 75 Euro per ton in 2040. The cost effectiveness for plug-in hybrids will improve comparably, to reach a cost effectiveness of roughly 225 Euro per ton in 2040.

Competing technologies

OVERVIEW

Improvement of conventional ICE technology

Several studies have indicated that advanced technologies can improve the efficiency of ICE vehicles by up to 50% at increasing, but still achievable costs (Passier et al, 2008). The recently adopted EU standards on CO_2 emissions from cars are likely to provide a strong incentive into this direction. However, unless strong mobility reductions are achieved simultaneously, it is unlikely that further progress in conventional car technologies,

2. This concerns the cost effectiveness from a national perspective, not considering subsidies and taxes. The financial balance will be different for the owner of the vehicle.

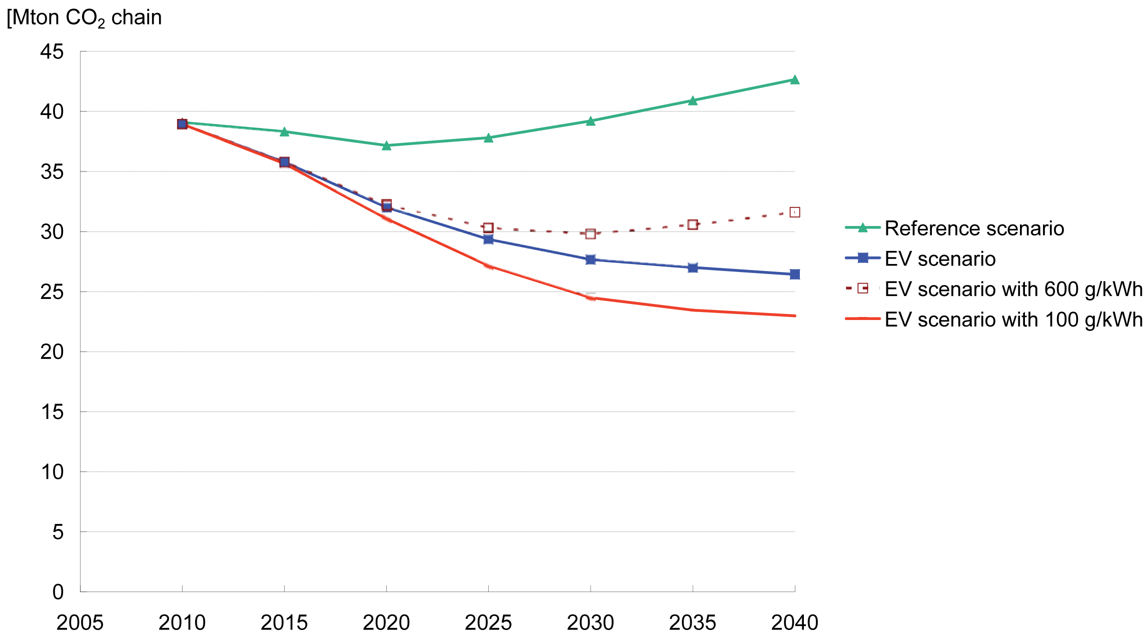

Figure 3. Well to wheel CO_2 emissions road transport: sensitivity analysis emission factor electricity

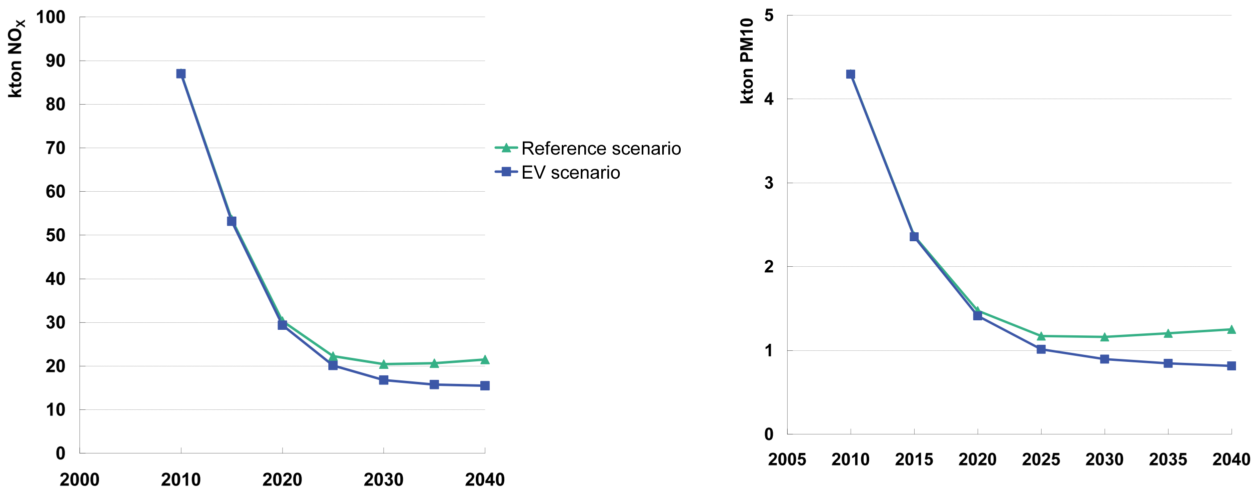

Figure 4 Direct remaining emissions road transport: NO_x (left) and PM_{10} (right)

Table 3. Cost effectiveness CO_2 emission chain - Electric transport and plug-in hybrid

	Electric transport			Plug-in hybrid		
	2020	2030	2040	2020	2030	2040
Δ CO_2 emission chain (Mton)	0,3	2,0	4,9	0,4	1,6	2,5
Δ Fuel cost (bln Euro)	0,0	-0,2	-0,3	0,0	-0,2	-0,2
Δ Additional costs vehicle fleet (bln Euro)	0,3	0,8	1,0	0,5	1,0	1,0
Δ Total costs (bln Euro)	0,2	0,6	0,7	0,4	0,8	0,7
Cost effectiveness (Euro/ton CO_2)	>300	200-300	125-150	>300	>300	200-300

including optimising of ICE, hybridisation, weight reduction, tyres, and aerodynamics, can improve the efficiency of cars further than about 50%. Consequently, emission reduction in the range of 80-90% can only be achieved with energy carriers that allow further decarbonisation than present technologies, such as electricity or hydrogen.

Biofuels

Liquid biofuels (biodiesel, bioethanol and alternatives including methanol and DME) can (up to certain levels) substitute petrol-based liquid fuels in internal combustion engines and are suitable for both passenger cars and trucks. The availability of sufficient biomass resources that meet sound sustainability criteria regarding biodiversity and competition with food production remains a critical issue. In this respect, second generation technologies are more favourable because they use non-food crops which also have a higher energy density. A short term advantage of biofuels is that they can be applied in the existing vehicle stock. In the long term, biofuels may be most effectively applied in long haul freight transport since this market is likely to be the most difficult in which to substitute hydrogen, and even more difficult for electric propulsion. This is mainly related to large energy storage requirements, and related fuelling times, for long haul trucking. FT diesel can substitute for regular diesel without engine modifications.

Hydrogen

The introduction of hydrogen in fuel cell cars would be an even more disruptive technology than electric transport because it requires changes in the drive train, distribution infrastructure and the setup of hydrogen production facilities. Particularly the fuel cell vehicle has high initial costs. For hydrogen to break through, demand must increase sufficiently to recover the high cost of building up an infrastructure, while the car industry must have a sufficient market perspective to justify the high development costs. For light vehicles, fuel cell propulsion is attractive, because the refueling time is less than the recharging time with electricity. For long-distance travel, hydrogen is less attractive as there are some difficulties in storing large amounts of hydrogen on board, and the fact that the advantage over conventional vehicles is limited in this sector given the relative high fuel efficiency of conventional internal combustion engines (HyWays, 2007). Bus transport can relatively easily be substituted by hydrogen propulsion.

CNG/SNG

In several EU countries, such as Italy, Germany, and increasingly the Netherlands, CNG (compressed natural gas) finds its way into the transport sector. Driving CNG is beneficial for local air quality, particularly until 2014, when the EURO 6 standard will be introduced. The climate benefit is limited to some 15-20% compared to a gasoline car and 5% compared to a diesel car. In the long run, CNG is not a predecessor for hydrogen in fuel cell cars, because there are too many differences between the gases and their infrastructures. CNG could be regarded a predecessor to green gas. This is most appropriate for biogas from digestion of residues, for which the potential however will be limited to some 10% of the fuel demand of Dutch road transport, while other applications of this biogas, in electricity generation are also possible. The other source of green gas is SNG from biomass gasification. However, the same resource can also be used for producing second generation FT diesel, a liquid transport fuel that does not require a separate refueling infrastructure and adjusted vehicle. Moreover, the biomass required for SNG or FT diesel should be grown sustainably and should not compete with food supplies.

Drive-train independent efficiency improvement

Furthermore, no regret options such as efficient tyres, aerodynamics, and energy efficient ICT can be introduced at short notice and implemented in the complete vehicle stock, having a relatively large impact in absolute terms. Last but not least, demand reduction should always be a major priority, because less (alternative) fuel is needed to satisfy the remaining demand.

COMPARING ELECTRICITY AND HYDROGEN

As they are both secondary energy carriers allowing zero emission vehicles (no emissions from the exhaust valve), electricity and hydrogen seem to be the obvious competitors. Although at the moment, electricity seems to be closer to the market it is definitely too early to pick a winner, given the large technical and market barriers still to be dealt with. Both have their strengths and weaknesses.

Several stakeholders will play a role in facilitating the market introduction of hydrogen and electricity. First, consumers and companies will have to provide the market demand and accept new technologies with somewhat different specifications. Furthermore, policy support by governments will be crucial to both hydrogen and electricity, (see the next section). Apart from the government and consumers, other important stakeholders that will determine the market success of hydrogen and electricity are the oil industry and electricity companies, respectively. For electricity companies, electric vehicles will be an expansion of their activities, also providing additional advantages, especially related to the potential electricity buffer of batteries in parked electric vehicles. For the oil companies, hydrogen production will substitute their present core business, but at the same time offer an opportunity to remain the dominant supplier of car fuels, instead of losing this position to the electricity sector.

The transitions to hydrogen or electric driving do not completely exclude each other, although it is not likely that both will break through simultaneously and at the same rate. In the long term, combinations are also possible. For instance a further development of the plug-in hybrid, where the ICE is replaced by a fuel cell which charges the battery. It will depend on costs and performance developments how the market shares of fuel cell cars, electric vehicles and plug-in hybrids will evolve.

Policy implications

At the moment, the high additional cost of an electric car or plug-in hybrid vehicle, mainly due to high battery costs, imposes a barrier for large scale market penetration. At the same time, mass production is needed to induce technology learning and associated battery cost decreases. Therefore, government support is essential. Table 4 gives an overview of the type of policy measures to be considered. National governments can stimulate the market penetration of electric and hybrid vehicles by offering fiscal benefits such as reduced registration, congestion or circulation taxes and a reduced excise tax on

Table 4. Policy instruments

Vehicle (purchase or use)	Fuel/infrastructure	Supporting policy
For hybrids: reduced registration tax	Low excise tax Electricity	Access to inner cities, reduced parking fees
For PHEV and EV: Large scale demonstration projects, compensation additional vehicle cost	Coordination setup recharging infrastructure	Regulation free choice Electricity supplier

the electricity. In addition, local governments can stimulate electric vehicles by offering exemption from parking charges or exclusive access to city centres. Furthermore, building up a recharging infrastructure needs government coordination, because it involves (international) standardisation. Additional regulation will be required to ensure that consumers can select their own electricity supplier when charging their car at public locations.

With increasing market maturity, technology-specific support can be replaced by more generic instruments such as the current EU CO_2 reduction standards for cars. It is important to design these standards in such a way that they not only induce incremental innovation, e.g. improvement of the ICE, but also provide incentives for developing those innovative technologies that are required for large emission reductions in the long term. This can be done by introducing weights rewarding CO_2 performance which go further than the current standards, and by providing a clear perspective in terms of long-term binding standards. Otherwise, the car industry may be forced to invest most of their resources to reach the short term targets, by gradually improving the (conventional) technologies.

Co-benefits electric vehicles

Electric vehicles also offer benefits in terms of security of energy supply; reducing demand for oil from unstable world regions. This is very important for governments and a potentially powerful argument to support the development of electricity for future transport.

In addition, electric vehicles can create a buffer between the mismatch in energy production and consumption (e.g. cars can be instructed to start charging from the control center when the wind is blowing). This is potentially attractive for electricity companies. The average car can be fully charged at a home charging spot within a maximum of 8 hours for a fully depleted battery, average recharge times are expected to be between 2 to 3 hours.

Conclusions

Both hydrogen and electricity provide the potential for road transport to achieve ambitious CO_2 emission reduction targets, corresponding to the ambitious climate goals for 2050 of about 80% CO_2 reduction. Consequently, apart from a certain share of advanced 2nd generation biofuels for freight transport and, possibly, a small fraction of advanced ICE based vehicles, a substantial share of road transport demand should be met by low carbon secondary energy carriers such as hydrogen and/or electricity. Still, in view of the limited availability of (renewable) energy resources, energy efficiency and mobility management remain very important.

Although electricity seems to be closer to the market than hydrogen, both technologies require a system innovation and are still in the demonstration phase, and therefore it is too early to pick a winner. Both electricity and hydrogen do rely heavily on CCS, particularly in the medium term, to ensure that CO_2 emissions reductions are also achieved when fossil fuel resources are used. Both technologies also provide flexibility in the choice of energy carrier and thereby contribute to a more diversified energy supply. The air quality advantage is becoming less important with the introduction of stricter emission standards for conventional cars. Finally, electric vehicles support the electricity system, since their batteries can be applied as a buffer between mismatch in energy production and consumption.

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Annex 1 TEMPO Transport model

ECN's transport model TEMPO (Transport Emissions Model for POlicy evaluation) determines the emissions and energy use of the entire transport sector based on several data inputs, including (anticipated) amount of kilometers driven (so-called *transport performance*). By comparing scenarios with different staring points, it is possible to determine the impact of certain measures on the emissions and energy use of the sector. This annex describes the TEMPO module on road transport.

Road transport is divided into a number of categories, including passenger cars, delivery vans, buses, trucks and lorries. Per category a further subdivision is made according to the primary fuel (gasoline, diesel or LPG). To enable calculations of future scenarios, advanced drive-train technologies or alternative fuels have been added to the model, including hydrogen fuel cell cars, electric vehicles, and (plug-in) hybrid versions for gasoline and diesel. Below is a schematic overview of the model:

Development of the car fleet

Starting with the historical fleet composition, the model determines the composition of the future car fleet via 5 year cycles. To this end, the most recent car fleet composition, per category (e.g. passenger cars on petrol), will be aged five years older, which will also lead to the omission of part of these cars. In the next step, the number of new cars required is determined, which, combined with the original dated fleet, are needed to achieve the desired future transport performance. The market shares per scenario then determine the distribution of new cars over new technologies. This way, a technology can be introduced in a realistic manner, indicating from which segment of the market it must be extracted.

Savings resulting from technology

In addition to switching to alternative technologies/fuels, three other technological developments have been included that could significantly influence the efficiency of future cars: 1) Hybrid powered engines (possibly plug-in), 2) low rolling resistance tyres, 3) Intelligent transport systems (smart ICT applications). These technologies can gradually penetrate the car fleet along with the inflow of new cars.

Determining energy use and emission

Every year, the standard energy use per type of vehicle is determined for a technology/fuel. This consumption is then adjusted for two aspects. The first adjustment is related to a number of scenario-specific exogenously defined efficiency improvements, which will be required, for example, to meet the current EU standards (e.g. passenger cars: 130 g/km in 2015). This could also include expected efficiency improvements resulting from more efficient driving. Secondly, consumption is also corrected for the present share of the three above-mentioned saving technologies based on the assumed saving percentages. The emissions are derived directly from fuel consumption.

Cost calculations

Per scenario the annual costs are determined. Currently, this has only been done for the (additional) costs of the car fleet and the total fuel costs.

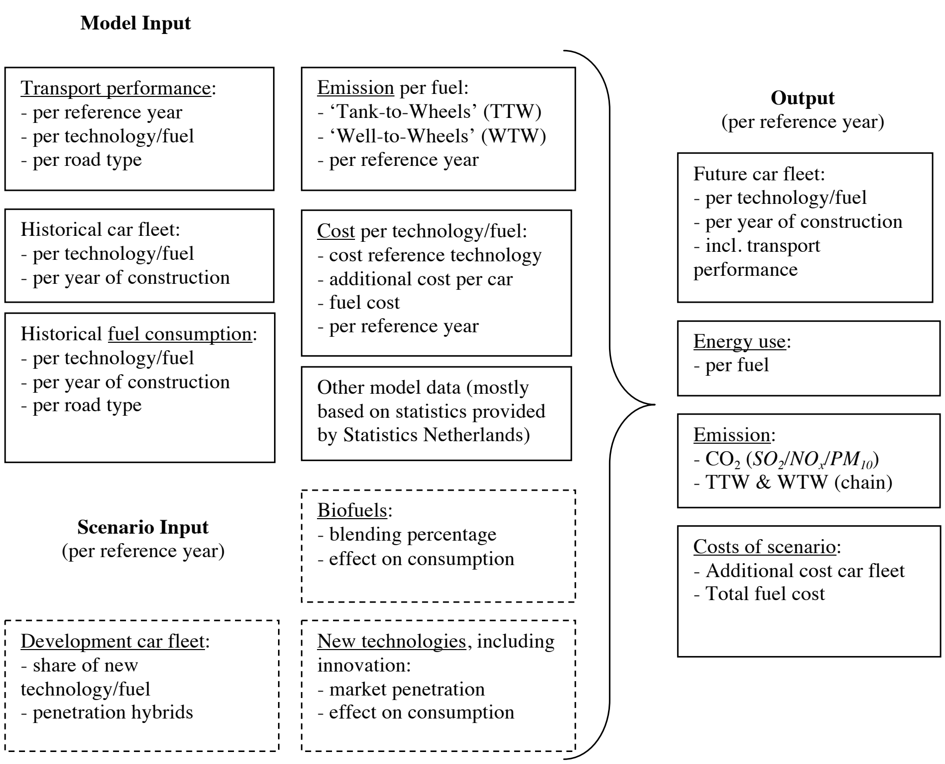

Figure 5. Schematic overview ECN's transport model TEMPO