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Opportunities for the Use of Renewable Energy in Road Transport

Policy Makers Report

March, 2010

TNO - Science and Industry
RWTH - Institute for High Voltage Technology
ECN - Policy Studies

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Executive Summary

RETRANS has special focus on electric vehicles and renewable electricity in road transport.
Electric and plug-in hybrid vehicles[1] are close to the market. As such they offer an opportunity for a structural transition to using renewable energy widely in road transport at an earlier stage than other technologies (e.g. hydrogen or advanced biofuels).

Synergy opportunities for the transport and the electricity sector through co-evolution
Synergies between innovations in the transport and the power sector support the business case and simultaneous uptake of electric vehicles and renewable electricity. The main opportunities are:

- Electric vehicles can reduce the mismatch between electricity demand patterns and the intermittent supply pattern of renewables like wind and photovoltaics. They can do so by serving as grid-connected electricity buffering capacity and by restricting charging to periods between peaks in electricity demand. This would require controlled charging of electric vehicles through the use of smart grid systems.
- In the short run, functions can be easily implemented into the charging behaviour of the vehicles that increase electricity grid stability and reliability. In the longer run electric vehicles can provide a range of other services to the grid such as standby power and storage capacity. The report shows that these services can be worth several hundred Euros per year to the grid operators and energy suppliers. This is especially true for the first 0.5% to 1% of vehicles replaced in the total vehicle stock[2].
- By connecting electric vehicles to a renewable electricity supply they can become truly zero-emission-vehicles. It should be assured that electricity used by electric vehicles is guaranteed to be fully balanced by the feed-in of additional renewable electricity, as this will help vehicle manufacturers reduce fleet emissions, provide an important marketing point for early-adopting consumers and will further increase the demand for renewable electricity.

A coordinated approach is required *now*

- To harvest these synergies and realize a co-evolution of the energy and transport systems, a coordinated approach for energy and transport policy as well as technical system integration is *urgently* required.
- Although the issue is complex, it shall not be left "for a later stage", but must be included in early pilot projects now. Early action in **standardisation** for e.g. charging and communication**, design of grid codes** to enable the vehicles to provide grid related services and **system architectures** to ensure the grid's ability to integrate a high number of electric vehicles is necessary to allow full utilisation of synergies at a later stage.
- Policy makers are urged to define this coordinated approach with the involved stakeholders, to ensure that the advantages of the synergies of renewable energies and electric transport are fully utilised.
- This coordinated approach needs to consider all aspects, e.g. grid services in the design of batteries, meters, plugs and billing software. Pilot projects should be undertaken through an integrated approach to trigger further technological development and investments.
- An integrated strategy is required that includes:
    - Coordination between actors;
    - A strong focus within the pilot projects on powering electric vehicles with renewable energy and on integration with smart grid developments;
    - Pilot projects that work on different aspects within the overall strategy;
    - Focus on niches in the first phase while preparing necessary pre-conditions for a large-scale roll out of electric vehicles in the second phase of market development;
    - An integrated policy framework that provides investment security and creates an advantageous level playing field for electric vehicles, competing with other vehicles;

[1] In the remainder of this document referred to as "electric vehicles"

[2] equivalent to 1 million electric vehicles and plug-in hybrid electric vehicles in EU on a total vehicle stock of > 200 million cars.

  - Development of specific policy instruments to stimulate coordinated uptake of electric vehicles powered with renewable electricity, utilising the synergies of electric vehicles and renewable energies.
- The report discusses a number of **innovative policy instruments** to stimulate the production of **additional** renewable electricity in conjunction with the market uptake of electric vehicles to ensure that electric vehicles are truly zero-emission vehicles. Examples are:
  - System stabilizing bonus and other financial rewards for renewable energy powered electric vehicles providing grid services;
  - Tax exemptions for electric vehicles powered by renewable energy;
  - Hard coupling: An additional renewable energy target for electric transport growing proportionally with raising market penetration of electric vehicles;
  - A strategy to trigger investments into renewable energy for use in electric transport could include the set-up of a dedicated energy fund that invests in the physical build-up additional renewable electricity generation capacity. Financial contributions to the fund can be provided by the automotive and energy industry, e.g. in return for zero-emission credits for vehicles sold.

Electric vehicles leading the way to sustainable mobility
- Electric vehicles need renewable energy to realise their full potential with respect to the transition towards a sustainable transport sector with minimal greenhouse gas emissions and strongly reduced dependence on fossil and other finite energy sources. Increased flexibility compared to nuclear power generation (in installation size and location, for instance) give renewable energy the edge over nuclear in this respect.
- Stimulated by proper policies and existing as well as new market drivers, electric vehicles can also serve to speed up the transition towards sustainability in the energy system.
- Synergies between energy and transport system, as identified in the example of electric vehicles and renewable electricity, may also exist for other options such as biofuels and hydrogen that allow the use of renewable energy in transport. As electric vehicles have limitations with respect to range, these alternatives are likely to also have a place in a future sustainable transport system, e.g. for long haul and heavy goods transport by road, as well as in navigation and aviation.

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1 Introduction

1.1 Preamble

The transport sector is one of the major emitters of greenhouse gases (and other pollutants). According to the IEA there is a need for a four-fold reduction of the carbon intensity of transport. Hence, the transport sector needs a transformation – a revolution in technology, infrastructure, transport concepts and political framework in order to achieve the goal of at least 50% CO_2 emission reduction by 2050.

The increasing energy use in the transport sector is adding also to the dependency of countries on oil imports. In the reference scenario of the IEA World Energy Outlook 2008 the transport sector is the largest contributor to oil-demand growth in non-OECD-countries, accounting for 57% of global primary oil consumption in 2030 compared with 52% in 2008 and 38% in 1980. Despite continuing improvements of the average vehicle fuel efficiency, the sheer increase in vehicles numbers and kilometres driven, in particular in upcoming economies, is expected to keep pushing up demand for oil in the transport sector.

To reduce the greenhouse gas emissions from the transport sector and its dependence on imported oil to the levels as indicated above requires a true transition of the transport sector and its energy system. The main ingredients to realise such a transition are:

- reducing the energy demand of vehicles;
- shifting towards less carbon-intensive and carbon-neutral, renewable energy carriers;
- shifting towards more energy-efficient or less carbon-intensive modes of transport;
- curbing the growth of transport demand.

For the short term (2010-2020) energy efficiency improvements in fossil-fuelled vehicles will be the most important means of achieving intermediate GHG reduction goals. However, in order to start a transition towards a sustainable transport system that meets ambitious sustainability targets for the longer term (2030-2050), we do need to start the development and initial implementation in the short term of options that enable the use of renewable energies in road transport.

This report discusses the current state of the art of the use of options for using renewable energies in road transport, and explores possible synergetic effects between the evolution of road transport and the increased uptake of renewable energy. Also, policy options are identified to accelerate the transformation of road transport towards significantly lower carbon emissions.
The focus of this report is on battery-electric and plug-in hybrid vehicles using renewable electricity. One reason for taking electric vehicles as example is that this option is currently receiving a lot of attention, with part of the interest stemming from electricity companies looking for options to use electric vehicles to resolve challenges related to the foreseen increased use of intermittent renewable electricity production. Given the state-of-the-art of electric and plug-in vehicles on the one hand and the immanence of problems associated with large shares of wind energy production already occurring in some countries, this option is likely to be the first where the synergies emerging from a co-evolution of vehicles and energy system can be harvested.

1.2 Why we need to start a transition towards applying renewable energy in transport

At the start of the 21st century the way we use energy in transportation is coming to a crossroads. High price volatility seems to support the thesis of an approaching peak oil scenario, just as the inherent dangers of climate change resulting from greenhouse gas emissions are becoming more obvious. However as of 2009 still more than 90% of transportation relies on fossil fuels burned in combustion engines, resulting in approximately a quarter of the world's CO_2 emissions. With transport volumes growing significantly world-wide[3] in the next decades our dependence on imported oil as well as the greenhouse gas emissions from transport will increase, if we do not switch to alternative propulsion systems using renewable energy sources.

1.2.1 Energy dependence and security of supply

From an economic point of view as well as from the perspective of resource depletion the transport sector's dependence on (imported) fossil fuels is a growing problem. Over the next several decades the world is expected to run out of cheap oil [IEA 2009a]. Unconventional oil sources are still abundant but can only be exploited at high costs. Furthermore, due to the worldwide growth of the transport sector, the production capacity for fossil transport fuels is expected to experience difficulties in keeping up with increasing demand, leading to high price volatility and price peaks. In 2008 oil prices soared to levels well above 100 US$ per barrel. Although the present economic down-turn will be suppressing energy prices for some time, the IEA expects that between now and 2030 the oil price will on average remain at a level of 100 US$ per barrel or more.

Almost all of the growth in oil demand is expected to come from non-OECD countries (about 40% from China, 20% each from India and the Middle East and the remainder from emerging Asian economies). This means that price developments will be largely dictated by economic growth patterns in non-OECD countries, rather than by those of the OECD countries.

[IEA 2009a] predicts an oil production increase of about 20% between now and 2030. Of this market growth the Middle East OPEC countries take the lion's share, while production of conventional oil in non-OPEC countries declines. At the same time an increasing share of the total production is in the hand of the national oil companies of the oil producing countries. This represents an increased economic dependence of the industrialised world on a limited number of sometimes politically unstable countries and an increasing capital flow towards these countries.

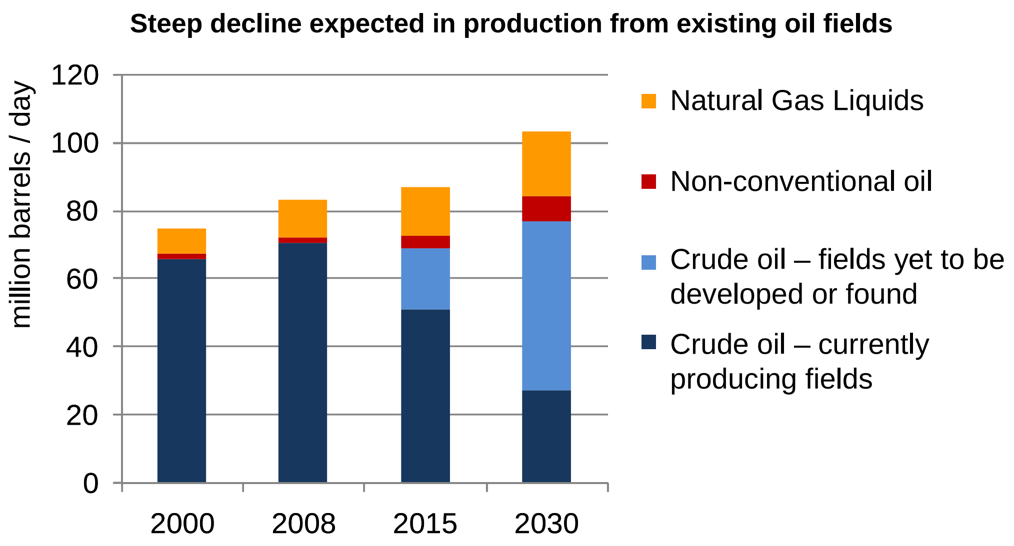

Figure 1 World oil production by source in the reference scenario [IEA 2009a]

Matching the above mentioned growth requires huge investments in exploration and development of new oil fields. This is not only caused by the increase in demand but even more by the expected steep decline in production from currently producing fields (see Figure 1). A gross capacity of 64 million barrels per day needs to be installed between 2007 and 2030, which is six times the current production capacity of Saudi

[3] OICA estimates that there are between 600 and 800 million cars on the road worldwide, with annual world-wide sales of around 50 million vehicles (source: www.oica.net).

Arabia, to meet the growth in demand and offset the decline in production from existing fields [IEA 2008a]. Overall [IEA 2008a and 2009a] conclude that "current energy trends are patently unsustainable" from a social, environmental, and economical point of view.

1.2.2 Greenhouse gas emissions

Man-made emissions of greenhouse gases contribute to global warming. The main greenhouse gases emitted by the transport sector are carbon dioxide (CO_2), and to a lesser extent methane (CH_4) and nitrous oxide (N_2O)[4]. Emissions of methane and nitrous oxide can be expressed in CO_2 equivalents on the basis of their Global Warming Potential[5] (see [IPPC 2007]). Besides these components emissions from black carbon (a component of particulate matter emissions from combustion engines) are currently gaining attention as another climate influencing emission [ICCT 2009].

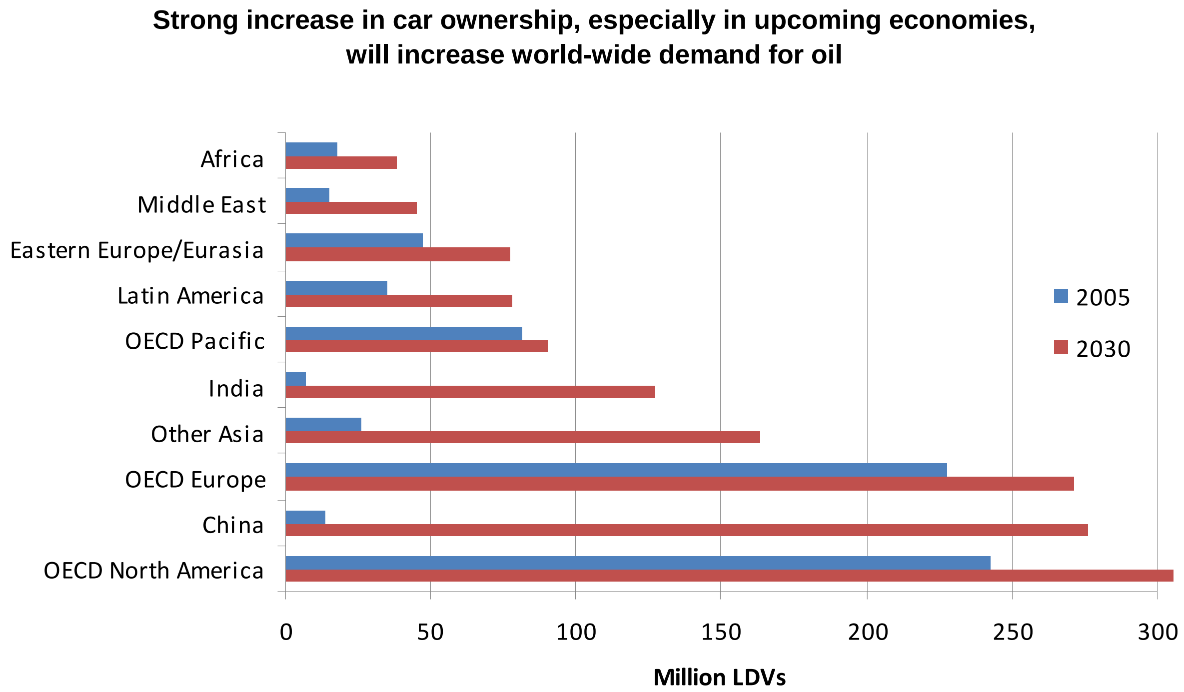

Figure 2 Development of light duty vehicle stock by region in the reference scenario [IEA 2009a]

Over the past decades in many industrialised countries greenhouse gas reduction policies have resulted in stabilisation or even reduction of greenhouse gas emission in all economic sectors except the transport sector. Due to increasing transport volumes in road transport, aviation and maritime shipping and as a result of vehicle weight increase counteracting a large part of the engine efficiency improvements achieved in road transport, the greenhouse gas emissions of the transport sector continue to grow. Especially in upcoming economies a huge increase in car ownership and transport in general is expected (see e.g. Figure 2). This, together with the growth in the use of oil for other applications and the increased use of coal and natural gas, is expected to lead to a 45% increase in world-wide energy-related greenhouse gas emissions between now and 2030 (see Figure 3).

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[4] Furthermore also emissions of coolants from mobile air conditioners contribute to global warming.

[5] GWP of a substance is the amount of CO_2 emission in kg that has the same effect on global warming as 1 kg emission of that given substance. The GWP over a 100 year time horizon for CH_4 is 25, for N_2O it is 298 (according to IPCC 2007).

Growing use of fossil fuels in upcoming economies leads to increase in world-wide greenhouse gas emissions

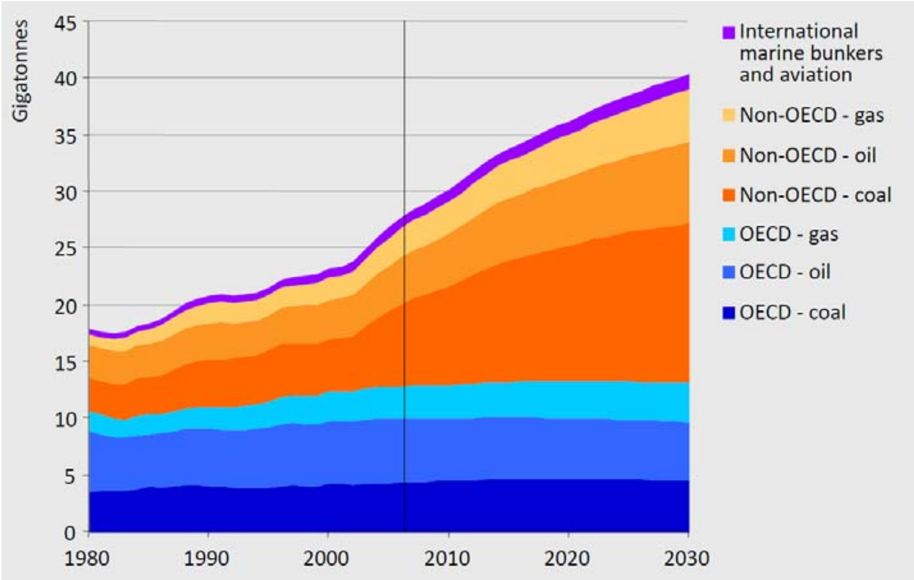

Figure 3 World-wide greenhouse gas emissions (in Gton CO_2-equivalent) resulting from the use of fossil energy [IEA 2008a]

To keep global warming below 2ºC the concentration of CO_2 in the atmosphere needs to be stabilised at 450 ppm[6] by the end of this century. This 2ºC target has been adopted by the European Community and many other governments, and is a strong guidance in discussions with respect to post-Kyoto climate goals and policies to be agreed at the Copenhagen summit in December 2009.

To achieve this goal, greenhouse gas emissions of the industrialised world need to be reduced by at least 80% in 2050 compared to 1990 levels. More recently the European Council has called upon developed countries to adopt a reduction target of 80 – 95%[7]. This is to compensate for the expected growth of emissions from upcoming economies. In fact, in the IEA reference scenario some 97% of the projected increase in energy related greenhouse gas emissions comes from non-OECD countries, of which three quarters from China, India and the Middle East. Emission growth needs to be curbed in these countries as well, as the total required emission reduction is larger than the current greenhouse gas emission from OECD countries together [IEA 2008a].

For Europe the European Environmental Agency has estimated that, if the present growth of greenhouse gas emissions from the transport sector is extrapolated to 2050, by that time the transport sector greenhouse gas emissions will exceed the total emission target for Europe (see Figure 4). It is clear from this that drastic greenhouse gas reductions will be required from the transport sector in order for it to play its role in reaching long term sustainability targets. From the fact that most of the growth in world-wide emissions stems from developing economies it is clear that also for these countries solutions must be made available to significantly reduce greenhouse gas emissions from transport relative to the reference projection.

An overall global GHG reduction target for the longer term has not been set, let alone a specific global reduction target for the transport sector. Given the growth in transport volume it is nevertheless clear that the reduction percentage required relative to future emissions in the baseline scenario is much larger even than the reduction target set relative to the 1990 reference situation. It is likely that the transport sector will

[6] ppm = parts per million

[7] See Presidency Conclusions, Brussels European Council, 29/30 October 2009, http://register.consilium.europa.eu/pdf/en/09/st15/st15265.en09.pdf

have to reduce total GHG emissions by 50 – 80% compared to 1990 in order to contribute to meeting this overall target. Given the expected growth in transport volume the required reductions per kilometre driven are even higher.

Without measures greenhouse gas emissions from transport will equal or exceed the total emission target for Europe

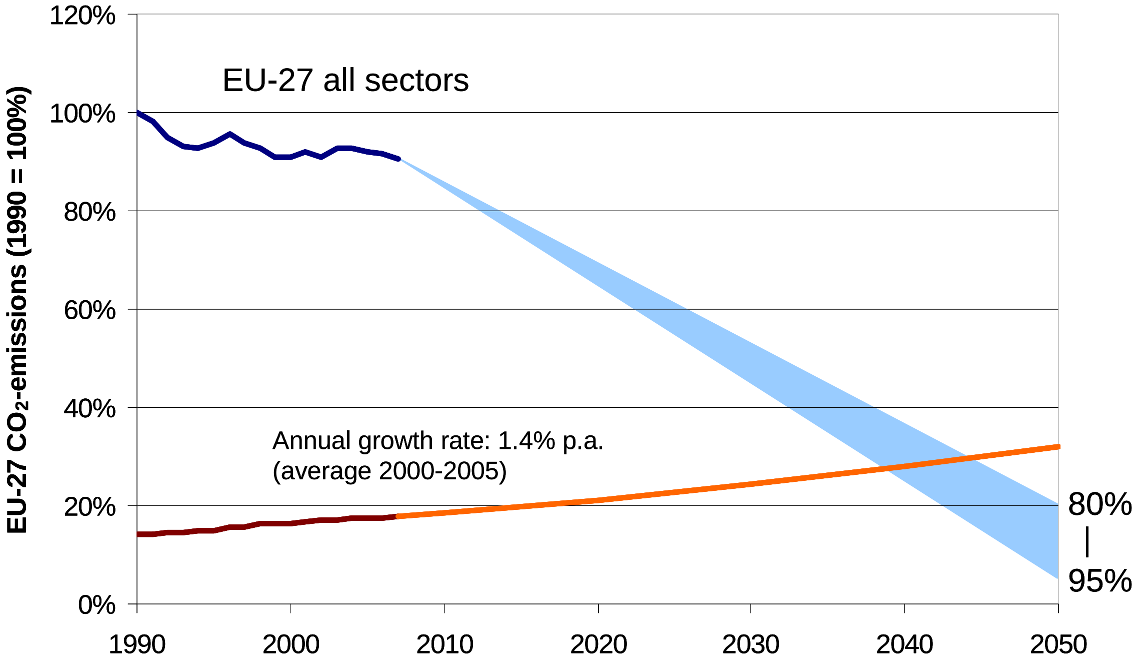

Figure 4 Comparison of projected GHG emissions from the European Transport sector with overall GHG emission targets for 2050 (graph adapted from [EEA 2009])

1.2.3 Local air quality

Besides global warming, the transport sector is also a major contributor to problems related to air quality at a regional and local level. In developed countries the most relevant substances in local air quality relating to vehicle emissions currently are particulate matter and nitrous oxides. Beyond 2020 the continuously tightening vehicle emission regulations in most countries are expected to have resulted in exhaust gas levels that are so low that they no longer constitute significant air quality and resulting health problems.

In developing countries a lot of challenges remain for reaching and maintaining air quality at acceptable levels. Especially in growing economies with increasing amounts of traffic in large cities the health risks and effects are still high and expected to increase even further. A large number of developed countries also still have significant issues with meeting local air quality targets in cities.

Alternative fuels such as natural gas and some biofuels may have a limited positive effect on air quality. For vehicles running on electricity or hydrogen it is clear that their zero-emission character may contribute significantly to improving air quality in cities.

1.2.4 Noise

Road vehicle noise is caused by engine and transmission noise at low speeds, while tyre and wind noise dominate at higher speeds. Noise emissions from transport are believed to remain a problem for the longer term. Solutions to lower the noise of traffic can be applied to the engine, transmission and tyres or can be reached by reducing the air resistance of the vehicle. Especially in urban areas with lower speeds, silent alternative propulsion systems, such as electric and fuel cell vehicles, may contribute to reducing noise.

However, due to the logarithmic nature of noise perception in relation to the energy level of emitted sound a high share of such silent vehicles in the fleet is necessary to significantly reduce noise levels in urban areas.

1.2.5 Other externalities

Next to the reduction of emissions of greenhouse gases, other pollutants and noise, other challenges are to be dealt with for the road transport sector. Examples are congestion, road accidents, odour nuisance, impact on ecosystems, generation of waste and land use. Some of these challenges are influenced by increased energy efficiency or the use of renewable energy in transport but not necessarily all in a positive way. For example the use of first generation biofuels indirectly increases land use for transport. Second generation biofuels are expected to perform better in this respect. On the other hand issues like congestion are not likely to be improved by the use of renewables.

1.3 Main candidate technologies for applying renewable energy in the transport sector

The focus of this report is on technologies that allow the use of renewable energy sources in road vehicles. A wide range of primary energy sources can be used for propelling road vehicles, as is indicated in Figure 5. Routes from source to vehicle are determined by the combination of primary energy source, secondary energy carrier (fuel or electricity) and energy convertors (e.g. combustion engine, fuel cell and electric motor) on-board the vehicles. Most energy carriers can be produced from existing non-renewable sources as well as from renewable energy sources, which allows a smooth transition towards a sustainable energy supply for the transport system.

The main candidate technologies currently available for the transition towards renewable energy supply for road transport are:

- Vehicles with advanced combustion engines running on (blends of conventional and) biofuels.
  This category also includes so-called charge-sustaining hybrid-electric vehicles which do not charge electricity from the grid;
- Battery-electric vehicles using renewable electricity;
- Plug-in hybrid vehicles running on renewable electricity fuelled by (blends of conventional and) biofuels in combination with renewable electricity;
- Fuel cell vehicles using hydrogen produced from renewable sources.

In chapter 2 the state-of-the-art of these different technologies is reviewed. Figure 5 presents an overview of different routes from primary energy source to final application including the options for using energy carriers from renewable sources in transport.

The wide range of energy carriers available for delivering renewable energy to road vehicles allows a smooth transition from a fossil-based to a sustainable transport system

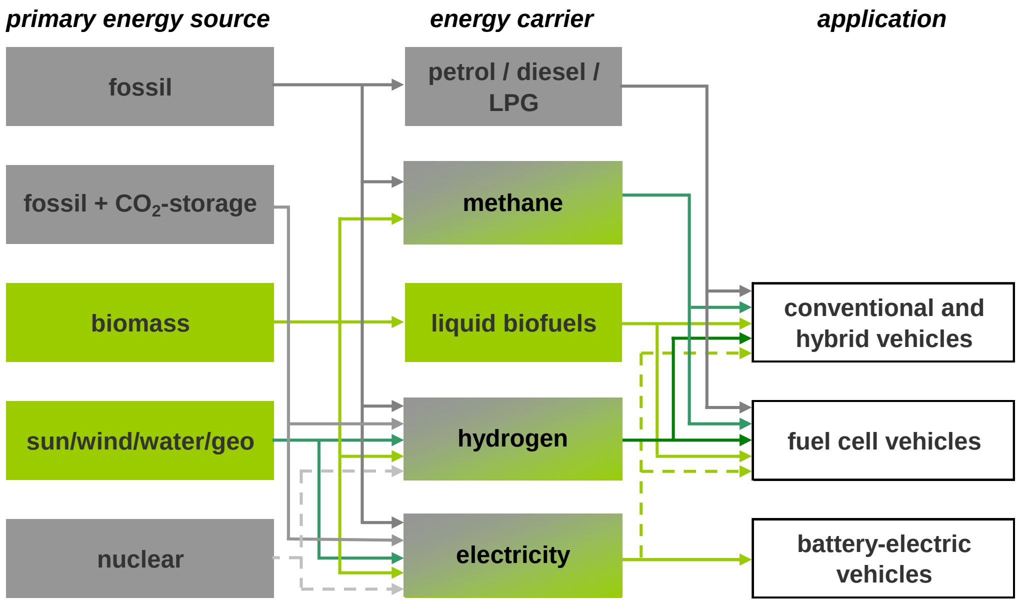

Figure 5 Routes from non-renewable (grey) and renewable (green) energy sources to applications in road transport

1.4 Creating synergy and co-ordination between the energy and the transport sector

The transition from the use of fossil fuels to renewable energy in transport requires co-ordinated changes, or in other words, a kind of co-evolution of the transport sector and the energy sector. The transition requires new technologies to be implemented in both sectors. Investments in the infrastructure for production and distribution of renewable energy carriers for transport can only be justified if the transport sector creates a stable market by implementing the technologies that enable the use of these sustainable energy carriers. Coordinated efforts by stakeholders in both sectors are more likely to occur if there is synergy between these developments and added value for both sectors. Finding such synergies may help to overcome technical, economical and institutional barriers. This is illustrated below for the example of electric vehicles powered by renewable electricity.

1.4.1 Opportunities for synergy between renewable electricity and electric vehicles

There are different direct and indirect ways in which the introduction of electric vehicles and of renewable electricity interact and possibly create synergetic effects. As an example some of these are discussed below. More detailed analyses can be found in chapters 3 and 4.

<u>Interaction between electric vehicles and existing renewable energy policies</u>

In Europe electricity production is part of the EU Emissions Trading Scheme (EU-ETS) for CO_2. Furthermore the EU and various other countries have renewable energy target expressed as percentage shares in the total energy supply. When energy consumption by transport is shifted from oil-based fuels to electricity, the demand for electricity increases. In that case both types of policies lead to requirements for increased capacity of renewable electricity production. This mechanism is further discussed in section 4.5.

<u>Vehicle batteries as storage medium for renewable electricity</u>

Solar, wind and (on the longer term) ocean energy are characterised by an intermittent production pattern which is determined by weather conditions and day-night patterns. Hydro-energy is less intermittent but still dependent on water supplies that can only be managed to a limited extent. With an increasing share of renewables in electricity production this may create problems in matching the supply pattern to the demand pattern for electricity. In first instance possible mismatches can be solved by the availability of mid- and peak-power generation plants that can be switched on and off quickly. In the longer term the large scale availability of such excess capacity is an expensive solution. So called smart grids with opportunities for demand side management and matching supply and demand at a more local scale promise to become a more cost-effective alternative. Another option for matching supply and demand is storage of electricity. This is generally done in large-scale facilities such as hydropower reservoirs or centralised battery capacity. The prospect of the wide-spread use of electric vehicles and plug-in hybrids now offers an alternative option for decentralised storage. This option is not entirely new. In the 90's the possibility of using night-time electricity from nuclear power plants was a strong motivation for activities by the French electricity company EDF in the field of electric vehicles. Smart-grids are an enabling technology for using electric vehicles as decentralised buffer capacity.

Road vehicles are used only a limited amount of time per day. Also in day-time they are parked most of the time. Therefore electric vehicles could serve as a buffer for storing renewable electricity and dealing with its supply fluctuations. This can be done in two ways:

- Preferential charging: In the simplest option a smart grid controls the charging profile of electric vehicles, and switches chargers on and off in function of the supply of renewable electricity. In this way renewable electricity is preferentially guided towards electric vehicles every time peaks in production exceed the overall demand. This renewable electricity is then used for driving the vehicles;
- Vehicle-to-grid services: A more advanced possibility is that electric vehicles, which are charged with excess renewable electricity in the way as sketched above, also deliver (part of) this energy back to the grid. This option is often referred to as vehicle-to-grid or V2G. Electric vehicles may also serve other functions in the electricity system besides storage of electricity. These include frequency stabilisation and providing spinning reserve.

An important enabling technology for realising the option of electric vehicles as a buffer for renewable electricity is "smart grids". Smart grids are able to communicate with energy consuming as well as energy supplying equipment connected to the grid. On the basis of real-time demand and supply information together with pricing signals the smart grid influences / controls the moments at which this equipment consumes or produces electricity. Distributed energy generation and storage systems can provide peak power at premium prices or absorb excess power at off-peak moments as well as provide smoothing of short term variations in the supply-demand balance. In the end this may even mean a shift from the present supply-follows-load paradigm to a situation in which load follows supply [Martinot, 2009].

The willingness of electricity companies to pay for storage and other services provided by EV owners will depend on the avoided costs of alternative means for matching demand and supply patterns. Assessing this requires not only insights in the costs of smart grids and other options, but also an analysis of the overall energy efficiency impacts at the electricity production and distribution system level. These synergies are further explored in chapter 3.

1.4.2 Co-evolution of the transport and energy system

The implementation of the above-sketched option of electric vehicles as an integrated part of a future electricity system with a high share of renewables requires co-ordinated technical development at the vehicle level (e.g. batteries, control systems) as well as the electricity system level (e.g. smart grids, renewable energy production, ICT). Such development can be seen as a co-evolution of the transport and the energy system. Besides technical connections such a transition will also require institutional connections between transport and energy sector and will require new institutional and managerial roles for car manufacturers, mobility providers and energy companies [Martinot 2009].

Developing a vision on this co-evolution and possible final system designs that this may lead to is useful, not only from the perspective of electric vehicles and renewable electricity for road transport. In the same way that the business case for hydrogen vehicles or biofuels will be determined by more than just the costs of vehicles and the production costs of the energy carrier for this application, it is conceivable that the business case for the options explored in this report is also strongly influenced by synergetic effects. These effects could result from the interaction with larger developments in the energy system as a whole.

1.5 Questions to be answered

Based on the above, the main questions to be answered in the following chapters are:

- What is the present status of technologies for applying renewables in the transport sector? When will they be technologically and market-ready?
- What are the costs and benefits of creating synergies between developments in the transport and energy sector? How do these costs and benefits influence the business case for renewables in transport?
- What are the main barriers in the transport and energy sector for implementing the technologies needed for large-scale use of renewable energy in transport?
- How can we stimulate the increased uptake of renewable energy in the transport sector and how can synergies between transport and energy sector be promoted? Can we develop a policy framework for this co-evolution?

1.6 Structure of this report

Chapter 2 reviews the state-of-the art of the main technological options for using renewable energy in transport. Chapters 3 and 4 zoom in on the option of applying renewable electricity in battery-electric and plug-in hybrid vehicles, and explore benefits, barriers or challenges and policy options for promoting the application of these options.

Finally chapter 5 draws conclusions from the previous chapters and makes an attempt to translate and generalise these into recommendations for a policy framework for stimulating the uptake of renewable energy in the transport sector.

2 State-of-the-art of renewable energy technologies for road vehicles

2.1 Relevant developments in conventional vehicles

Spurred by CO_2 emission legislation in various countries, as well as by a growing demand from users since the peak in fuel prices in 2008, the world-wide car industry is drastically gearing up its efforts to improve the fuel efficiency of conventional cars on petrol and diesel. The European CO_2 emission legislation, adopted in December of 2008, requires the average CO_2 emission from new passenger cars to drop from 160 g/km in 2006 to 130 g/km in 2015[8]. For 2020 the target is 95 g/km, while for the longer term even reductions to 80 g/km or less are considered feasible. CO_2 or fuel efficiency legislation for cars is also in place in Japan, China, Taiwan, and the US. Japan also has standards for trucks. Legislation for vans and trucks is in preparation in Europe.

The technologies available for achieving reductions in CO_2 emissions from conventional vehicles include[9]:

- efficiency improvements in internal combustion engines, including direct injection for petrol engines, variable valve timing, and engine downsizing;
- hybrid-electric propulsion as a further improvement of vehicle energy efficiency;
- reduction in tyre rolling resistance and air drag;
- weight reduction;
- exhaust heat recovery;
- energy-efficient components.

Hybridisation in the context of developments of conventional vehicles on petrol and diesel refers to so-called "charge sustaining" hybrids which do not draw electricity from the grid. Instead all on-board energy use is derived from fossil fuel burned in the combustion engine. The combination of combustion engine and electric propulsion in these vehicles avoids part-load operation of the engine with low efficiency. Hybrid vehicles further reduce fuel consumption by allowing brake energy recovery (regenerative braking).

Besides the above options the development and use of vehicles running on compressed natural gas should also be mentioned. The direct benefits of using natural gas in road vehicles may be limited from a greenhouse gas and energy dependence point of view, but the technology does open a transition path towards the use of biogas. Biogas from municipal and agricultural waste and especially from manure has very low well-to-wheel greenhouse gas emissions.

These developments effectively make conventional vehicles a moving target for the development of cleaner and more efficient alternatives. The cost effectiveness of alternative energy carriers and propulsion systems compared to future fossil fuelled vehicles depends on the relative cost developments and CO_2 performance for all involved technologies. Advanced conventional vehicles have the benefit of large scale production leading to faster reductions in costs of additional measures. Combined with the decreasing relative environmental benefits of alternatives, this creates a serious challenge. However, some technological options for conventional vehicles, especially concerning efficient components and the reduction of weight and driving resistances, also improve energy efficiency of vehicles using alternative energy carriers. For the application of biofuels efficiency improvement in engines and the application of hybrid propulsion is extremely relevant.

[8] As measured on the standardized type approval test.

[9] An overview of CO_2 reduction potentials and costs of such measures can be found in [TNO 2006].

State-of-the art of improved conventional vehicles

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Market status

- Improvements in fuel efficiency are spurred by recent legislation on vehicle CO_2 emission in various countries / regions.
- Technologies for meeting 2015 goals are currently brought to the market.

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Challenges

Technical

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Non-technical

- Technologies used to improve fuel efficiency lead to higher vehicle purchase costs and lower operating costs. Consumer myopia with respect to future cost savings provides a barrier for marketing fuel efficient vehicle technologies even when the payback time is significantly shorter than the vehicle lifetime. CO_2 emission legislation or other incentives are needed to create a market and a level playing field for manufacturers.

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Opportunities

- All alternative propulsion systems and energy carriers benefit from the application of measures leading to a reduction in vehicle energy demand, e.g. through reduced air drag, or weight. It reduces the demand for renewable energy and increases driving range.
- The application of biofuels may benefit from improvements in conventional vehicle energy efficiency.
- The introduction of vehicles running on compressed natural gas opens a transition route to using biogas with low well-to-wheel GHG emissions.
- The inherent characteristics of the hybrid propulsion system offer opportunities for improved driveability and comfort (high torque at low speed, fast accelerator response, continuously variable transmission).
- The large scale market introduction of hybrids creates opportunities of scale and learning effects for electric motors, batteries and power electronics, which will also benefit the introduction of battery-electric, plug-in hybrid and fuel cell vehicles.
- Regardless of the configurations that in the end turn out most successful, increased electrification of the propulsion system and other vehicle components is a trend that is generally believed to occur anyway. Increased availability of on-board electricity resulting from hybrid propulsion will also be a driver for electrification of other vehicle components, offering opportunities for significant efficiency improvements.

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Uncertainties

Technical

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Non-technical

- Fast introduction of more fuel efficient cars may have a stabilising impact on fuel prices. To what extent this hampers the introduction of alternatives, which benefit from high fossil fuel prices, is as yet unclear. More insight in the dynamics of fuel prices in response to future developments in energy efficiency and overall demand growth would be useful.
- Over the next decades a large share of the oil production may come from unconventional sources (e.g. Canadian tar-sands), which require more energy for extraction of oil as well as for the production of fuels. This will lead to strong increases in well-to-wheel emissions for internal combustion engine vehicles on fossil fuel, which counteracts reductions achieved at the vehicle level.

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2.2 Vehicles using electricity

Electric vehicles are currently receiving much attention. Their zero-emission driving, low noise and possibility for charging with renewable energy are appealing attributes in the context of sustainability ambitions of national governments, municipalities, environmental NGOs and transport companies developing green mobility products, and other companies aiming to improve their CSR score[10].

Two types of vehicles are being developed: battery-electric vehicles[11] which drive on electricity from the grid alone, and so-called plug-in hybrids. The latter combine an electric drive system with a conventional engine and can run on electricity and fuel.

2.2.1 Battery-electric vehicles

Advances in lithium-ion battery technology allow for driving ranges in the order of 200 km or more (compared to 50-100 km some 10-15 years ago). Whether lithium-ion is the breakthrough technology that will finally enable a successful large-scale introduction of battery-electric vehicles is not yet entirely clear. Issues of battery lifetime and safety in automotive applications are still to be proven. Concerning safety the fire hazards, associated with the use of lithium, need to be minimized.

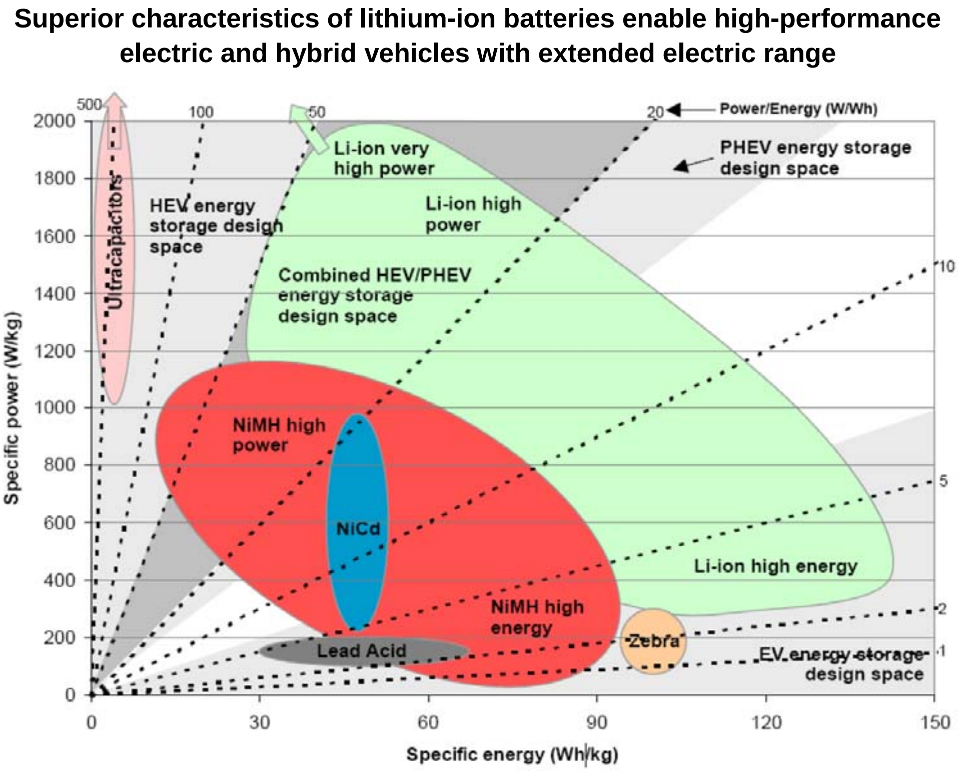

Figure 6 Comparison of specific energy and power for a range of battery types (Source: [BERR, 2008], based on data from Ricardo)

Figure 6 indicates that different vehicles require different battery types. Electric vehicles require batteries with a high energy density (kWh/kg). The amount of batteries needed to drive e.g. 150 km will then automatically have sufficient power (kW) to propel the vehicle. Hybrid vehicles require small batteries with limited energy content but high specific power (kW/kg). The demands on batteries for plug-in hybrids are expected to be somewhere in between the two extremes.

[10] Corporate Societal Responsibility
[11] Also referred to as full-electric vehicles or pure electric vehicles.

The present attention for electric vehicles and the **success of the lithium-ion battery** have also renewed the interest in other battery technologies with promising energy densities. Examples are metal-air batteries and redox-flow batteries. Also the R&D into lithium batteries with higher storage capacity or better fast charging capabilities has increased over the last years. Such competition between battery technologies is important for the long term success of the electric vehicle. It will first of all accelerate innovation and cost reduction. But also in view of the possibly finite lithium resources, emerging oligopolies in the market for lithium and lithium batteries and the lead time for scaling up production capacity it is important to create competitive alternatives. [Andersson 2002] estimates that enough lithium should be available to produce between 190 and 12.000 million battery electric vehicles with a battery pack of roughly 20 kWh each. With the lower estimate resources would not be sufficient to replace a significant share of the worldwide car fleet with EVs, but with the upper limit resources are more than abundant. An overview of available lithium resources is given in [RYDH 2002] and [Andersson 2001]. Based on US Geological Survey data [IEA 2009d] reports a world lithium reserve of 13 Mton. In the BLUE Map scenario this is just sufficient to provide the cumulative demand for a market where shares of electric and plug-in vehicles gradually increase to 30% of new vehicle sales each. In the EV Succes scenario, where EVs reach 80% market share in 2050, the required lithium is twice the estimated reserve [IEA 2009d].

For a 200 km range a typical electric vehicle needs a battery capacity of 40 kWh or more. Slow charging of such a battery from a typical 3 kW plug requires up to 15 hours. With daily driving distances generally below 100 km the daily charging time with slow charging will be about 5 to 8 hours. Lithium-ion technology offers the opportunity for fast charging. This requires **charging stations** with higher power, connected to the grid at points where this high power is available. Impacts of fast charging on battery lifetime and charging efficiency are still to be determined. Availability of fast charging stations may allow the use of battery-electric vehicles for driving longer distances (using e.g. 15 min. charging stops at highway filling stations) and also limits risks for the user associated with limited range ("range anxiety"). Experience from past field trials in France and Sweden, however, indicates that available fast charging facilities were hardly used. Their availability thus may serve a psychological purpose more than a practical purpose. The Swedish experience is that "EV users will not stop to charge but will rather charge where they stop". As discussed in chapter 3 there are various reasons why EVs should preferably charge most of their energy at night. If fast charging only needs to be available to alleviate range anxiety and for daytime charging in case of longer trips, it may be difficult to create a positive business case for fast charging infrastructure.

Another way of shortening the charging time for battery-electric vehicles is the use of **battery exchange or battery swapping**. At charging stations the empty battery is taken out of the vehicle and replaced by a fully charged battery. This process takes only a few minutes. Besides shorter charging times this also necessitates alternative ownership models. Battery replacement requires a battery rental or lease model. These alleviate the high initial investment costs and translate these into predictable operational costs. Battery replacement, however, also requires a high degree of standardisation of battery packs as well as vehicle design. To what extent vehicle manufacturers are willing to standardise their vehicle design to allow battery replacement is as yet unclear. The extent to which alternative vehicle designs for battery replacement interfere with vehicle crash safety and driving stability is also unclear. The business case for battery replacement, determined among other things by the costs of battery change stations, the amount of batteries needed per vehicle, and the ratio of battery charging and battery exchange with which EV owners satisfy their energy needs, is as yet not clear.

Costs of Li-ion batteries currently on the market are between 1000 and 2000 €/kWh according to e.g. [BERR 2008] and [McKinsey 2009]. The latter states that cost reductions between 5 and 8 percent per year would be possible up to 2030. The IEA estimates that US$300-600/kWh could be an achievable target for battery costs by 2015 [IEA 2009c]. Various sources even claim that cost reductions to 200 - 300 €/kWh are possible in the longer term future. This would reduce the battery costs from typically €20,000 - €40,000 per vehicle to €4,000 - €6000 per vehicle. The high costs of batteries also lead to high estimates for CO_2

abatement costs for electric vehicles as a means to reduce GHG emissions (see e.g. review in [Smokers 2009]). Abatement costs, however, are very sensitive to the developments in investment costs as well as to the assumed energy prices.

Given the high costs of batteries, it is preferable that the battery life equals or exceeds the vehicle lifetime (10 to 15 years / 100,000 – 200,000 km). Whether this is the case for lithium-ion batteries, and how this is affected by the use of the battery, is still to be determined in practice.

The high **purchase price** resulting from the application of expensive batteries may be a barrier for consumers to buy electric vehicles, even if the lifetime energy cost saving is larger than the additional investment costs. Uncertainty about **battery lifetime** and the **residual value** of vehicles and batteries further adds to this. The uncertainty regarding residual value has to do with lack of knowledge about the remaining capacity of the battery at any given point in time. This uncertainty could be overcome by using accurate battery monitoring systems.

The problem of high purchase costs may be overcome by taking the battery out of the vehicle sales price and offering it to customers in a lease concept. This concept helps to reduce consumers' uncertainty / risks with respect to battery lifetime and residual value. Experience in France (La Rochelle) has shown that battery leasing significantly increases the willingness of consumers to buy electric vehicles. Renault is planning the same marketing concept for the EV models it plans to launch in the coming years.

At this moment most battery-electric vehicles available on the market are conversions by small firms. Various OEMs are testing and demonstrating battery-electric vehicles in field trials (e.g. BMW and Smart in Berlin). More or less commercially available battery-electric vehicles include the Mitsubishi iMiEV, the Fiat Doblo Elletrico, and the purpose-designed Think. Various manufacturers have announced commercial market introduction and mass-production of electric vehicles in the coming years (2011-13).

Energy consumption of battery-electric vehicles varies between 100-150 Wh/km for a very small, lightweight urban passenger car, 150 – 200 Wh/km for a midsize car or van with conventional body up to 200 – 250 Wh/km for larger vehicles. Two light-weight electric sports cars are on the market: an aftermarket conversion of the Lotus Elise, which consumes 113 Wh/km (ECE-cycle) and the purpose-built Tesla Roadster with an electricity consumption of 135 Wh/km.

Energy consumption increases with increasing electric range due to the mass of the battery. Doubling the battery capacity roughly leads to only a 75% increase in range[12]. Energy consumption furthermore strongly increases with increasing driving speeds, so that the range in urban driving is generally larger than in highway driving. For electric vehicles stop-and-go traffic does not lead to high energy consumption because the efficiency of the electric motor is less dependent on load and because brake energy can be partially recovered. Energy consumption is furthermore determined by ambient temperatures and the energy consumed by auxiliaries (lighting, air conditioner and heater).

Fast charging could reduce the overall energy efficiency due to higher internal resistance losses in the battery and the charger. Little is known of this for the current generation of batteries and charger technologies.

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[12] The energy density of Li-ion is about 150 Wh/kg. Assuming an electricity consumption of 150 Wh/km a 200km range would thus require at least a 200kg battery pack. In practice, however, most vehicles only use 80% of the available battery capacity to avoid battery degradation. A 200 km range thus requires about 250 kg of batteries. In light duty vehicles a 10% weight increase generally leads to about 6.5% increase in the vehicle's energy consumption. Given an electric vehicle of 1250 kg empty mass with 200 km range and an energy consumption of 150 Wh/km, doubling the battery capacity increases vehicle mass to 1500 kg. This increases energy consumption to 170 Wh/km, so that the range of the vehicle with double battery capacity is just over 350 km, 75% increase.

Currently many regions are setting up field trials with electric vehicles. These test sites will deliver crucial information on the technical and market readiness of electric vehicles, but will also help to create an initial market that is essential for generating increased investments in electric vehicle technology.

The current activities in the market will also reveal and increase the **need for standardisation** and will as such speed up the process of creating standards. In the case of electric vehicles creating a standard for the plug is a starting point, but a relatively easy one. In Europe high level agreement on a plug standard has already been reached. More challenging, and more important for optimal system integration in the longer term, is the standardisation of (charging) infrastructure especially with respect to grid codes, communication protocols, roaming and billing systems and e.g. smart grid control algorithms. Car manufacturers, grid operators and other stakeholders need to be involved in all these aspects in order to achieve optimal solutions and long term compatibility between vehicles and the energy system. The issue of compatibility is further highlighted in chapter 3 in the context of vehicle-to-grid services that may be delivered by EVs and PHEVs.

State-of-the art of battery-electric vehicles

Market status - Lithium-ion battery technology now allows electric driving ranges of > 200 km. - Electric propulsion has a high energy efficiency. - Some conversions and small-volume purpose-design electric vehicles available commercially. - Some OEM vehicles close to the market. Many OEMs prepare commercialisation for 2013-15. - Plug standardisation achieved in Europe. - Pilot projects are being started in many cities. - First development of charging infrastructure is starting.	**Challenges** *Technical* - Limited driving range combined with long recharging time if charged at home (on a 110 / 220 Vac outlet). *Non-technical* - High initial costs of battery-electric vehicles, combined with uncertainties associated with battery lifetime. - Uncertainty about residual value of vehicles and batteries. - Requirements for a new charging infrastructure, especially difficult to realise in densely populated urban areas. - Standardisation of charging infrastructure, plugs and grid-vehicle communication (including payment/billing systems).
Opportunities - Electric propulsion offers good driveability. - Electricity can be produced from any primary energy source, be it fossil or renewable. In combination with carbon capture and storage, electricity may also create a route for CO_2-free energy from fossil sources. - Role of battery-electric vehicles as buffers for storing excess renewable electricity production and smoothing of short term variations in the supply-demand balance (see chapter 3). - Role of battery-electric vehicles as a pull for increasing the share of renewables in electricity generation (see chapters 3 to 5).	**Uncertainties** *Technical* - Battery lifetime, to be proven in field trials. - Battery safety issues, incl. fire hazards from the use of lithium as well as impacts of battery weight and packaging on vehicle crash safety behaviour. - Impact of fast charging on battery lifetime and energy efficiency. - Development of battery costs: Which innovations in product design and production processes will offer opportunities for cost reduction? - Development of alternative battery technologies. - Conventional vehicles are a moving target. *Non-technical* - Lead time for increasing battery production capacity. - Material availability issues for batteries and electric motors (magnets). - Role of battery-electric vehicles in the mobility system: Will they replace conventional vehicles or will they be used as additional vehicles, leading to increased car ownership per household and possible rebound effects due to increased mobility. - Development of future vehicle and energy tax regimes. How will these deal with battery costs and possible taxes on electricity? - Treatment of electric vehicles in future CO_2 legislation for vehicles, and role of battery-electric vehicles in future developments regarding e.g. the EU-ETS trading system for CO_2 emissions.

2.2.2 *Plug-in hybrid vehicles*

Plug-in hybrids are hybrid electric vehicles equipped with a plug so that they can charge electricity from the grid in addition to on-board generation of direct motive power or electricity using the combustion engine. In general plug-in hybrids are equipped with a larger battery than the charge-sustaining hybrids discussed in section 2.1. Compared to charge-sustaining hybrids the creation of a large pure-electric range is easier in charge-depleting hybrids, and does not go at the expense of overall energy efficiency.

Plug-in hybrids come in a range of configurations between two extremes: One extreme is a full-hybrid (ref. Toyota Prius) with an increased battery capacity plus grid connection to increase electric driving range. At the other end of the spectrum we find vehicles that are basically battery-electric vehicles equipped with a small internal combustion engine that functions as a range extender.

As far as passenger cars are concerned some prototype / conversion plug-in hybrid vehicles are available in Europe and the US, but no plug-in hybrid vehicles are yet in series production. GM has plans to introduce the GM Volt / Opel Ampera in November 2010. Toyota is developing a plug-in version of its Prius, of which a small series will be delivered to government and commercial fleets in 2010 for field testing.

Similar to what is discussed above for battery-electric vehicles the performance and lifetime of the battery for plug-in hybrids is still an issue. The nickel-metalhydride (NiMH) battery in the charge-sustaining Toyota Prius has proven extremely reliable due to a carefully designed battery and energy management system and the avoidance of deep discharges. With plug-in hybrids the charging and discharging of the battery is largely determined by the user rather than by the vehicles energy management system. How this affects battery lifetime is still to be determined.

Little concrete information is currently available on the energy consumption of plug-in hybrid vehicles. Depending on the application, duty cycle and initial battery state-of-charge, different amounts of fuel and electricity will be consumed per kilometre. The ratio between electricity and fuel use is furthermore strongly dependent on the configuration of the propulsion system. Most available studies fail to analyse this in sufficient detail. Results of more detailed simulations on various plug-in hybrid propulsion system configurations are presented in [IEA 2007], but these are still difficult to generalize for the purpose of this review. The availability of test data or real-world figures from existing vehicles is virtually zero. A better understanding of this issue is required for analysing the impact of plug-in hybrids on the electricity grid and the possibilities for using these vehicles as a storage medium for sustainable electricity. It is strongly recommended that this knowledge gap is bridged by means of comparative assessments using detailed simulation tools as well as laboratory and field testing of existing plug-in hybrid vehicles under various conditions. Ongoing and planned publicly funded field test are expected to provide useful information in the coming years.

Energy consumption of a plug-in hybrid in electric mode is expected to be similar to that of a battery-electric vehicle with the same vehicle mass. Electricity consumption and fuel consumption in combined mode strongly depend on propulsion system configuration and driving pattern. Fuel consumption in combustion engine mode[13] is possibly higher than for comparable conventional vehicles due to the weight of the battery, depending on whether or not regenerative braking is available in this mode.

[McKinsey 2009] estimates the additional costs of a plug-in hybrid compared to a conventional car to be € 16.000 in 2006, and projects that these costs could fall to € 3.500 by 2030. This is for a vehicle with 60 km electric range and a battery capacity of 14 kWh. [King 2007] states additional costs of £6,500 for a plug-in with 35 km electric range and £20,000 for a vehicle with 350 km electric range.

[13] I.e. when running on power supplied by the combustion engine.

State-of-the art of plug-in hybrid vehicles

Market status	**Challenges**
- Some conversions available commercially. - Two OEM vehicles close to the market. Some OEMs prepare commercialisation for 2013-15. - Plug standardisation achieved in Europe. - Pilot projects are being started in some cities.	*Technical* - High initial vehicle costs. - Concerns over battery lifetime. *Non-technical* - Similar issues as for battery-electric vehicles concerning the need for a charging infrastructure and standardisation.
Opportunities	**Uncertainties**
- Plug-in hybrids may combine benefits of battery-electric vehicles (use of clean electricity, smooth drive) and conventional vehicles (fuel availability, long driving range, established reliable technology), while avoiding some of the disadvantages of battery-electric vehicles (short range, limited availability of charging infrastructure). - Similar opportunities as with charge sustaining hybrids related to improved driveability, propulsion system electrification and creating economies of scale and learning effects for electric propulsion system components. - Increased driving range compared to battery-electric vehicles, avoidance of "range anxiety".	*Technical* - Concerns regarding impact of charging from the grid on battery lifetime and overall energy efficiency at the vehicle level. - Similar uncertainties as with battery-electric vehicles regarding developments in performance and costs of batteries. - Conventional vehicles are a moving target. *Non-technical* - The lower electric power demand for plug-in hybrids compared to battery-electric vehicles may lead to lower effective utilisation of the charging infrastructure and to higher costs per kWh delivered. - Similar uncertainties as with battery-electric vehicles regarding material availability issues.

2.2.3 *Electric vehicles as storage medium for (sustainable) electricity*

Battery-electric and plug-in hybrids can be used as a distributed storage system for matching the supply pattern of renewable electricity from wind and solar to the demand pattern. Besides preferential charging of electric vehicles at times of peak renewable electricity production, governed by a smart grid system, and using the renewable electricity for driving, these vehicles can also be used to deliver stored energy back to the grid (vehicle-to-grid). To what extent the use of electric and plug-in hybrid vehicles as buffers for renewable electricity will become technically possible and economically attractive is influenced by the following vehicle-technology-related issues:

- A charging profile, optimised by smart-grids to maximise the buffering of excess electricity, may not be optimal for the efficiency and lifetime of batteries. Currently charging profiles are designed to match the specifics of a given battery chemistry and to maximise battery lifetime.
- Batteries have a finite lifetime, usually expressed in the number of available charging-discharging cycles. The use of electric vehicle batteries as buffers in combination with supplying electricity back to the grid will result in a lower number of cycles available for driving and in general a shorter battery life in terms of the number of kilometres that can be driven within the battery lifetime. Even if the battery lifetime would exceed the lifetime of the vehicle, then still the residual value of the battery will be affected if it is used for vehicle-to-grid services[14].

[14] Currently business models are being explored in which batteries, after having served for a number of years in vehicles and having lost some of their capacity as a result of that, are given a "second life" for use in stationary

- The level of battery costs that can be compensated by premiums provided by electricity companies depends on the economic benefits generated at the system level by having electric and plug-in hybrid vehicles available as storage medium. Various studies indicate that such benefits are existent [Martinot 2009] but the size will depend on a number of other developments in the energy system occurring over the next decades. This issue is further explored in chapter 3.

Another technical issue to be considered here is possible energy losses associated with using electric vehicles as buffers, which are determined by the charge-discharge efficiency of the battery and the efficiency of the charger. The efficiency will be lower for fast charging than for slow charging. These efficiencies should be taken into account in determining the business case as well as the overall efficiency at the energy system level.

2.2.4 Well-to-wheel CO_2 emissions and energy efficiency

Compared to the conventional vehicle with an internal combustion engine, the drive train of the electric vehicle is much more energy efficient. The overall efficiency from charging the battery until propelling the vehicle is around 85% for an electric vehicle, compared to an overall efficiency of around 25% for the conventional vehicle. This means that the electric vehicle itself is very energy efficient and therefore gives a good possibility to reduce the total energy consumption per kilometre driven. However, the well-to-tank emissions which are produced during electricity generation have an important contribution on the overall CO_2 emissions of the whole chain. From this perspective, it is really important how the energy is produced. There is a big difference in the efficiency of the different electricity production processes, and especially a big difference between the usage of renewable energy such as wind energy and the usage of coal or gas fired plants.

The extent to which the use of electric vehicles leads to reduction of CO_2 emissions thus depends directly on the power plant mix used for generating the electricity with which the electric vehicle batteries are charged. The best possibility of creating a true “zero emission”-vehicle is to use electricity from renewable energy sources. Figure 7 shows the impact of using different power sources on the comparison of well-to-wheel CO_2 emissions from electric and plug-in hybrid vehicles with those of conventional vehicles. Coal based power plants produce a high amount of CO_2 emissions up to 1000 gCO_2/kWh. If electric vehicles are charged with electricity from coal the maximum emission reduction possible is 29%. Other types of power plants have different emission values. Renewable energy sources are able to save up to 99% of CO_2 emissions with electric vehicles compared to conventional internal combustion engines (ICE) running with gasoline. Nuclear power plants are not considered in this study, as there still are significant issues with regard to the CO_2 emissions in the supply chain and the storage of nuclear waste.

Because plug-in hybrids (PHEVs) cannot drive their entire range with the stored electricity, they have a higher emission rate than EV, even when charged with electricity from renewable energy sources (RES). The exact value depends on the pure-electric driving range, the fuel consumption when running on the engine and the driving pattern of the user which determines the ratio between electric driving and use of the vehicle's combustion engine.

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energy storage applications. Such storage facilities could even serve a purpose for allowing electric vehicle charging stations at locations with limited grid power.

Well-to-wheel CO_2 emissions of electric and plug-in hybrid vehicles depend on the power source

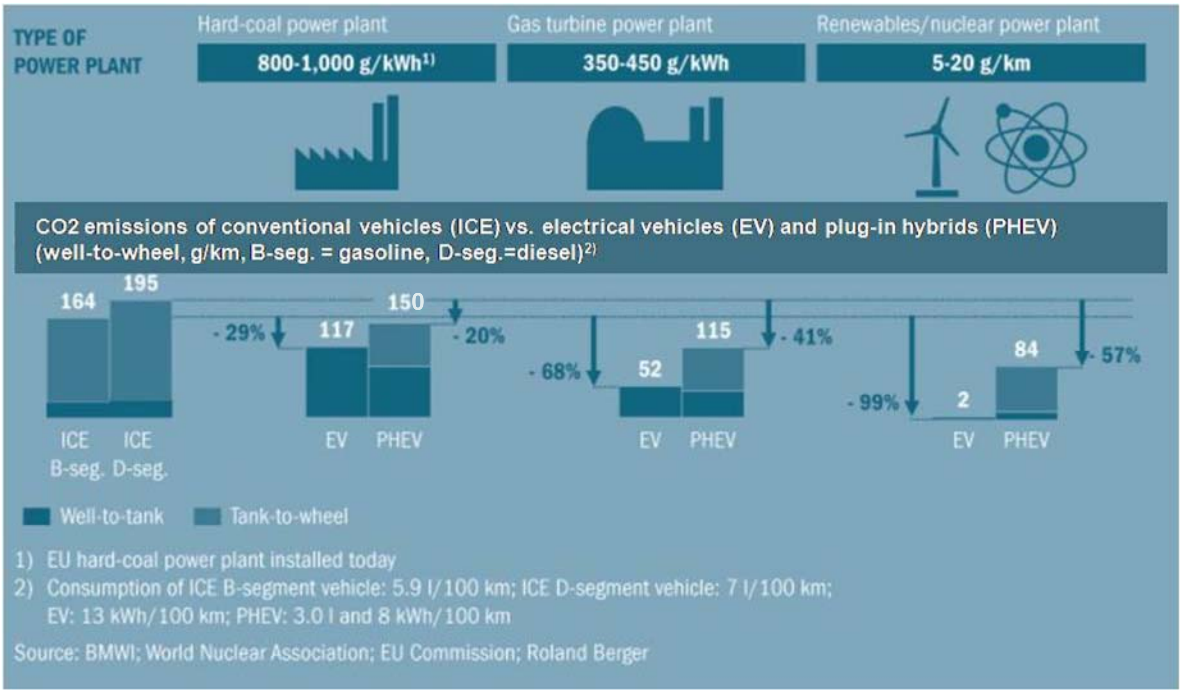


Figure 7 Comparison of CO_2 emissions from electric vehicles (EV) and plug-in hybrid vehicles (PHEV) with those of conventional, internal combustion engine vehicles (ICE) [RB Powertrain]

Usually, electric vehicles are using the electricity mix from the grid and thus do not derive their energy exclusively from renewable energy sources (RES). Figure 8 shows the emissions for electric vehicles in comparison to an average conventional vehicle for various countries. Depending on the power plant mix, the emissions per km vary from under 10 gCO_2/km in Norway (high percentage of renewable energy sources especially water power) to over 170 gCO_2/km in Poland (power generation mainly from coal-based power plants). The power plant mix in the most of the countries is a composition of different types of power plants as mentioned before.

Well-to-wheel CO_2 benefits of electric vehicles are different in different countries

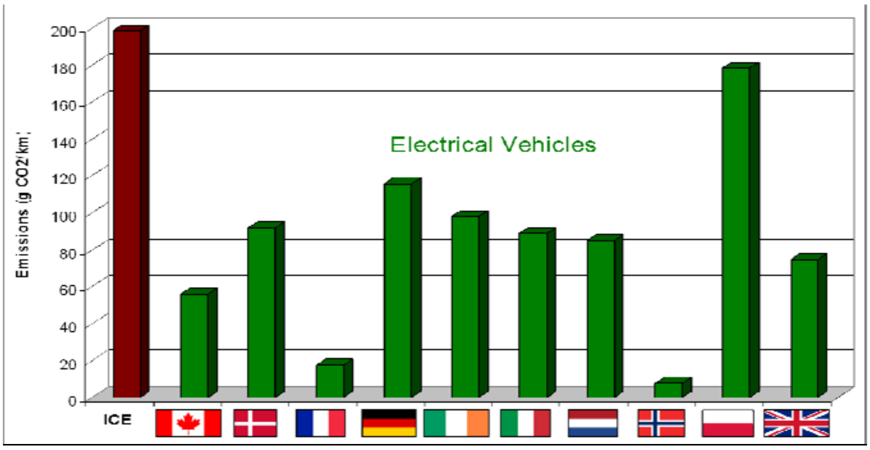


Figure 8 Comparison of WTW CO_2 emissions between an average internal combustion engine (ICE) vehicle and electric vehicles in different countries (Source: IFHT, RWTH Aachen, calculation based on data from GEMIS)

Assuming that electric vehicles are charged with electricity from the average mix in a country, different shares of electric vehicles are required in different countries to reach the same level of CO_2 emission reduction. In a country with high CO_2 emissions from electricity generation, the influence by using electrical vehicles will be only a few percent or the penetration have to be very high to reach the desired emission reduction aims.

A 10% share of electric vehicles in the passenger car fleet of Norway reduces overall emissions from passenger cars by about 9.7%. The same percentage of electric vehicles in Poland would cause only a reduction of around 1% of the emissions. To reduce the emissions from passenger cars in Poland by 10%, electric vehicles would have to replace more than 98% of all cars. In Germany an emission reduction of 10% through the use of electric vehicles would require an electric vehicle share of approximately 24% in the passenger car fleet (i.e. about 9.9 Mio electric vehicles in Germany).

When electric vehicles are exclusively charged with electricity from renewable energy sources, a penetration rate of 10% would also lead to rate of 10% replacement of fossil fuels by renewable energy in the transport sector[15]. However, as shown before, the percentage of renewables in the power plant mix is lower than 100% in every country. To satisfy 10% of the energy demand for passenger cars with renewable energy by using electric vehicles charged with electricity from the average electricity mix, a penetration rate of 70% of electric vehicles in Germany or of 37% in Denmark has to be reached. These percentages are high and cannot be reached within the next decade. Therefore it is important to consider further alternatives such as biofuels or hydrogen (if not produced from electricity) as described in the previous chapters. Alternatively one could device a policy framework by which the increased use of electric vehicles is accompanied by investments in renewable electricity generation capacity, so that the additional demand for electricity caused by these vehicles can be supplied by the additional renewable electricity generation. Such a framework is developed in chapters 4 and 5.

[15] This would not lead to a 10% share of renewables as electric vehicles deal more efficiently with renewable energy than conventional vehicles deal with fossil fuels. The resulting share of renewables (accounted in energy content of primary or secondary energy carriers used) will thus be less than 10%.

Government plans aim for significant EV fleet shares by 2020

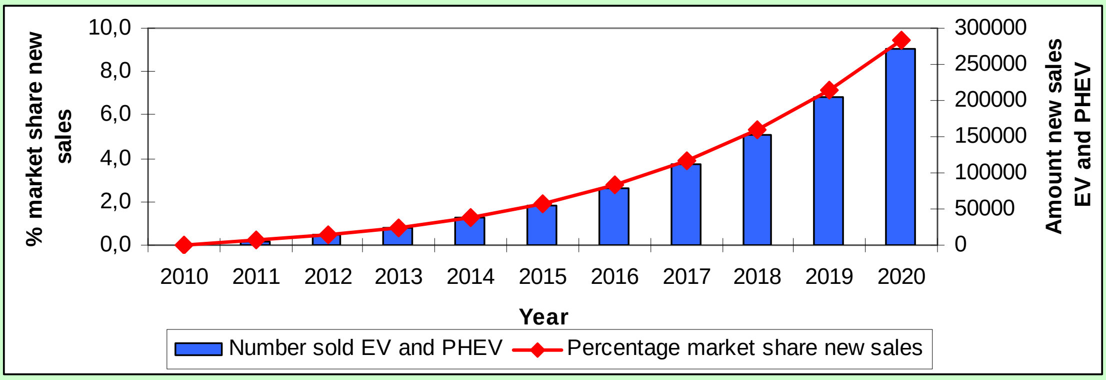


Figure 10 Development of the total selling rate of electric vehicles per year in Germany to gain a fleet of 1 million EVs and PHEVs in 2020 [IFHT, RWTH Aachen]

As an example, in Germany the government aims to have 1 million of the country's vehicles replaced with electric of plug-in hybrid vehicles by 2020, which is around 2.4%. Figure 9 shows the required selling rate per year for reaching this target. In 2020 nearly 10% of the market share of new vehicles has to be either electric or plug-in hybrid, which equals more than 284,000 vehicles. To develop the required production infrastructure and to gain economies of scale, it is necessary to start early with the introduction of electric and plug-in hybrid vehicles. Otherwise even an aim as low as 2.4% in 2020 cannot be reached. Governments have a role in fostering early market development e.g. by stimulating the creation of niche markets, as well as in promoting investments in charging infrastructure. Through a range of measures (see also chapter 4) they can stimulate demand which will encourage manufacturers to produce the required amounts of vehicles.

Figure 10 provides an estimate of the development of world-wide sales of electric and plug-in hybrid vehicles based on an extrapolation of targets from existing national stimulation plans [IEA 2009c]

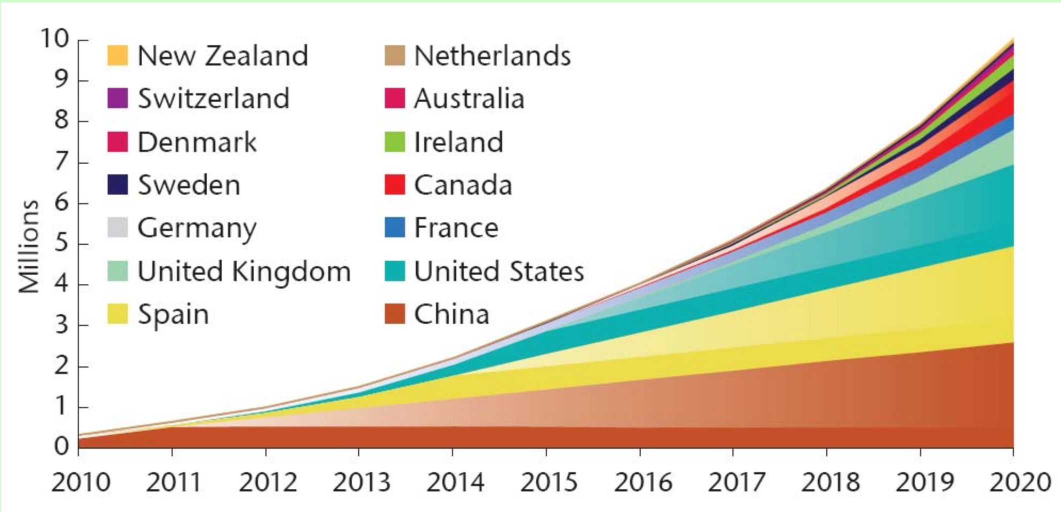


Figure 10 National EV/PHEV sales if national target year growth rates extend past 2020 [IEA 2009c]. Opaque wedges are announced national targets; semi-transparent wedges are EV/PHEV sales if rate of growth in the year the national target is achieved is extended through 2020.

2.2.5 *Life-cycle aspects of electric and plug-in hybrid vehicles*

The shift towards sustainable vehicles will at some point involve drastic changes in propulsion technology, potentially leading to significant changes in the life cycle impacts. In the case of electric and plug-in hybrid vehicles especially the use of batteries and the electric motors will have an impact. For fuel cell vehicles e.g. the use of platinum in the catalyst may significantly change life-cycle impacts. The use of advanced lightweight materials, such as fibre reinforced composites, to reduce vehicle weight may also be expected to significantly affect life-cycle impacts. For batteries and other components of sustainable vehicles such impacts relate to pollutant emissions, GHG emissions and waste produced in the production (incl. mining and production of materials) and in the process of decommissioning (collection and disposal or recycling). Producing batteries and e.g. electric machines also implies use of scarce materials and possible depletion or resources. For electric machines the availability of rare earth metals may become a problem. Such impacts from the production chain are assessed in a Life Cycle Analysis (LCA).

In view of this it is of paramount importance that policies that promote the deployment of battery-driven vehicles also promote the set-up of a satisfactory battery collection and recycling system. Environmental legislation applying to battery production, collection and recycling facilities should also be reviewed and if necessary amended to avoid adverse impacts.

Currently the GHG emissions associated with production and recycling of vehicles (incl. mining and production of materials) are of the order of 10% of the GHG emissions emitted in the use phase as a result of energy consumption for driving. This ratio may change in the future, among other this due to the fact that vehicles will become more energy efficient and will emit less CO_2 during driving as a result of existing and upcoming legislation. Consequently the energy used and amount of greenhouse gases emitted in production and recycling will become a higher percentage of the energy consumed and GHG emission produced in the use phase;

It should be noted here that developments that may contribute to meeting long term GHG reduction targets may conflict with other environmental policies. An example in Europe is the regulation for CO_2 emissions from passenger cars vehicle efficiency and the Directive 2000/53/EC on end-of-life vehicles. The latter directive requires that "no later than 1 January 2015, for all end-of life vehicles, the reuse and recovery shall be increased to a minimum of 95 % by an average weight per vehicle and year. Within the same time limit, the re-use and recycling shall be increased to a minimum of 85 % by an average weight per vehicle and year." Composites used to reduce vehicle weight are intrinsically difficult to recycle. They can be collected and incinerated with energy recovery, but according to the directive no more than 10% of the vehicle weight may be processed in this way. As an all-composite structure could amount up to 20% of a vehicle's weight, the use of such materials would thus be in direct violation with Directive 2000/53/EC. Batteries should be designed to allow good recyclability in order to avoid conflicts with the end-of-life vehicle directive.

2.3 Biofuels

Many different types of biofuels exist which can replace fossil gasoline and diesel. For example, bio-ethanol, bio-MTBE (methyl-tertiary-butyl ether) and bio-ETBE (ethyl-tertiary-butyl ether) are substitutes for gasoline, while biodiesel[16], pure plant oil (PPO)[17], and synthetic biodiesel are substitutes for diesel. Biodiesel and bio-ethanol presently have the largest market shares and are expected to dominate the biofuels mix up to 2020. Significant amounts of biogas might also be expected to be used in on road transport, mainly in public transport (city buses) and e.g. municipal fleets. So-called first generation biofuels are currently produced mainly from dedicated (food) crops that can be grown in subtropical climates (e.g. rapeseed, sugar beets, cereals) and regions with tropical climates (e.g. oil palm, sugar cane,

[16] Often referred to as Fatty-Ester Methyl Ether (FAME)
[17] Also known as Virgin Plant Oil (VPO)

jatropha). Second generation biofuels can also be produced from waste-streams (e.g. agricultural waste or wood-pallets) and various forms of lignocellulosic biomass, which do not compete with food production, using more advanced production methods currently under development.

Biofuels can be burned in conventional combustion engines with or without adaptations depending on the type of fuel used. Low-percentage blends in conventional petrol or diesel can be used in unmodified conventional engines. Various pure biofuels require engine adaptations to deal with the specific characteristics of the fuel. Some biofuels on the other hand enable engine adaptations that improve performance or energy efficiency.

2.3.1 First generation biofuels

Biodiesel is commonly produced from vegetable oils, extracted from oil palm, rapeseed, sunflowers, soybeans, etcetera. The vegetable oils are converted through transesterification in fatty acid methyl esters (FAME) which can be used as diesel. In principle, biodiesel can be blended with conventional diesel in any ratio. Its use in the mainstream market is presently limited to 5% on volume basis (labelled B5). For most manufacturers the maximum biodiesel share in conventional diesel is limited to 5 to 20% depending on the engine type, because of concerns about engine lifetime and oil dilution. In dedicated fleets, where engines can be adapted to the use of high blends of biodiesel, the fraction of biodiesel can be higher, up to 100% (labelled B100).

First generation bio-ethanol is produced by fermentation of sugars. These sugars can be extracted from feedstocks like sugar beet and sugar cane, or the sugars can be made from starch in crops like wheat or corn. Furthermore sugars can also be extracted from residues like potato waste. Bio-ethanol is commonly used in low blends in gasoline, typically 5% (E5) or 10% (E10) on volume basis. Higher blends can be used in Flexible Fuel Vehicles (up to E85), which are currently offered by a wide range of manufacturers. Currently, bio-ethanol is not produced in large quantities within Europe. In the US ethanol is made from corn. On a global scale Brazil is a major producer, using sugar cane as biomass source.

ETBE and MTBE are derivatives of ethanol resp. methanol, and are used as a fuel additive (limited to 15% by volume). Bio-ETBE and bio-MTBE, derived from bio-ethanol or bio-methanol, can thus not be used as neat biofuel (pure form). An advantage of ETBE and MTBE in low blends is that they are better compatible with current fuel specifications. For that reason, in Europe about 75% of the bio-ethanol is currently applied in the form of ETBE, and only 25% in the form of ethanol. However, since the ETBE partially originates from isobutylene, which is of fossil origin, only part of it is counted as a biofuels (47% for ETBE, 36% for MTBE).

<u>Well-to-wheel GHG emissions from biofuels</u>
Although production and use of biofuels can be seen as a closed carbon cycle, in practice most biofuels are far from carbon neutral. Emissions of greenhouse gases occur in various steps in the production chain from biomass cultivation to the use of the fuel in the vehicle. These emissions are resulting from fossil fuels consumed e.g. by agricultural machinery or fuel production plants, but also from the use of fertilisers (CO_2 emissions in production and N_2O emissions from farmland). Well-to-wheel greenhouse gas reduction potentials[18] for biofuels depend mostly on the biomass feedstock used and the production process (see e.g. [JRC 2007], [SCOPE 2008], [JRC 2008], [BUBE 2009]). The following numbers do not include effects of indirect land use change: Ethanol produced from Brasilian sugar cane leads to reductions of 80% or more, while ethanol produced from corn grown in the USA results in maximum reductions of 30 to 50% and in some cases even a net increase in greenhouse gas emissions. Well-to-wheel greenhouse gas emissions from biodiesel are between 20% and 80% lower than from fossil fuels. Biogas, when produced from manure, may even have a well-to-wheel greenhouse gas reduction of over 100% due to avoidance of direct methane emissions to the atmosphere.

[18] Reduction in total well-to-wheel greenhouse gas emissions expressed in g/km CO_2 equivalents.

Without accounting for effects of (indirect) land use change, many 1st and 2nd generation biofuels offer the potential for significant GHG emission reductions compared to petrol and diesel

Figure 11 Overview of well-to-wheel energy use (X-axis) and GHG emissions (Y-axis), for a number of fossil and 1st and 2nd generation biofuels, excl. indirect land use effects [JRC 2007]

More recently it was shown that also the conversion of existing ecosystems to cropland may produce large emissions of greenhouse gases. The magnitude of these effects depends on the type of ecosystems that are converted and are most prominent for forests and peat land. These effects associated with land-use change may also occur in an indirect way. When existing agricultural land is used for biofuel production the growing demand for food worldwide will cause conversion of natural ecosystems to cropland for food production in other places. Research into these issues is currently on-going, but initial results show that the greenhouse gas emissions resulting from land-use change may partly or even completely offset the well-to-wheel greenhouse gas reductions estimated in the traditional way as discussed above [SCOPE 2008a, CE 2008].

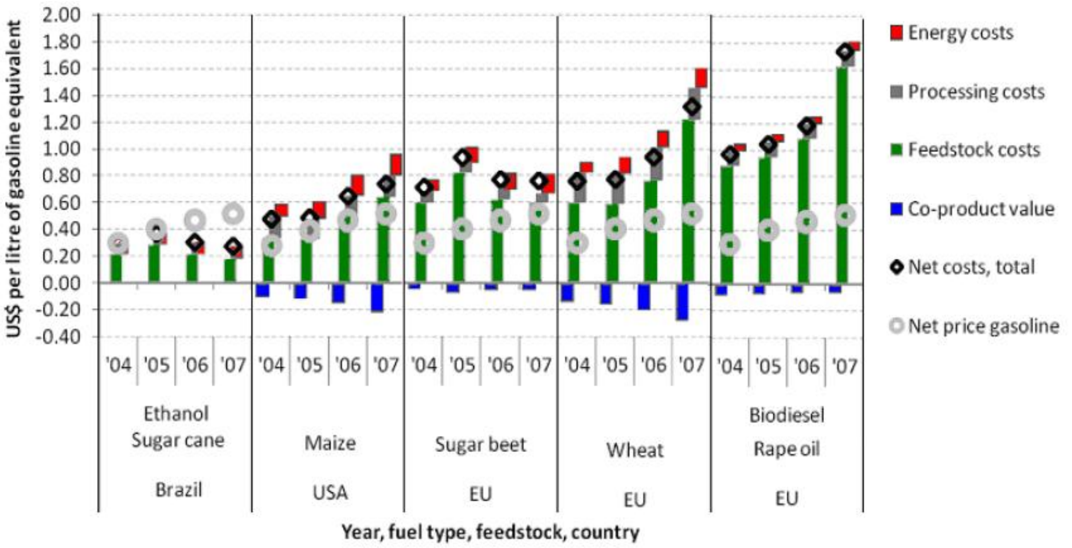
Cost-effectiveness and land use for biofuels

But even for biomass to biofuel chains with favourable well-to-wheel greenhouse gas emissions the question is whether the use of biomass for fuelling vehicles is the most cost-effective option for reducing greenhouse gas emissions. Using biomass as feedstock for electricity production is generally a more cost-effective means of reducing greenhouse gas emissions than conversion of the same biomass into biofuels for use in road vehicles. Production costs for 1st generation biofuels are illustrated in Figure 12. [CE 2006] shows that greenhouse gas abatement costs of biofuels, i.e. the costs per unit of CO_2 avoided, are higher than e.g. for co-firing biomass in coal-fired power plants. This conclusion is confirmed by the SCOPE biofuels project [SCOPE 2008a]. However, in the BUBE project it is argued that in a longer-term 2°C world, the cost-effectiveness might completely be reversed - biofuels may be used for transport first, and not for heating and electricity as there will be more "effective" non-C options there [BUBE 2009].

Another major concern with biofuels is the amount of land needed to produce enough biofuel to replace a significant share of fossil fuel use. According to [SCOPE 2008a] meeting a global 10% biofuel substitution target would require 118 to 508 million hectares of agricultural land, depending on crop type and assumed productivity level. The current area of arable land in the world amounts 1,400 million hectares. These land needs for the expansion of biofuel production may conflict with a growing demand for food worldwide.

The reason for this high land use is the relatively low energy yield per hectare of biomass. The energy yield per hectare of biomass production is generally orders of magnitude lower than for other means of producing renewable energy. For different biomass sources it varies between 10 and 100 GJ per hectare per year. For photo-voltaic energy the yield is between 3000 GJ/ha/y for e.g. the Netherlands and 9000 GJ/ha/y for concentrated solar power in Southern Europe. This shows that besides e.g. well-to-wheel energy efficiency and greenhouse gas emissions per kilometre driven, also additional metrics related to land use efficiency should be included in the comparison.

Only sugar cane ethanol from Brazil is competitive with fossil gasoline. Other 1st generation biofuels are more expensive



Source: Data from Aglink-Cosimo database, LMC International, IEA and other sources. The co-product value of exported electricity generated from bagasse in some plants in Brazil is not shown.

Figure 12 Production costs of 1st generation biofuels 2004-2007 [IEA 2008b]

State-of-the art of 1st generation biofuels

Market status	Challenges
- Wide availability of 1st generation biofuels, mostly offered as low-percentage blend into fossil gasoline and diesel. Limited availability of E85 and pure biodiesel. - Conventional engines accept limited percentages of biofuel blended into conventional fuel. - Flexfuel vehicles for ethanol/gasoline mixtures widely available with limited additional costs. - Limited availability of engines for pure biodiesel. - Use of biofuels promoted or even mandatory as result of policy in many countries.	*Technical* - Impact of some biofuels on operation of current-generation engines and exhaust gas aftertreatment systems, limiting the share of biofuels that can be blended into conventional fuels. - Required engine adaptations for applying pure biofuels and the necessity for a dedicated distribution infrastructure. *Non-technical* - High production costs. - Limited well-to-wheel greenhouse gas reduction potential of various first generation biofuels. - High societal greenhouse gas abatement costs resulting from the above. - Sustainability issues related to the well-to-tank energy chain for biofuels (greenhouse gas emissions resulting from land-use change, water use, impacts on biodiversity etc.). - Difficulties with respect to certification of biofuel production chains regarding sustainability aspects.
Opportunities	**Uncertainties**
- The main advantage of biofuels is that they work in more or less conventional engines and that they require little changes to the existing fuel distribution infrastructure (especially when blended into conventional fuel). - Biofuels benefit from all efficiency improvements in conventional vehicles.	*Technical* - -- *Non-technical* - World-wide availability of biomass for production of biofuels. - Possible competition with food production or biomass production for other applications (e.g. chemical feedstocks or electricity generation). - Cost development of first generation biofuels. For countries that rely on import of biofuels the price is likely to stabilize just below the oil price. When internationally traded, biofuels become a commodity where the price is determined by competition with alternatives (in this case fossil oil) rather than by production costs.

2.3.2 Second generation biofuels

In addition, several types of biofuels are currently under development that could become available in the middle or long term. Most of these technologies make use of lignocellulosic biomass ('second generation') in the form of wood residues, paper waste, agricultural waste, and dedicated energy crops. These are converted into biofuels using advanced processes, which could result in lower production costs (mostly due to the fact that they use cheaper bio-energy crops and residues) and in higher well-to-wheel greenhouse gas reductions. Examples are Fischer-Tropsch diesel (also known as Biomass-to-Liquids or

BTL), bio-ethanol produced by hydrolysis-fermentation from lignocellulosic biomass and Hydro-treated Vegetable Oil (HVO). The latter process offers the opportunity to produce fuel with good, diesel-like quality from 1st generation biofuel feedstock.

Fischer-Tropsch diesel or Biomass-To-Liquid (BTL) is produced by gasification of biomass feedstock followed by Fischer-Tropsch synthesis. The process produces a range of hydrocarbon outputs, including high quality synthetic fuels such as naphta, diesel, and kerosene. The technology of gasification and Fischer-Tropsch synthesis is proven technology for coal and gas (coal-to-liquid, CTL, and gas-to-liquid, GTL), but is still in the R&D stage for biomass (BTL, biomass-to-liquid), with a few small-scale pilot plants operating [TNO 2009].

Due to the higher overall efficiency in the production chain (including feedstock cultivation), second generation biofuels are expected to have a higher energy yield per hectare than first generation biofuels. This also alleviates problems related to competition with food production and indirect land-use change. Present costs of these fuels are still high but costs are expected to decrease strongly in the coming decades (see e.g. Figure 13). For this reason the greenhouse gas abatement costs of second generation biofuels are expected to become an order of magnitude lower than for first generation biofuels.

2nd generation biofuels are still expensive but have large potential for cost reduction

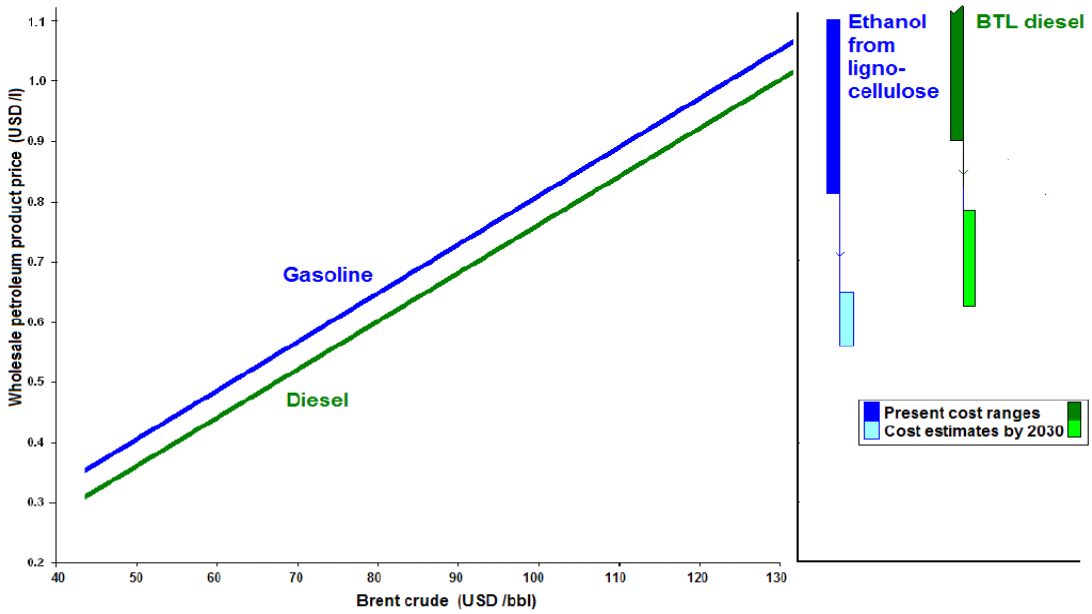


Figure 13 Production cost ranges for ‘second generation' biofuels in 2006 (US$/litre gasoline equivalent) compared with wholesale petroleum product prices correlated with the crude oil price over a 16 month period [IEA2008b]

2.3.3 Biofuels for long haul trucks, aviation and shipping

In a number of transport sectors, electrification is not likely to be possible due to driving range, weight limitations or payload requirements. Examples of these are long haul trucks, shipping, and aviation. The availability of high quality and affordable 2nd generation biofuels could become an important prerequisite for improving the sustainability of these modes of transport. Currently, there is increasing interest in creating biofuels from algae. Combined with the advanced processing developed for second generation biofuels, this can yield the high quality biofuels needed for demanding applications (i.e. aviation). The costs of these fuels are still high. As an intermediate solution, HVO (hydrogenated vegetable oil) can also have the specific properties demanded in aviation but at a lower cost. However, since HVO is mostly made from feedstocks that are typically classed as "first generation", it also has a number of the same drawbacks.

Several test flights using either biofuels or fuels synthesized by the same processes that can be used to convert algae to biofuel have been conducted, proving at least the technical feasibility [REF 2008/2009].

As for shipping, an opportunity to use cheaper, lower quality biofuels then required for on-road transport exists since marine engines are typically suited to use a lower fuel quality then their on-road counterparts. Until now, there has only been research on smaller marine engines that normally burn diesel fuel. No biofuel research has been undertaken on large marine engines that currently use fuel oil [AEA 2009].

2.3.4 Development of a framework for better use of biomass

The IEA-sponsored BUBE-project (Better Use of Biomass for Energy) is currently exploring the above-mentioned issues with biomass in order to develop a document for national governments and negotiation parties that provides guidance on the issue of biomass energy within the framework of the UNFCCC negotiation process for a post-Kyoto climate agreement [BUBE 2009]. The project intends to answer four questions:

1. What is the best way of using biomass (electricity, heat, transport fuel or material use)?
2. What barriers need to be overcome and what opportunities arise?
3. Which criteria, indicators and policies should be used to identify and stimulate the best sustainable use of biomass?
4. How much sustainable biomass is available for energy use, considering trends in the production and consumption of food, feed and fibre and other biomass using sectors?

The framework to be developed for a ‘better’ use of biomass will cover GHG emission reduction, energy security, competition with food and feed, land use change, socio-economic effects in non-OECD countries, and cost and cost effectiveness. It will not only concern the choice between bioenergy options and pathways, but also of the sector in which bioenergy is used – more specifically, which fuel is replaced by the biomass.

State-of-the art of 2nd generation biofuels

Market status	Challenges
- Production processes still in R&D phase. - Some small pilot plants in operation. - Flexfuel vehicles for ethanol/gasoline mixtures widely available with limited additional costs.	*Technical* - High production costs of 2nd generation biofuels: Current cost ranges for both ethanol from ligno-cellulose and BTL diesel only become competitive with fossil fuels at oil prices around 100-130 US$ per barrel. - In case of ethanol the required engine adaptations for applying pure biofuels. *Non-technical* - In case of ethanol the necessity for a dedicated distribution infrastructure for pure or high-% blend biofuels.
Opportunities	**Uncertainties**
- The main advantage of biofuels is that they work in more or less conventional engines and that they require little changes to the existing fuel distribution infrastructure (especially when blended into conventional fuel). For BTL diesel the fuel even has superior quality compared to fossil diesel and does not require changes in distribution infrastructure. - The Fischer-Tropsch process for producing synthetic fuel from biomass (or other sources of carbon) offers the opportunity to produce so-called designer fuels with superior quality compared to conventional fuels. These designer fuels will allow application of advanced combustion principles with higher engine efficiency and lower exhaust gas emissions. - Combination of fuel efficient cars with second generation biofuels (or second generation biofuels with sufficiently low well-to-wheel greenhouse gas emissions) offers opportunities for 80% or more greenhouse gas emission reduction at the vehicle level.	*Technical* - Unknown cost development of 2nd generation biofuels. *Non-technical* - Sustainability issues related to the well-to-tank energy chain for biofuels, and difficulties with respect to certification of biofuel production chains regarding sustainability aspects, but to a lesser extent than for1st generation biofuels due to higher chain efficiencies. - World-wide availability of biomass for production of biofuels, but to a lesser extent than for 1st generation biofuels due to different feedstock and higher energy yield per hectare. Unknown time-scale for reaching technical maturity.

2.4 Hydrogen and fuel cell vehicles

Hydrogen is a versatile energy carrier that can be produced from any fossil or non-fossil primary energy source. It can be converted into mechanical energy in combustion engines and into electric energy using fuel cells. As BMW is the only car manufacturer that has developed hydrogen vehicles using combustion engines, the focus here will be on fuel cell vehicles running on hydrogen. Using hydrogen in combustion engines may be useful intermediate solution, reducing technical barriers and lowering vehicle costs in the early stages of market development. But in the long run this option has lower energy efficiency than fuel cells and does not solve issues with respect to hydrogen storage.

Demonstrator fuel cell vehicles have been developed by most manufacturers. A number of fleet tests are currently ongoing, involving mainly passenger cars but also city buses. Around 1997 many manufacturers announced series production by 2003, but currently the large scale market introduction of fuel cell vehicles is not expected before 2015 or 2020. Remaining problems with fuel cell vehicles relate to fuel cell costs, start-up time, component lifetime and system behaviour at temperatures below zero. In September 2009 a collective of 7 car manufacturer groups[19] signed a letter of understanding in which it is stated that "based on current knowledge and subject to a variety of prerequisites and conditions, the signing OEMs strongly anticipate that from 2015 onwards a quite significant number of fuel cell vehicles could be commercialised. This number is aimed at a few hundred thousand units over life cycle on a worldwide basis".

For hydrogen vehicles the on-board storage remains an issue. Storage in pressurized tanks results in a low volumetric energy density and requires large tanks to allow an acceptable range. This problem might be partly solved by the present trends towards 700 bar tanks (compared to the 350 bar systems available up to now). However, even in that case the volume per unit energy is still 6 times higher than for storage of conventional fossil fuels, and the compression of hydrogen takes around 7-13% of the energy stored [Enerdata 2009]. Hydrogen can also be stored as a cryogenic liquid (at 20 K or - 253 °C). Problems with this option are costs and possible blow-off of hydrogen during prolonged vehicle stand-still. Another possibility under development is storage in so-called metal-hydrides in which hydrogen is absorbed in a solid metal.

The tanks used to store 5 kg of hydrogen at 700 bars cost around US$2000-3000 nowadays. Prices for the fuel cell are expected to decrease when produced in higher volumes. Present costs are around 600 - 1100 €/kW. For large scale production in the longer term possible values of 80 to 95 €/kW are expected some 20 years after commercialisation [Schoots 2009]. Such values are necessary to make fuel cell propulsion systems competitive with internal combustion engines. An important factor in the price of fuel cells is the usage of costly platinum (half of the cost of the fuel cell system). Research is being done on replacing the platinum with other materials, which could give cost reductions in the future (see also next page).

Fuel cell vehicles produce no emissions during use, but the well-to-wheel greenhouse gas emissions depend on the primary energy source and conversion technology used for producing hydrogen (see Figure 14 based on [ECN 2004]). Current hydrogen production for industrial processes is generally by steam reforming of natural gas. Another option is to use electrolysis for hydrogen production. In this case electricity is used to produce hydrogen from water. The efficiency of the electrolysis process is around 50-80 %. Combining this with a fuel cell system efficiency of 50 – 60% and the losses in distribution and compression of hydrogen gives a chain efficiency for fuel cell vehicles from electricity source to electric motor of between 30 and 40%. This compares unfavourably to the 80-85% efficiency of the chain from electricity source to electric motor achievable for battery electric vehicles (distribution and charger losses plus in-out efficiency of the battery). It is therefore clear that, the route via electrolysis and hydrogen is a fairly inefficient route for bringing electricity from fossil or renewable sources to the wheels. This leads to high well-to-wheel CO_2 emissions and low chain efficiency for producing hydrogen from e.g. the EU average mix for electricity production.

[19] Daimler, Ford, GM/Opel, Honda, Hyundai/KIA, Renault/Nissan, Toyota

Chain efficiency for hydrogen production depends on pathway but is generally low

Fuel pathway	MJ/MJ	gCO_2/MJ	gCO_2/km
Compressed H_2 (700 bar) from natural gas (steam reforming)	1.87	103	133
Liquid H_2 from natural gas (steam reforming)	2.14	124	160
Compressed H_2 (700 bar) from EU mix electricity (electrolysis)	4.46	208	270
Compressed H_2 (700 bars) from wind energy (electrolysis)	1.66	0	0
Compressed H_2 (700 bars) from biomass (via syngas)	1.91	22	29

Figure 14 Energy efficiency [in MJ/MJ] and green house gas emissions [gCO_2/MJ] for hydrogen production using various pathways from different primary energy sources [ECN 2004]
Note: the gCO_2/km values in the last column are indicative WTW emissions for a fuel cell vehicle with 180 Wh/km energy consumption by the electric motor combined with 50% fuel cell efficiency.

Despite the above mentioned energy losses in various chains for using hydrogen to propel vehicles, hydrogen vehicles still pose an important option for moving towards a sustainable transport system powered by renewable energy. The attractiveness of the option will among other things depend on developments in the costs of fuel cells and renewable energy and the extent to which the development of a hydrogen infrastructure also benefits sustainable developments in other sectors. Fuel cell vehicles may provide an alternative for vehicle applications where a longer driving range is required than can be met with full-electric vehicles. Because hydrogen can be stored it may also help to alleviate the issue of unbalance between intermittent renewable energy production and the demand pattern.

Fuel cells require **platinum** as catalyst. The availability of platinum might become a constraint when fuel cell vehicles would be used on a large scale. Estimates found for the world reserve of platinum vary between 15,000 and 100,000 tons (see e.g. [DfT 2009] and [IEA 2009d]). Assuming a fuel cell needs 20 grams platinum and all reserves will be used for producing fuel cells for vehicles, there would be enough to produce between 750 million and 5 billion cars. Obviously recycling of platinum would reduce the need for virgin material and allow continuous production of fuel cell vehicles. When fuel cell vehicles replace gasoline vehicles this also reduces the need for platinum related to the production of 3-way catalysts. According to [IEA 2009d] the platinum content of fuel cells could even become lower than that of ICE vehicle catalysts. In the IEA BLUE Map scenario 30% of new vehicles in 2050 are fuel cell vehicles. Cumulative demand for platinum until 2050 amounts to 10% of the materials base reserve [IEA 2009d].

Battery-electric vehicles deal more efficiently with renewable electricity than fuel cell vehicles on hydrogen

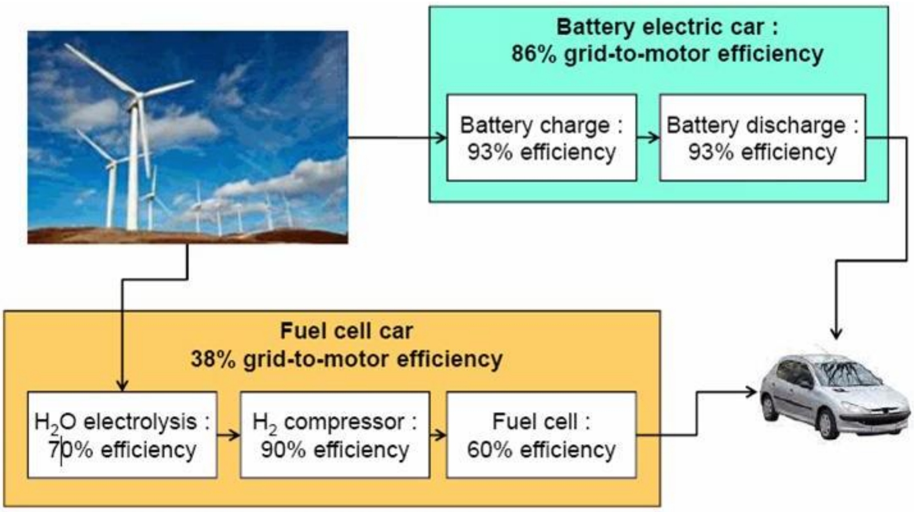


Figure 15 Comparison of the energy efficiency for bringing renewable electricity to the electric motor of a fuel cell and battery-electric car [Enerdata 2009]

State-of-the art of fuel cell vehicles running on hydrogen

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Market status

- Large co-ordinated R&D programmes running in the EU and USA.
- Limited number of pilot projects on-going.
- OEMs have recently announced first commercialisation of fuel cell vehicles by 2015.

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Challenges

Technical

- All presently available options for storage on-board vehicles (pressurized or as cryogenic liquid) have serious drawbacks. Alternative storage technologies are still in the R&D phase.
- Production of hydrogen using electrolysis involves significant energy losses in the energy chain. Well-to-wheel green house gas emissions and energy usage are heavily dependent on the method of hydrogen production. It is hard to achieve lower WTW emissions and energy usage than can be achieved with a pure-electric vehicle.
- Fuel cells are still expensive (but costs are steadily coming down) and still have technical issues to be resolved for vehicle applications.

Non-technical

- Hydrogen requires a completely new production and distribution infrastructure.

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Opportunities

- Hydrogen can be produced from any primary energy source, be it fossil or renewable. In combination with carbon capture and storage, hydrogen may create another route for low-CO_2 energy from fossil sources.
- Hydrogen is already produced (from methane) in large scale facilities for use in the chemical industry and refineries. These facilities can be used a starting point for setting up a hydrogen production and distribution infrastructure.
- Hydrogen is a clean fuel. Used in combustion engines only NO_x emissions need to be managed. Used in fuel cells it is emission free.
- Hydrogen can provide a sustainable alternative for fossil-fuelled combustion engines in long-haul trucks, for which battery-electric or hybrid propulsion are no viable alternatives.
- Hydrogen can be stored, enabling temporary storage of excess renewable energy.
- Fuel cells have a high conversion efficiency.
- Fuel cells on-board vehicles may be used as decentralised micro-generators, delivering electricity back to the grid.

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Uncertainties

Technical

- Cost development of fuel cells.
- Development of efficient routes for production of hydrogen from renewable sources.
- Conventional vehicles are a moving target.

Non-technical

- Development of hydrogen as energy carrier for applications in other sectors than road transport.
- Economic viability of a large scale hydrogen distribution infrastructure.
- The world-wide availability of platinum, which is used as catalyst in fuel cells.

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2.5 Comparison of options

Up to 2020 conventional vehicles are likely to continue their market dominance. In the coming decade fuel consumption and CO_2 emissions will be greatly improved as a result of legislation and changing consumer demand.

As a result of dedicated biofuel policies, in many regions a market has been established for 1st generation biofuels. The majority of biofuels is sold as low percentage blend with conventional gasoline and diesel. Further market penetration is currently halted by societal concerns over the overall sustainability of 1st generation biofuels and the possible competition with food production. The net well-to-wheel greenhouse gas reduction benefits of many 1st generation biofuels are highly uncertain at the moment.

Second generation biofuels promise lower costs, higher well-to-wheel GHG emission reduction potentials, and better overall sustainability due to higher energy yields per hectare, the possibility to use waste biomass and more efficient production processes. Production processes, however, are still in the R&D and demonstration phase. It is as yet unclear when these technologies will reach technical and market maturity, but generally it is believed that 2nd generation biofuels will only start to gain significant market shares after 2020.

Battery-electric, plug-in hybrid and fuel cell vehicles all use electric drivelines. The technology for electric drivelines, i.e. electric motors, power electronics and controllers, is technically mature and very energy efficient. The main uncertainties, as far as vehicle technology is concerned, are related to the technical maturity and costs of batteries, fuel cells and hydrogen storage systems. Both technologies appear to provide robust CO_2 reduction potentials. The well-to-wheel greenhouse gas emissions strongly depend on the primary energy source and conversion routes to electricity and hydrogen.

At this point in time battery-electric and plug-in hybrid appear closest to market entry, but whether market development really sets off this time still depends on a lot of uncertain factors.

3 Implications and possible benefits of electric vehicles for the uptake of renewable energy sources

3.1 Introduction

If every electric vehicle would charge renewable energy exclusively, the currently available energy from renewables in Germany would suffice to charge 27.7 million electric vehicles (two thirds of all vehicles in Germany). In Denmark more than 4 million EVs could be charged. That is nearly twice the amount of passenger cars existing in Denmark today. However, using existing renewable electricity supply to power electric vehicles does not achieve significant GHG reductions at the overall system level that are required to meet long term climate change targets. Although a shift from conventional to electric vehicles using the present average electricity mix already saves some CO_2, a long term transition towards a sustainable transport system based on electric and plug-in hybrid vehicles requires a strong increase in the capacity of renewable energy supply. If somehow a direct coupling can be made between electric vehicles and renewable energy, then the introduction of electric vehicles could be used to promote investments in renewable electricity generation.

As already indicated in section 1.4 electric and plug-in hybrid vehicles may be used to increase the potential uptake of renewable energy generation into the electricity system. The business case for such a co-evolution of transport system and energy system is determined by the following factors:

- The costs of electric vehicles, specifically the costs of batteries;
- The costs of renewable electricity;
- The costs of adaptations to the grid necessary to allow large scale use of electric vehicles. These include investments in charging infrastructure, reinforcements of local and regional grids and possibly additional power plants for meeting increased peak demands that may occur in the absence of sufficient load management for charging electric vehicles and / or the costs of implementing smart grids;
- The costs of adaptations to the grid necessary to allow a large uptake of renewable electricity generation.
- The value of benefits of having electric vehicle batteries available as distributed energy storage capacity for providing other functions in the grid (vehicle-to-grid services);
- The impact of using electric vehicle batteries to provide vehicle-to-grid services on battery lifetime or degradation. These affect the residual value of the battery and thus present a cost to the vehicle owner.

3.2 Adaptations to the electricity system required for the large-scale uptake of electric vehicles

The energy requirement per year for a typical battery-electric vehicle is 3000 kWh on average (200 Wh/km x 15,000 km p.a.) depending on the vehicle type and the annual mileage. Washing machines for comparison consume around 770 kWh a year. Thus an electric vehicle only needs 4 times the amount of energy of a washing machine. The total energy requirement of 1 million electric vehicles e.g. in the Netherlands (3 TWh) would represent only 3% of the total annual electricity production (about 100 TWh). The reason for the special focus on electric vehicles from a grid perspective, presented in this chapter, is based on the required power connection between electric vehicles and the grid and on the possibility to regulate the charging process without reduction of the usability of the vehicle for the user. Slow charging requires a power of around 3 kW, which is equivalent to the average power per house for which the capacity of local grids is dimensioned. To reduce charging times from 6 – 10 hours to e.g. half an hour (fast charging) a power connection of more than 40 – 50 kW would be required.

3.2.1 Early requirements for a charging infrastructure

Availability of charging infrastructure is essential for the market introduction of electric vehicles. These can only be a mature alternative to conventional vehicles, if everyone has the possibility to charge his vehicle anywhere and at any time. The different charging alternatives, with respect to e.g. charging locations or the availability of fast charging stations, have an effect on the electric vehicle's range and charging times and thus on the possible market share.

Electric vehicles can be charged when they are parked at home, at work or on public parking locations on the roadside or in parking houses. The type of connection to the grid will depend on the location and on the required power. Figure 16 shows different options to charge the battery. To enable all possible vehicle owners to charge their cars an area-wide infrastructure is necessary with private places at home or at work as well as public places such as along the streets or in multi-storey car parks.

Electric vehicles can be charged at home, along streets and in (multi-storey) car parks

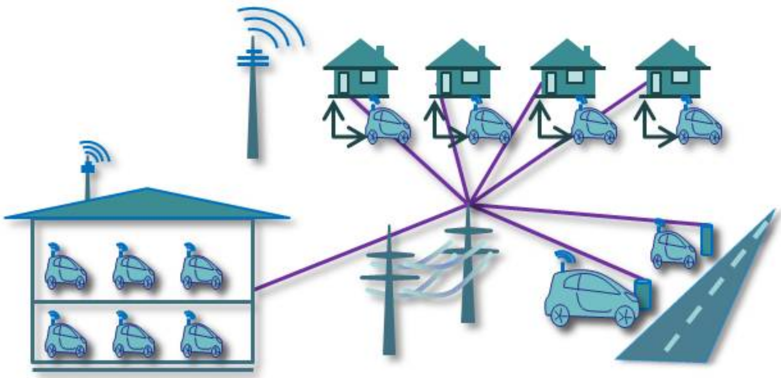

Figure 16 Different charging places for electric vehicles [IFHT, RWTH Aachen based on KEM 2004]

Public charging stations require an early development for an overall accounting system as e.g. with a subscriber identity module card (SIM card) used in mobile phones. Especially for low penetration a sufficient infrastructure has to be provided to guarantee an optimal use of electric vehicles. Standardisations for the plug have to be established to enable the vehicles to charge at every charging possibility.

In the early years the provision of infrastructure for a low amount of vehicles is relatively expensive because the distribution grid operators have to invest in the infrastructure before high penetration rates of electrical vehicles can be reached and therefore have to take the risk of an unprofitable investment. The total cost for different charging places with or without possibilities for a battery exchange (Better Place project) cannot be quantified and therefore need further research.

Furthermore, special electricity tariffs can be used to promote that electric and plug-in hybrid vehicles charge with electricity from renewable sources only and become "zero emission" vehicles. Today the costs of "green" electricity are around 5-10% higher than for conventional electricity. Therefore a certain number of vehicle owners will choose "grey" electricity if no other policy measures are taken.

3.2.2 Necessary adaptations to the electrical grid

Generally, consumers supplied with electrical energy require a very high quality of supply, which is provided most of the time in most of OECD countries. As a result of the high reliability of energy provision, most consumers are not aware of the sensitivity of the entire power system against external effects such as changes in consumption or generation structure. Hence, the possibility to connect electric vehicles to the grid for charging is often taken for granted.

The impacts on the power grid caused by an introduction of electric and plug-in hybrid vehicles are of diverse character. The penetration rate and the vehicle specifications such as battery capacity or charging power affect possible impacts on the grid as well as the benefit, which can be obtained. Electric and plug-in hybrid vehicles can enhance grid stability and supply quality as well as they can facilitate the introduction of renewable energy sources (RES), e.g. the storage possibility or the ancillary services.

In order to provide some of the possible benefits or grid related services a certain number of available EV or PHEV must be ensured. But also most of the negative effects identified can be neglected during the introduction stage as low penetration rates do not influence the remaining grid capacity significantly.

Figure 17 shows a scheme of the composition of a conventional electrical grid. Every level represents different voltage rates and grid structures. The maximum voltage level connects the whole grid in a country and establishes connections to neighbour grids. The levels below only have connections to the level above and to grids in lower voltage levels. The connection between different voltage levels is carried out by a transformer which converts electric power from one voltage level to another. Wind parks feed energy into different voltage levels, according to their installed capacity. Dispersed power generation from e.g. combined heat and power or solar panels assets is connected to the lower voltage levels depending on their size.

Electric vehicle charging points can be connected to low and medium voltage grids

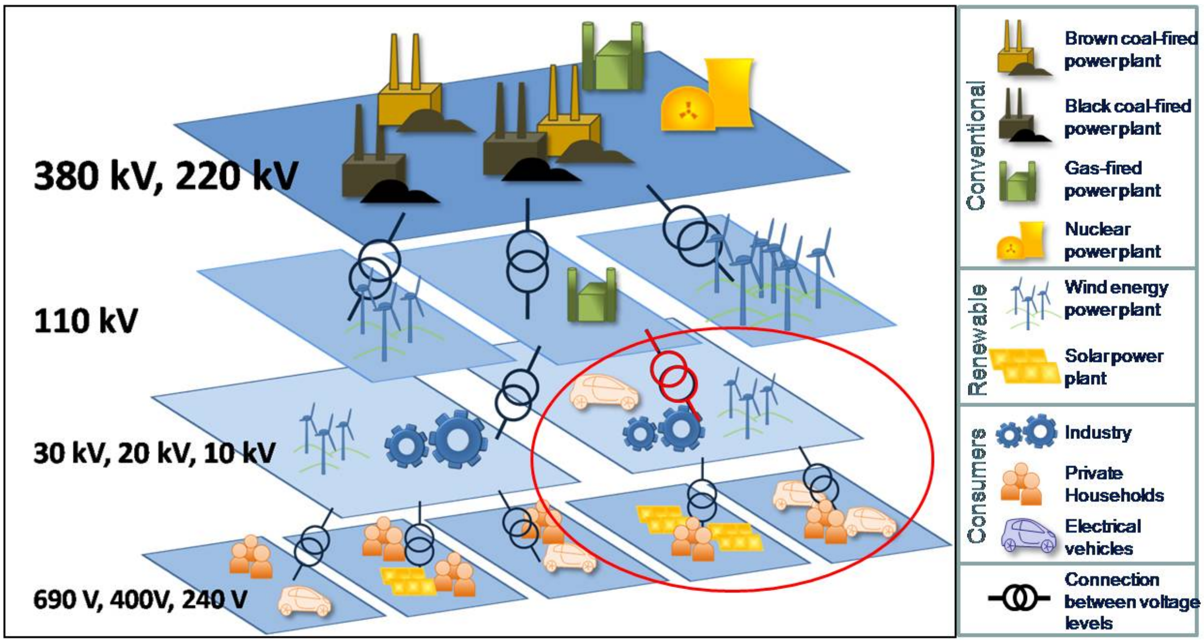

Figure 17 Composition of the electrical grid from the power generation to the point of consumption [IFHT, RWTH Aachen]

The lowest voltage level supplying consumers is called distribution grid. This grid usually consists of cables, while higher voltage levels mainly consist of overhead lines. As shown in the red circle electric vehicles can be connected to different voltage levels depending on the charging alternative e.g. charging at home or in a multi-storey car park. The red marked transformer can get overloaded in case of a weak grid or due to a high penetration of electric vehicles.

The quality of the grid can vary for different countries and regions. Different grid structures are not equally vulnerable. Normally rural grids are more at risk than urban grids. The grid in highly developed industrial countries is very well connected and a high capacity for the integration of electric vehicles is available. In developing nations the grid is weaker developed and less connected to other countries. To integrate electric and plug-in hybrid vehicles an opportunity to support the stability of weak grids should already be implemented before the rollout of these vehicles. Applications requiring smart grids are better suited for well developed grids. Grids in developing nations have to be strengthened to enable them to integrate a high penetration of electric and plug-in hybrid vehicles (more detailed in section 4.9).

The impacts on the grid will differ for different regions and even for different districts. First niche markets may already include large fleets or a large share of EV in specific urban areas e.g. because of clusters of higher income. The consequences can be that the possible impacts described below may occur earlier than expected in these specific geographic spots.

3.2.3 Possible impacts on the grid and recommended action

- Simultaneous charging of a large amount of electric vehicles can cause an unacceptable **voltage drop** from the transformer to the end of the lines. Rural grids are particularly at risk because they usually possess long lines. The voltage drop should not exceed a specified range (in Europe: ±10%). Available reactive power facilities can be used to keep the voltage within this specified range. In the future this function may also be provided by the electric vehicles themselves [Schwab 2006]. An application in converters of electric and plug-in hybrid vehicles that regulates the rate of reactive power can be used to provide voltage stability. The voltage drop caused by charging electric vehicles can be reduced around 50% without any communication between the vehicles and the grid. Therefore smart meters are not required for any kind of decentralized regulation. A certain penetration rate is not needed to provide this service.
- The nominal frequency of the supply voltage has to be either 50Hz or 60 Hz depending on the regulations in each country in order to guarantee power quality. Every loss or surplus of power in synchronic networks causes a **deviation from the nominal frequency**. Developing strategies for grid support at distribution level could be achieved by incorporating several characteristics such as frequency dependent charging of electric vehicles. Thus, inverters can contribute to frequency stability and increase grid reliability. The requirements for this application are identical to those necessary for the voltage stabilization.
- High penetration rates might lead to a **changed and increased power flow**. Assets like e.g. transformers are limited by thermal conditions and might get overloaded [Küchler 2005]. To prevent overloaded assets charging strategies can control the charging process of electric vehicles. This procedure falls in the category of demand side management. The following picture shows that a charging control could eliminate peak loads or balance the load over the day. The maximum margin for the charging load depends on the previous consumption without charging vehicles (red: load form charging electric and plug-in hybrid vehicles; blue: consumption without electric vehicles)

Load management (regulation) for electric vehicle charging reduces stress in the grid and peak power requirement and leads to flatter demand pattern

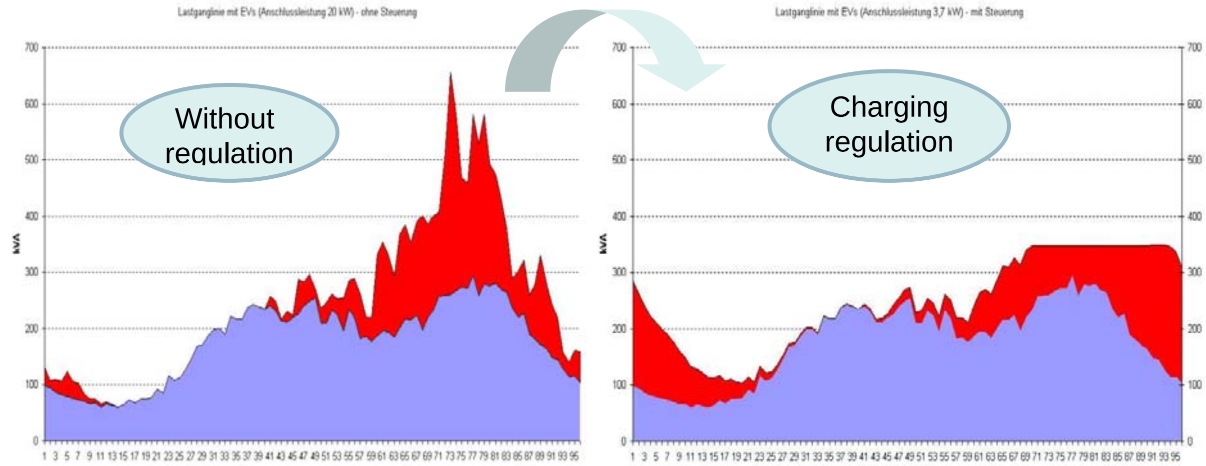

Figure 18 Example for a charging regulation, penetration rate per household 80% [IFHT, RWTH Aachen]

If the capacity of the transformer at a certain location is nearly fully utilized, a charging regulation is necessary even for small penetration rates. An integration of the charging regulation can not be related to a certain penetration rate but depends on the structure and load of the transformer. The **controlled charging requires the existence of smart grids** because an intelligent local network station has to regulate the charging process trough a communication with the vehicles. In a next step the charging regulation can be used to reduce the energy demand during a fault in the string to which electric vehicles are connected.

Furthermore some **other effects** due to a high integration of EV and PHEV can occur which make it necessary to adapt the infrastructure of the grid. The cost of these adaptations cannot be quantified because they are necessary to guarantee the stability of the electrical grid. They have to be provided by the transmission and distribution system operators.

- The **short-circuit power** is essential for grids and influences operation with respect to power quality. The maximum possible current must not exceed a certain level in order to prevent mechanical and thermal overstress of assets. It is necessary to keep a minimum short circuit current in order to detect faults. Utilizing electric and plug-in hybrid vehicles to store regenerative generated power and feed it back into the grid causes a decrease in available short circuit power. In case of a lack of short circuit power in electrical grids, it might be necessary to oversize converters. Sometimes it might be necessary to install additional short circuit power in the grid [Haubrich 2008].
- A sudden disconnection of several GW of generation might cause instability in the power system as the abrupt reduction of the power generation can not be replaced by alternatives in such a short period of time. A similar phenomenon has to be analyzed whilst integrating electric vehicles particularly with respect to **sudden simultaneous charging or discharging** of a large number of electrical vehicles due to frequency or controlled actions. The possible consequence of a destabilization of the entire power system has to be avoided. Initiation of random disconnections over time can prevent a synchronized response. It is required to guarantee that a destabilization of the grid in case of faults or response to signals cannot happen. This random disconnection has to be included into the regulation of electric and plug-in hybrid vehicles. These measures are necessary only if the penetration of vehicles reaches a significant amount and causes charging power to reach 300MW (135.000 electric and plug-in hybrid vehicles, 3.7 kW).
- Due to technical requirements of the alternating current the grid is operated with a three phase system. **One phase connected electric vehicles** may cause unbalanced loading of the grids, if many vehicles are connected to the same phase within small areas. This could cause unbalanced voltage operations. Unbalanced operation must be avoided to reduce stress on electrical machines. Designated connection

points, which are evenly distributed over three phases, could balance the load/generation over all phases. Measurement of phase voltages can also help to prevent unbalanced operation e.g. by initiation of a reduction of charging power [Haubrich 2008].

- Electric and plug-in hybrid vehicles have an influence on the existing **security concepts**. Nowadays on the middle- and low-voltage levels fuses are placed at the beginning of a string. Changes in load flow direction might have influences on the selective disconnection of faults (only faulty parts must be disconnected). To guarantee that local overloads can be detected even with changes in the load flow direction, local measurement and detection of load and current have to be installed. This is necessary before a bidirectional charging connection is used to guarantee the security during a fault for assets and humans [Kleimaier 2001].

3.3 Consequences of a high uptake of renewable energy sources into the grid

As stated above the CO_2 advantage of electric vehicles in comparison with conventional vehicles depends on the percentage of renewables in the energy production. This suggests that the production of renewable energy should be enhanced according to the penetration rate of electric and plug-in vehicles, especially in countries with a low percentage of RES. However, some problems regarding power supply due to a high development of renewable energy sources can occur.

The kind of problem depends furthermore on the development the transmission grid will make in the future. Actually two different overall scenarios exist, describing how RES can be integrated into the electrical grid which gives different perspectives of the relation between EVs and RES-E:

- **Super grid**: Various systems intending to dramatically increase transmission capacity are known as super grids. The possible benefits include enabling RES to provide electricity to distant regions e.g. large off-shore wind parks or import of RES-E to Europe from large solar power plants in Africa[20], and the ability to increase usage of intermittent energy sources by balancing them across wide distances. Major obstacles to super grids are the significant cost and local opposition to siting new lines.
- **Micro grid**: Decentralization of the distribution system is the main idea of this scenario. Micro grids would have local power generation and allow smaller grid areas to be separated from the rest of the grid in case of a failure. Micro grids consist of a large share of distributed small-scaled power plants e.g. wind power plants or PV that are located in a small area. The use of the transmission grid is reduced to a minimum.

The general principles of micro and super grids are quite opposed but they can exist in parallel. Some rural areas might be able to supply themselves as a micro grid. In this case EV and PHEV can support this system e.g. during times of low energy production. On the other hand cities and other urban areas have to be supplied with a high amount of energy from large power plants. To integrate RES into this system super grids might be necessary. A high penetration of EV can help to balance the load fluctuations in super grids. In this report we will generally analyse the potential of EV in this context. The results are relevant for both scenarios.

Renewable energy mostly comes from hydro, biomass and wind power plants and in future from solar. Renewable energy from hydropower and biomass has a technical behaviour similar to conventional power plants: constant feed-in with a predictable schedule and a certain power. These characteristics are useful as the power generation and consumption must always be balanced as much as possible as energy storage is very cost-intensive. Therefore, a major divergence of consumption and production would lead to a break down of the power supply.

Renewables like wind and solar are characterised by an intermittent supply pattern. They have to be treated with special attention as they are not predictable in their energy generation like conventional power plants

[20] see e.g. DESERTEC project, www.desertec.com

or other renewables. The power generation fluctuates with the availability of wind or solar radiation, respectively. Therefore an increased use of especially wind will lead to an increasing mismatch between supply and demand. However, the characteristics of solar power plants strongly depend on their type, e.g. photovoltaic, solar heat etc, and the country it is built in. Solar heat power plants combined with a storage possibility in countries with intensive solar radiation can work as base load power plants as well. Photovoltaic produces the highest energy amounts in peak load times and consequently reduces the peak loads.

A high percentage of renewable energy sources ask for special attention to the design and regulation of energy systems, markets depending on the conditions in different countries and the composition of the power plant mix. In this report the focus is on those problems caused by wind energy. Solar power is not considered as this represents only a small percentage in the total power generation at the moment [REN21].

To clarify the problems that can occur, Figure 19 shows a possible future in Denmark with a very high wind energy production that temporally exceeds the consumption. The red line illustrates the energy demand in Denmark over January 2008. On the weekends the demand is lower than during the week because of a reduced demand from the industry. The blue area displays the wind production. Over the weeks there is a considerable fluctuation of wind energy generation. On some days the production is constant and even higher than the consumption (assuming 50% installed wind energy in the power plant mix) and on other days the generation cannot meet the demand.

A high share of intermittent renewable energy supply leads to mismatch between supply and demand patterns

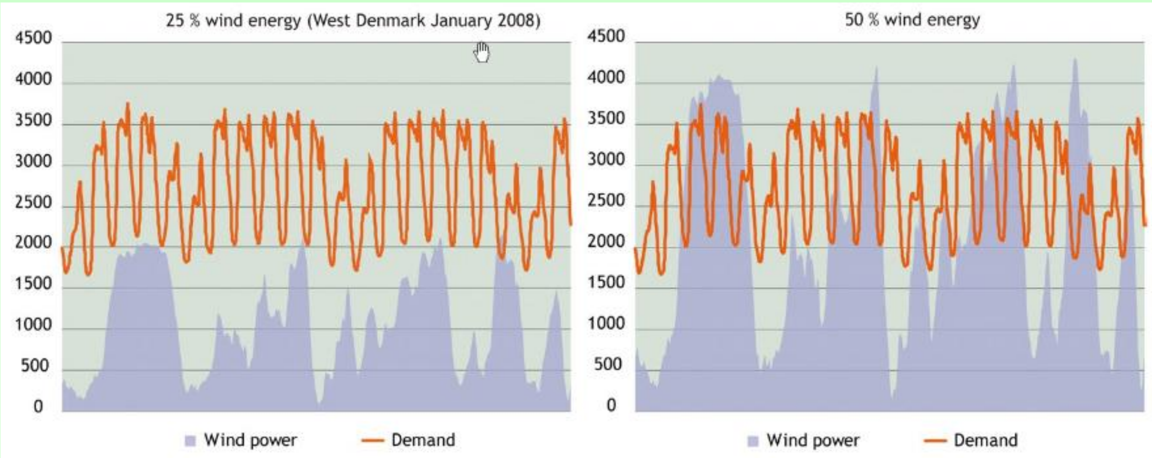

Figure 19 Comparison between the demand pattern and the wind energy production pattern in Denmark [EcoGrid 2007]

[EcoGrid07] has analysed the possible problems of a high wind penetration in Denmark. The Danish government has the target to reach a 30 % share of renewable energy in the total installed capacity in 2025. That implies a doubling of the wind power capacity installed today which in turn will have significant impacts on the Danish power system. Today Denmark is benefitting from the provision of a significant amount of balancing services arising from import and export managed by electricity markets. The increase of wind power in Denmark or in neighbouring countries will cause more competition because of the higher demand for balancing services and thus increasing costs of these resources.

The consequences of a high fluctuation of the wind energy generation as shown in the pictures grow with the size of the installed wind power capacity. If intermittent renewable energy exceeds 10-30% of the power supply the existing mechanisms for managing load and supply fluctuations cannot handle the intermittency any more [KEL 2003]. For different countries the resulting problems and possible solutions differ as described in the following.

Case 1: The wind energy production is higher than the consumption.

- The excessive production of wind energy has to be sold at low prices to other countries that can reduce their power generation from conventional power plants and use the imported wind energy to meet part of their consumption. The balancing of the power production and consumption is necessary to stabilize the grid. This only works, however, if other countries do not have the same overcapacity in the power production at the same time.
- An alternative is the disconnection or power output reduction of the wind power plants to reduce the power generation. This results in a coupling of the generation and consumption. The disadvantage is the loss of income for the owner of the wind power plant and that renewable energy generation capacity is unused.

➔ Besides the restriction of conventional power plants, a possible solution is the storage of the excess energy. Today most electricity storage systems are expensive aside from the cheap existing capacities of hydropower storage systems [VDE 2009]. Possible technologies are, among others, electrochemical and hydrogen storage systems and new hydro-energy storage facilities. An alternative possibility is demand side management. This allows the grid operation to control the consumption pattern. This supports the coupling of the generation and energy demand. In view of the environmental targets to be attained, a restriction of the power generation from renewable sources should be avoided except for extreme circumstances.

Case 2: The wind energy production is lower than the consumption with a high percentage of wind power

- The gap of the wind energy must be filled by other energy sources such as e.g. conventional power plants. A high installed capacity of wind energy leads to a reduction of investments in conventional power plants, especially for base load power plants. Base load power plants provide cheap energy during the whole day. They cannot be turned on and off easily because this is expensive and can sometimes take more than 8 hours. The peak load plants that need to be in stand-by to provide energy when the supply from renewables is insufficient are a relative expensive source of electricity. Costs per kWh increase if these plants are utilised less.

➔ To fill the supply gaps of wind power generation a high capacity of smaller power plants such as e.g. gas turbines or a storage system as described before are necessary. With demand side management the gaps in consumption can be temporarily reduced.

Case 3: Regional divergence between the power generation of RES and the energy consumption

- Optimal locations for generating renewable energy are in many cases far away from the location of high consumption (bigger cities). The biggest wind power plants (on- and offshore) are near the coast or in areas with a high wind velocity. Renewable energy power plants in general require space which is scarce in densely populated areas. This regional imbalance can change the load flow and lead to an overload of high voltage lines. If the transmission grid is well developed (e.g. in European countries) the energy can be transferred through the existing high voltage transmission grid. A large rise of renewable energy production, however, can cause an overload of the power lines to happen more frequently, especially in countries with weak transmission grids. This could lead to the problem of case 1 in a small grid area even in cases when the production is not higher than the consumption. The energy then has to be consumed geographically closer to where it is generated.

➔ A solution for this problem could be energy storage or an upgrade of the transmission grid. The cross section of the power lines could be enlarged so that more energy can be transmitted. Another alternative is to build new power lines. Both methods take a long period of time and are very expensive. Monitoring of critical lines could also help to increase the transmission capacity.

The probability for case 1 and 2 is high for smaller countries with a long coast line (e.g. Denmark) or with a high solar radiation. The critical percentage is depending on the consumption of each country. Case 3 is more relevant for larger countries e.g. the USA.

Rising demand for ancillary services

An overall problem in all cases is the unpredictability of the power generation from renewable energy, i.e. the possible deviations from the predicted production. Meteorological forecast tools for wind or solar energy help to plan the resource scheduling of power plants to guarantee a stable power supply. In the case of a mismatch between the predicted renewable power generation and the actual production, ancillary services have to secure the stability of the grid. With a higher amount of renewable energy supply the power of the ancillary services may need to be increased to prevent a breakdown of the grid.

Ancillary services guarantee that the generated energy and the load are equal. In case of a disruption in the supply the system operator has the obligation to balance the supply and demand within the electrical grid. The ancillary services are divided into:

- Primary reserve, the frequency response reserve
- Secondary reserve, the spinning and non-spinning reserve
- Tertiary reserve, replacement reserve

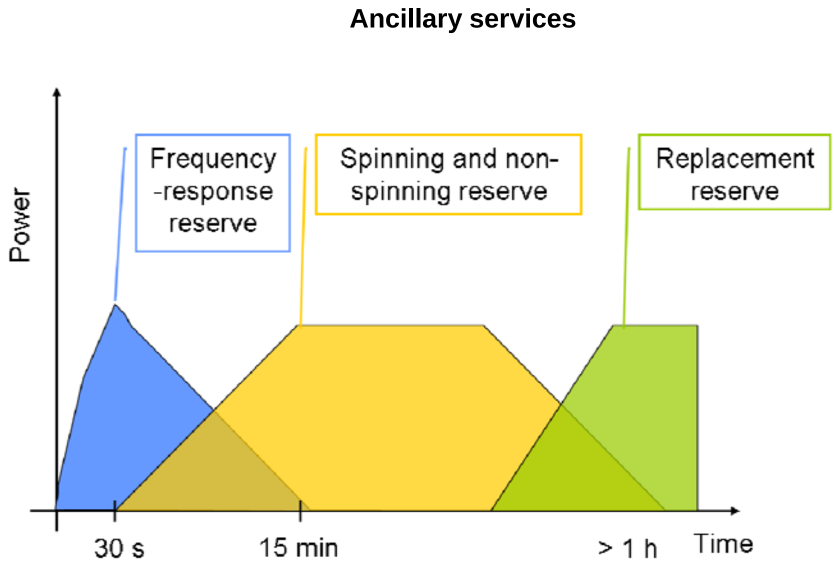

Figure 20 Representation of the different kinds of reserve power and the time intervals they are used in after

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The difference between the three services is mainly based on different starting times and the duration of the services delivery. Nowadays the ancillary services are normally provided by large conventional power plants. With the uptake of decentralized renewable energy generation the availability of conventional plants for these services might decrease and alternatives must be found. The exact specification for the ancillary services varies for each country and grid operator.

Low market penetration level sufficient for effective grid services

The number of electric vehicles that are necessary to provide ancillary services is surprisingly low. Around 800,000 electric vehicles, that are connected to the grid and ready to provide ancillary services, are able to provide the frequency response reserve for the whole of Europe (assumptions: 3000 MW primary reserve in Europe, EV with a power connection of 3.7 kW). The same number of electric vehicles is necessary to provide the secondary power requirements in Germany regarding power for a short time. To guarantee the larger energy amounts that are needed for providing tertiary reserve, significantly more vehicles are needed.

To clarify the need for ancillary services Figure 21 shows what happened during a hurricane in 2005 in Denmark [ENERGINET.DK]. The wind energy production was very high and nearly reached the demand. Due to very high wind speeds the wind power had to be shut down to avoid damages. In only a few hours the wind energy production was reduced about nearly 100% and had to be substituted by other power plants. To damp this effect EVs can be used to provide ancillary services during the fault or feed-in energy during the time the wind power plants are not able to produce energy.

Effect of a wind power shutdown during a hurricane on the wind power generation

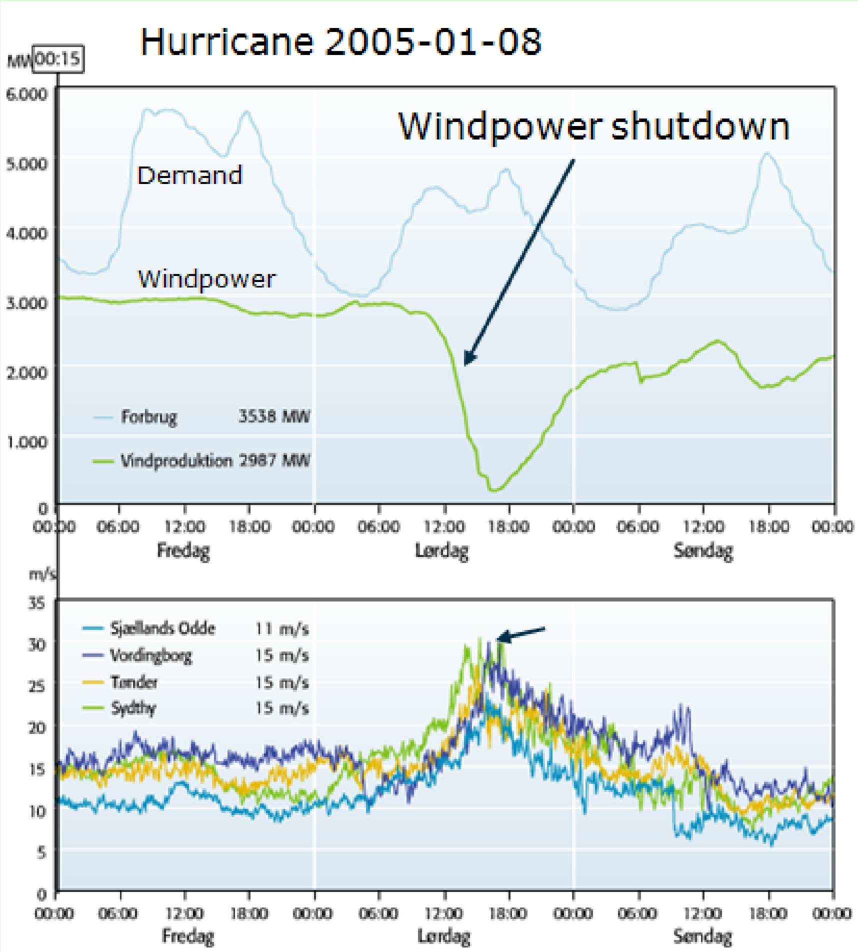

Figure 21 Course of the wind power generation and demand during a shutdown due to a hurricane in Denmark 2005 [EnergiNet.DK 2010]

3.4 Electric vehicles as means to increase the uptake of renewable electricity

The basic concept for grid related services provided by electric vehicles is called Vehicle-To-Grid (V2G) [KEM 2004]. V2G means that electric and plug-in hybrid vehicles are connected to the electrical grid during their parking time. In times when the energy consumption is low the EVs could charge their batteries without stressing the electrical grid. Additionally they could provide valuable grid services such as providing spinning reserve or regulation. Excess renewable energy could be stored in the batteries and be supplied back to the grid in times when the energy is needed.

These possible V2G services provided by electric and plug-in hybrid vehicles could help to prevent the possible negative consequences caused by a high share of intermittent renewable electricity production. Due to the variable nature of energy production from wind or solar energy sources these forms of renewable energy supply have a high symbiosis with the storage possibilities of electric and plug-in hybrid vehicles. The advantage of this kind of distributed storage compared to large central storage systems is that the collective storage capacity of batteries from vehicles could be of any size only depending on the number of vehicles. Furthermore the costs for investments into the batteries are in first instance for the car owner. It is however likely that the car owner will claim to be financially compensated for services rendered by making his car battery available for energy storage. For the three problem cases mentioned above electric and plug-in hybrid vehicles could be a solution.

3.4.1 Case 1: Demand side management to store a surplus of renewable energy

As shown before, the production of wind energy can be higher than the consumption from time to time. To use this surplus energy the charging pattern of electric vehicles connected to the grid can be controlled to match the surplus supply. Consequently the vehicles would constitute a flexible demand.

The amount of load that could be controlled through demand side management varies with the number of electric cars and the type of power connection for the charging. Furthermore, it depends on the driving behaviour of the vehicle drivers during the day, because only the consumed energy can be recharged. Consequently the possible charging power of all electric vehicles varies over the day.

Figure 22 shows the capacity (expressed as available power uptake) that can be additionally provided by electrical vehicles to store a surplus of energy from renewable energy sources over the day based on own calculations. The additional power that can be absorbed for storage differs over the day due to the driving and charging behaviour of the vehicle owner (based on driving behaviour in Germany). To allow temporary storage of a surplus of renewable energy in the battery it is important that the target for normal charging is not 100% of the state of charge (SOC, battery charging level) but rather 90%. If vehicles are always charged to 100% SOC then no capacity for additional storage is available after the charging period has stopped but the EV remains plugged in. If the charging stops at 90% of the battery capacity, the last 10% can be used to store additional energy from renewable sources. To provide these functionalities the vehicles must be connected to the grid. Therefore the peak of the power curve is during the nighttimes when nearly everyone is at home and has his EV connected to the grid. This allows storing additional energy in a case of a surplus of energy from RES. Figure 22 shows that, under the assumptions described here, in Germany 1 million electric vehicles could result in 1 GW of continuously available storage over the whole day. The grid requirements are not accounted for in these calculations.

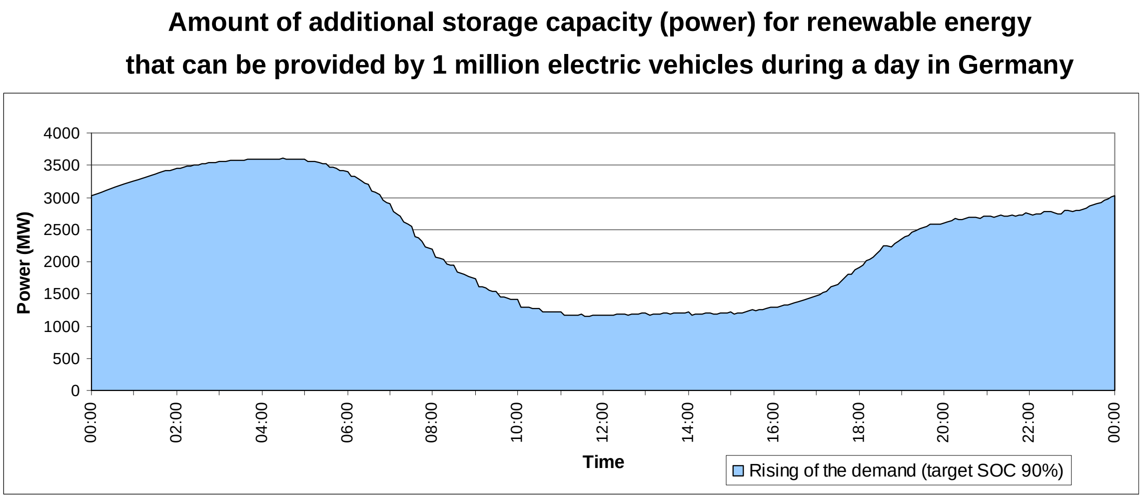

Figure 22 Additional power capacity to store a surplus of renewable energy from 1 million electric and plug-in hybrid vehicles in Germany, based on unidirectional power supply, 3.7 kW charging power and nominal charging op to a target State-Of-Charge of 90% [own calculations, IFHT, RWTH Aachen]

Creating effective storage capacity requires high market penetration levels of electric vehicles

Today the installed wind power in Denmark is 3130 MW. Using electric vehicles to provide a capacity for temporary storage of wind power equal to 30% of the installed wind power capacity would require about 1 million vehicles (50% of the fleet) in Denmark. In Germany the same constellation would require 7.2 million vehicles (17.5%) and in the USA 7.5 million (less than 3 %) EV and PHEV are needed to raise the demand up to about 30% of the installed wind energy [WWEA 2008]

Altogether charging of a surplus of energy from renewable energy sources requires a charging strategy so that the battery has a spread to store more energy.

3.4.2 Case 2: Energy feed-in to cover a shortage of renewable energy

The fluctuation in the electricity generation of wind energy plants may also lead to temporary shortages in the power supply. The energy stored in the batteries of electric and plug-in hybrid vehicles can be fed back into the grid to satisfy the demand. This can reduce the number of conventional power plants necessary to support the energy production during wind energy shortages.

If 10,000 of the electric vehicles that are connected to the grid stop their charging, the demand is reduced by 37 MW instantaneously. If they additionally feed in 75% of the energy stored in their batteries, the demand can be further reduced by another 37 MW and 262.5 MWh can be provided. With a power of 37 MW the 262.5 MWh last for around 7 hours. With a higher power connection between vehicles and grid (fast charger) these values differ according to the table below.

Table 1 Available power from electric vehicles connected to the grid depending on the power of the charging connection

Vehicles	Power Connection	Power	Energy	Duration
10,000	3.7 kW	37 MW	262.5 MWh	7.1 h
10,000	11 kW	110 MW	262.5 MWh	2.4 h
10,000	22 kW	220 MW	262.5 MWh	1.2 h

To deal with the worst case of a total outage of the wind energy production in the USA (about 25,170 MW today) by stopping the charging process only, a total of 6.8 million electric vehicles (2.7% of passenger car fleet) connected with 3.7 kW each are needed. The same situation in Denmark requires 854,000 electric vehicles (40.6% of the passenger car fleet) and in Germany around 6.5 million vehicles (16.3%). The option to feed energy from the batteries back to the grid would reduce the number of required vehicles about 50%. Assuming the availability of the vehicles for such purposes is around 75% of the time, the total amount of required vehicles rises by about 25%.

3.4.3 Case 3: Demand side management to balance the power generation and consumption

Electric and plug-in hybrid vehicles can enlarge as well as reduce power demand during the day by regulation of their charging pattern. A rising demand in regions near the power generation of renewable energy reduces the surplus of energy that could otherwise not be transmitted to other regions because of technical boundaries of the transmission grid. This works in the same way as for case 1 with the small difference that only a small section of the electrical grid is observed instead of the complete grid.

3.4.4 Ancillary services provided by electric vehicles

The ancillary services with respect to power matching are necessary for short durations up to a few hours. These services can also be provided by electric and plug-in hybrid vehicles. The required minimal power and energy can only be achieved with a **group of vehicles / pooling**. At the same time the group guarantees required availability for these services. Therefore it is necessary to centralize the control of vehicles in a way that the requirements for these services can be fulfilled. Vehicles which charge at home or at charging stations along the streets can be grouped to fulfil the requirements. Vehicles in a multi-storey car park are automatically combined to form a group. To group the vehicles an aggregator is needed. This aggregator can be the TSO or DSO but also an independent third party. Due to the unbundling in the energy sector the last option seems to be the most probably solution. The refund for the aggregator has to be paid from the revenue of the ancillary services.

The participation of electric and plug-in hybrid vehicles in the market for ancillary services depends on the grid codes of each country. To participate at the primary reserve market in the UCTE the grid code has to be changed for electric and plug-in hybrid vehicles. For the other reserve energy markets a pooling is possible. The pooling of electric vehicles is necessary for each ancillary service. A single vehicle could not participate. Only the pooling guarantees that a sufficient amount of vehicles is available during the whole day and that the required power can be provided. The regimentation has to be adjusted to simplify the participation for a group of vehicles. To provide 100% of the primary reserve in the former UCTE grid 3000 MW power is required. This can be fulfilled by a fleet of around 1,000,000 electric and plug-in hybrid vehicles in Europe. To participate in this market the availability for the service must be guaranteed. Therefore the availability of the vehicles is chosen to be 75% that means that it is assumed that 3 of 4 cars are connected to the grid over the whole day and can provide the services they are paid for.

3.4.5 General requirements to participate in the grid related services

The general requirements for the participation of electric and plug-in hybrid vehicles in all grid related services are:

- For feeding energy back into the grid: bidirectional power connections;
  - Bidirectional means the energy can be taken up from as well as delivered back to the grid;
- Regulation and coordination of the vehicles e.g. during the charging progress:
  - communication with a local network station (ICT);
  - advanced ICT is needed if the whole grid should communicate;
- Measuring equipment in the vehicles;
- Accounting and payment system.

For some vehicle to grid (V2G) services a bidirectional power connection is required while others can also function with only a unidirectional connection. For the regulation and coordination the electric power companies have to communicate with the vehicles and control the charging. This way they can trigger the vehicles to provide the different grid-related services. The measuring equipment is necessary for the accounting of the standard charging and the other V2G services.

Interaction between electric vehicles and the grid can get more complex with a growing share of electric and plug-in hybrid vehicles

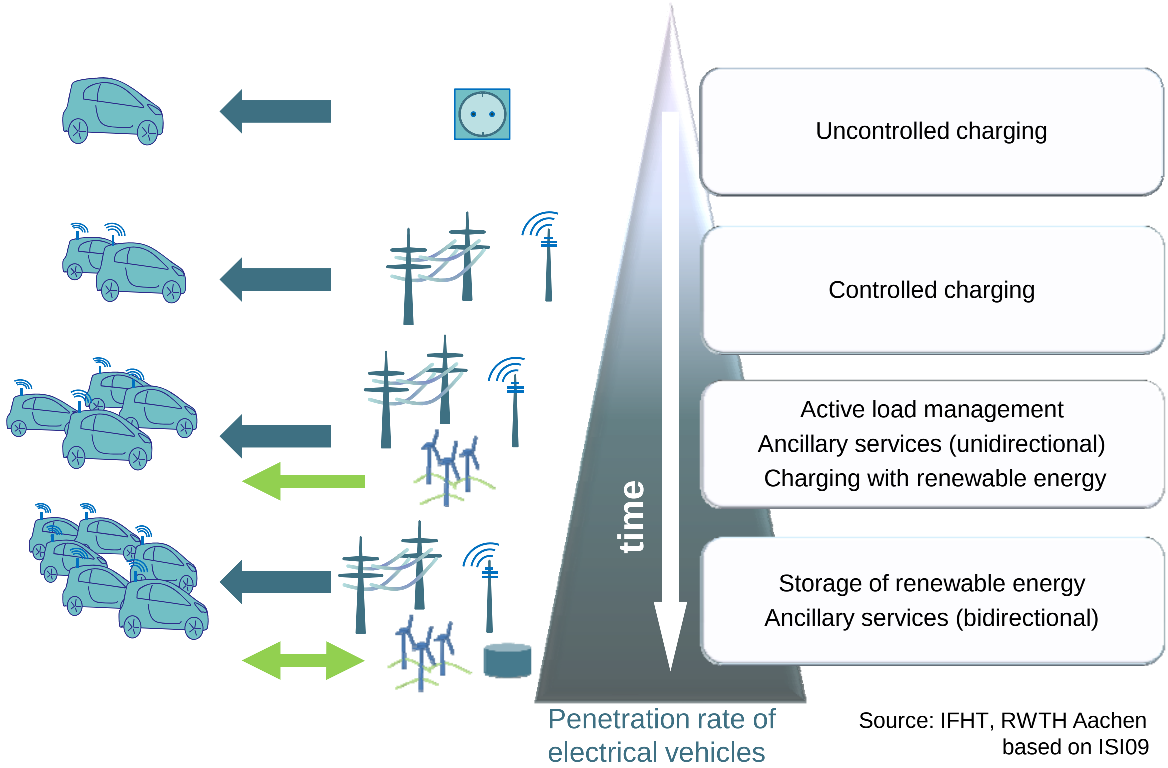

Figure 23 Stages for grid related services of electric and plug-in hybrid vehicles

Figure 23 shows the various stages of extension for different V2G services. Each step includes the developments of the levels before. In the early years the uncontrolled charging requires no additional functionalities. The first steps for a better integration of electrical vehicles consist of building a charging infrastructure and an accounting. Controlled charging and demand side management require a communication structure between the vehicles and the local network station. A unidirectional connection is sufficient. Providing negative ancillary services and a selective charging only in times of a surplus of renewable energy are the next stages of extension. Business models must be established and the political requirements for the participation in the spinning reserve must be adjusted in a way to enable electrical vehicles and plug-in electrical vehicles to participate. The grid has to be optimized for use of EV and PHEV as a possibility for storing energy. The last step is the bidirectional connection that is necessary to provide positive ancillary services and to feed energy back to the grid [ISI09]. The steps can be expected to be exogenously pushed.

The requirements as mentioned at the beginning can be integrated in “smart meters”. Smart meters replace the conventional electrical meter and allow new functions such as a detailed monitoring of consumption data. It generally communicates with the local utility via a network for monitoring and billing purposes.
Advanced smart meters allow a communication in real time with every vehicle (and other connected devices) so that operating strategies can be used. These operating strategies can control the charging and avoid overloads of the grid e.g. with load management [TOM 2007].

Smart meters are a first step in the direction of smart grids. An intelligent interaction between vehicles (and other energy supply/demand) and utilities can be enabled by smart grids by using digital technology to save energy, reduce cost and increase reliability and transparency. Beyond that a smart grid infrastructure simplifies the providing of charging strategies to secure the grid stability or the participation at different business cases. The benefit of electric vehicles for the increased uptake of renewable electricity depends strongly on the development of smart grids because these enable the necessary communication between the grid and the vehicles.

3.5 Business case of electric vehicles in relation to functions performed in the electricity system

The availability of a sufficient number of affordable vehicle models for different customers is a premise for the adoption of electric and plug-in hybrid vehicles into the automotive market. Today high purchase costs, dominated by the costs of batteries, prevent electric vehicles from being competitive in comparison to conventional vehicles. On the other hand the costs for energy and for maintenance per kilometre are generally lower for electric vehicles than for conventional vehicles.

A high penetration of electric and plug-in hybrid vehicles requires that the following main problems are solved:

- requirements for a charging infrastructure;
- limited range combined with long recharging times;
- high purchase costs of battery electrical vehicles, combined with uncertainties associated with battery lifetime.

Different business models can help to avoid or mitigate these disadvantages with the result that a market entry is possible. The value of grid services provided by electric vehicles may influence this business case.

3.5.1 The cost to EV owners of using EV batteries for vehicle-to-grid energy supply

The business case for electric vehicles as buffers for renewable electricity is thus determined by the cycle life and costs of batteries, by the costs of alternatives for matching demand and supply available to electricity companies and by possible benefits at the energy system level. Before we assess the value of the benefits it is useful to explore the costs associated with using EV batteries for vehicle-to-grid energy supply.

The current state-of-the-art of lithium-ion batteries are characterised by battery lifetimes of 1000 - 2000 cycles. With current battery costs between 1000 and 2000 €/kWh the costs of battery lifetime reduction are in the order of 0.50 – 2.00 € per kWh for energy supplied back to the grid. The battery lifetime reduction depends on the depth of discharge of the battery. If the battery is only discharged to 70% of the total capacity, this cost can be reduced significantly because the amount of possible charging cycles depends on the depth of discharge. Additionally, a strong reduction in battery costs and/or increase in battery lifetime are thus necessary to bring these costs down to levels that are below the production costs of conventional grey or renewable electricity. A cycle life of 5000 combined with costs of 200 € per kWh, which might be possible in the more distant future, would result in storage costs of 0.04 €/kWh. Such technical and cost developments are necessary anyway to improve the business case for battery-electric and plug-in hybrid vehicles. To what extent electric vehicles in the end become a cost competitive alternative for conventional vehicles on the one hand and for alternative options for storage or matching demand and supply is difficult to predict. But the value of having EVs available as buffer for renewable electricity may help to improve the business case for EV users.

3.5.2 The value of ancillary services provided by electric vehicles

Grid related services are able to generate a benefit that can help to make the electric vehicle financially attractive for a higher number of customers. This includes revenue from a possible participation at the already existing markets for ancillary services in each country to stabilize the grid and revenue from demand side management to control the electricity demand. Providing grid related services is only profitable from a user-perspective once the revenue is higher than the associated costs of battery aging. Higher penetration rates enable grid related services requiring a higher number of EV and PHEV. These services might generate revenue for the battery owner but with higher penetration rate the revenues will sink because of the oversupply of these services.

In Table 2 the main characteristics for the possible revenue of ancillary services are listed. Attention should be paid to the conditions for the revenues varying between every grid region as e.g. the European grid ENTSO-E. Every country has its own terms and conditions for ancillary services. The amount for each reserve varies likewise depending on the size of the country and the grid quality. But besides that, revenues depend mainly on the provided service and the used power connection. The higher the power connection is the fewer vehicles have to divide the earnings for the service.

Table 2 Possible revenue of ancillary services provided by electric and plug-in hybrid vehicles assessed for the situation in Germany (based on [VDN07], [VDN 2009], [TRA 2008], [Regelleistung 2009])

(Analysis for each country necessary because of different grid codes and legal requirements) (50% availability of EV and PHEV, a=year, based on prices in 2009 in Germany reserve energy market.)							
Ancillary services	*IN GERMANY*			Negative spinning reserve (unidirectional/bidirectional)		Positive spinning reserve (bidirectional)	
		Power / time	Vehicles needed (pooling)	Attributes	Possible revenue	Attributes	Possible revenue
	Primary reserve	~2 MW, t < 30 s	3.7 kW: > 1000 EV 11 kW: > 400 EV	Only for a bidirectional power connection, legal permission necessary, frequent service			3.7 kW: 300-400 €/a 11 kW: 700-800 €/a
	Secondary reserve	>10 MW 5s< t <15 min	3.7 kW: > 5500 EV 11 kW: > 2000 EV	Pooling of EV legal possible	Demand rate: 3.7 kW: 10-130 €/a 11 kW: 40-380 €/a free charging possible	Pooling of EV legal possible	Demand rate: 3.7 kW: 60-100 €/a 11 kW: 180-300 €/a Plus 0.10 €/kWh
	Tertiary reserve	>15 MW t ≥ 15 min	3.7 kW: > 8000 EV 11 kW: > 3000 EV	Pooling of EV legal possible, rare service	Demand rate: 3.7 kW: < 15 €/a 11 kW: < 35 €/a free charging possible	Pooling of EV legal possible, rare service	Demand rate: 3.7 kW: < 15 €/a 11 kW: 20-60 €/a Plus ~350 €/kWh

Table 2 contains results of an assessment of possible revenues for electrical vehicles owners resulting from providing V2G services. Due to different conditions in each country the values are not representative but permit an assessment of the amount of the revenues. Due to the fact that electrical vehicles are not participating in the reserve markets today the calculations are based on the market prices for the ancillary services in Germany in 2009. The total amount of the capacity has to be satisfied over an auction. Every allowed participant (allowance depends on the grid codes and a prequalification) have to bid either a price only for the available power capacity (primary reserve) or two prices for the available power capacity and for the provided or consumed energy (secondary and tertiary reserve). The bidder with the lowest bid will be chosen and can participate in the reserve market for the bidding period. To guarantee that the sold power capacity and energy can be provided for the required time the condition is that always 50% of the vehicles are available.

The **primary reserve** can only be provided by electric and plug-in hybrid vehicles if a bidirectional power connection exists because they have to be able to provide positive and negative power. The revenues are high compared to the other services with up to 800 € per year but the frequent provision of this kind of service might stress the battery and affect its lifetime negatively. The amount of energy exchanged is small due to the short service times so that the state of charge of the battery is nearly constant. In Germany the minimum power capacity that can participate in the primary reserve market is 2% of 100MW of conventional power plants. If the grid codes are changed and the pooling of vehicles is allowed[21] to participate, this 2 MW can be provided by electrical vehicles. Connected with the smallest power connection of 3.7 kW, 1000 vehicles can already provide 2 MW and therefore participate at this market. Assumed this would be legal, 1.5 million vehicles could provide the total necessary power of 3000MW in the EU. With higher power connections, even less vehicles can already participate.

The participation at the market for the **secondary reserve** requires about 5500 vehicles to provide the minimum power capacity of 10 MW. The earnings depend on the price for the power capacity and the price for the energy. The price for the power capacity can be as high as 380 € per year. Today, if negative secondary reserve (storage) is required the vehicles can be charged for free depending on the very low prices for negative energy in Germany's markets today. This would reduce the electricity cost additionally without stressing the battery. If 10 % of the annual energy requirement for driving could be charged for free, the cost can be reduced about 60€ per year depending on the electricity cost in each country. The fed-in energy for the positive secondary reserve would provide additional earnings too, but this would stress the battery unnecessarily. Therefore, only participation at the negative secondary reserve market is recommendable.

The **tertiary reserve** is rarely demanded and therefore favourable from the battery's point of view. Revenue can be gained from providing capacity (power) without actually providing any energy. Though, the prices for the power capacities with 15-60€ per year are low. This requires also a high overhead due to the communication. On the other hand, the energy fed-in for the tertiary reserve is extremely well paid. The participation for electric and plug-in vehicles in this market is recommended.

The **storage of excess electricity from renewable energy supply** is another market. Using demand side management the grid operator can regulate the charging of the EV into times when a surplus of energy from renewables is predicted. This allows the grid operator to buy the energy cheaper and to pass these reduced costs to the battery owner. The participation in such a business concept would thus lead to lower electricity costs for the user. The accurate amount is not predictable yet because only from January 1st, 2010 onwards, wind energy will be traded at the European Energy Exchange (EEX).

The **feed-in of the stored energy from renewable energy supply** is the last presented business model. The value of this energy will be determined by the market price at the EEX in high demand times. The revenue can be calculated as the difference between the price for the energy during the charging and the selling price less the cost for the battery use. Due to the current lack of experience with the lifetime of batteries depending on the depth of discharge, exact values are not predictable. The risk of damage of the battery is high for the electric vehicle owner even if revenue is possible. For this business model it may be more suitable that the battery is owned by the grid operator. The vehicle owner would buy the car without the battery and lease it instead.

With an advanced battery technology and lower battery prices all the business models can be successful if the necessary requirements from section 3.4 are complied with. This can support the integration of electric and plug-in hybrid vehicles especially in the early years. Due to the limited number of vehicles necessary for providing the above-discussed grid services a high penetration rate will eventually reduce the revenue per vehicle as shown schematically in Table 2. The curve can vary for every grid related service and country so that a general determination is not possible.

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[21] Pooling means in this context that a certain number of vehicles are combined to a vehicle pool. This allows guaranteeing the needed availability of power and energy to participate at the ancillary services markets. How many vehicles are needed depends on the driving behaviour in each country and can only be assessed.

The value per vehicle of services provided to the grid reduces with increasing share of electric vehicles

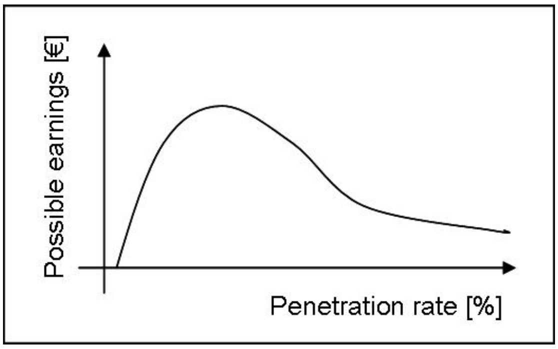

Figure 24 Individual battery / car owner's revenues depending on the penetration rate

Are the values of ancillary services significant and useful to support the business case for electric vehicles? As indicated above the per annum values of providing various ancillary services vary between several tens of Euros to a few hundred Euros. In the present situation, with electric vehicles costing € 20,000 - € 40,000 more than their conventional counterparts, such amounts will not tip the scale in favour of electric vehicles. With battery costs going down electric vehicles are expected to become more competitive in the future. Being able to obtain revenues for grid services of the order of a few hundred Euros per car could provide a useful boost to the attractiveness of electric vehicles at a critical moment on S-curve when they move from early adopters to first mass markets.

In any case the **value of the provided grid services should be higher than the incurred battery depreciation resulting from providing those services.** Without practical experience with the actual participation of electrical vehicles in grid services, it can not be determined if or when that will be the case. The greatest question is how the provided services reduce the battery lifetime. Laboratory simulations and monitoring of batteries during field trials in with electric vehicles providing grid services will be necessary to provide the required insights. Unknown battery cost can reduce the revenue from the ancillary services insofar that these services might not be cost-effective!

The issue of battery depreciation resulting from providing ancillary services is mainly relevant in case of feeding energy back into the grid (positive ancillary service and feed-in of stored energy back into the grid). Also the expected reductions in battery costs will have a dominant impact on the net business case. Development of second life applications for EV-batteries (e.g. in stationary storage facilities) may improve residual value also leading to lower battery costs for providing grid services. Given the fact that these services require smart grids and a bidirectional power connection the use of these services will not be in the first years of the market launch of electric vehicles.

Negative ancillary services and the one-way storage of renewable energy (preferential charging) are not expected to cause a significant reduction in the battery lifetime because the battery has to be charged anyway. Therefore, for these services the contribution to the business case for electric vehicle owners is always beneficial even if the revenues are low.

Another possibility to provide these services can be to use the second life of batteries that starts after their application in the vehicles. The battery would have about 80% of their former capacity but the price would be lower so that providing the ancillary services generates lower costs. Consequently this leads to business cases that are more cost-effective. This application will be realistic at the earliest in 10-15 years.

4 Policy options for the introduction of electric vehicles and stimulation of renewable electricity.

4.1 Introduction

In the previous chapters, a thorough overview on all technical aspects related to the large-scale introduction of electric vehicles has been elaborated. A number of technical and non-technical challenges currently prevent a large scale introduction into the transport and power system. It is clear that a transition will not happen autonomously. Consequently, support from the government and other actors in the system is required to kick-start developments and to provide a level playing field for truly zero emission vehicles.

Connecting the introduction of electric mobility to an increased use of renewable energy in the transport sector poses additional technical and non-technical challenges. These challenges require cross-sector cooperation as well as integrated policies. Policy makers are well aware of the complexity they are facing with the introduction of electric vehicles. Recently a number of roadmaps have been published on the national level (e.g. Canada and France) or by international organizations (IEA) that particularly point out the necessary policy measures.

The current report provides recommendations to tackle the challenges towards large scale application of electric transport. First, the position of electric vehicles is analyzed from an innovation perspective to determine the position of technological development. This will allow for a better prognosis of the next steps that need to be made in order to achieve higher penetration of vehicles, infrastructure and renewable energy production.

Secondly, policy approaches are presented for vehicles, charging infrastructure and the stimulation of increased renewable electricity production. Both sectors have to be seen in conjunction since their evolution has to be timed well. Subsequently, new policy approaches are presented that aim towards the co-evolution of transport and power sector and ensuring ‘green’ electricity usage.

The analysis considers three policy levels:
- Measures that aim to stimulate the deployment of electric and plug-in hybrid vehicles and the installation of the grid modifications for charging these vehicles;
- Instruments that stimulate the production of renewable electricity;
- Cross-sector policies to ensure a coordinated co-evolution of vehicle fleet and infrastructure.

4.2 Overview of challenges

The large-scale introduction of electric vehicles faces major challenges related to: (1) the vehicles, (2) the recharging infrastructure and its interface with the electricity grid, and (3) the end-consumers. For each part, the challenges for large-scale introduction are summarized below.

4.2.1 Light-duty vehicles (passenger cars and vans)

Initially the electric vehicles will be suffering from higher purchasing costs for the end-consumer compared to conventional cars. High battery cost and low production numbers are the main reasons for this. However, the high purchase costs for the end-consumer are expected to be compensated by lower operating costs. Other uncertainties exist about the impact of frequent battery charging on the battery lifetime and safety of batteries. The range of most vehicles is currently limited to 100 to 200 km which is already sufficient to cover the daily needs of large user groups. Recharging time is another issue. With a normal household plug it takes between 5 to 10 hours to recharge. For faster charging, special infrastructure is necessary that allows higher electricity throughput.

4.2.2 Recharging infrastructure

Electric vehicles will charge their batteries from the electric power grid. Currently there is a lack of vehicle recharging infrastructure in the built environment. The integration of electric vehicles with the electricity grid is therefore a major issue. In densely populated areas few houses have a garage or driveway that can be used for charging the vehicle. Therefore, public recharging infrastructure has to be built up to ensure that first users have easy access to a power supply. Standardization needs to ensure that there will be a uniform charging socket and power plug. As a next step, smart ICT solutions will be required for advanced charging based on regulation and coordination of the power flow between the vehicles and the grid. This is even more necessary when electric vehicles are to be used as peak power storage medium for intermittent renewable energy. Grid capacity has to be gradually upgraded to accommodate higher penetration of electric vehicles. New business models can regulate charging of the vehicles in times when electricity is at its lowest price, by using smart ICT.

4.2.3 User demands and needs

Research into users' attitudes and demands towards electric vehicles has delivered conflicting results. While some studies claim that people are hardly flexible enough in their car purchasing choices and driving behaviour to start using electric vehicles (Gould & Golob, 1998), others present more optimistic results. For example Kleindienst Muntwyler et al. (2002) have shown that electric vehicles are already able to meet the actual driving needs of a considerable market segment, despite the current limitations. Furthermore, demonstration projects have shown that people are excited about the novel driving experience with an electric vehicle and even adapt their driving behaviour to accommodate the electric car as frequently as possible in their routes (Elzen, 2006).

Research results may conflict because research participants may be reluctant to compromise their current mobility standards if only being presented the theoretical option to use an electric car. On the other hand they display more flexibility when having to practically integrate an electric vehicle in their driving routines. Further (market) research can help to better identify early adopters and improve the understanding how people accomplish the integration of electric cars in their everyday life. Thereby, strategies for market integration of electric vehicles can be better aligned with users' demands and needs.

4.3 Electric transport from an innovation perspective

Recent media reports suggest that millions of electric and plug-in hybrid vehicles will be on the road in the not too distant future. A number of automotive manufacturers (OEMs) have announced start of mass production as early as 2011, e.g. GM, Mitsubishi and Renault-Nissan. That has animated governments worldwide to announce ambitious deployment targets such as Canada (500,000 vehicles by 2018), Germany (1 million by 2020) and the Netherlands (1 million by 2025 (Lower House of the Dutch Parliament, 2009)). However, it is unclear if these targets can be actually met given the current state of technological development.

Deployment scenarios for electric vehicles show ambiguous results and are hardly predictable due to the high number of influencing factors. If an emerging economy would decide to shift R&D strongly in favour of electric vehicles and also offers deployment support at the same time the picture will change considerably. It has to be kept in mind, however, that while electric vehicle technology develops further, also their main competing technologies will improve.

The International Energy Agency (IEA) has analyzed the future perspectives and market shares for several energy technologies, among them also electric vehicles and biofuels and hydrogen as energy carriers for transport. In the Blue Map scenario, that assumes high policy support for electric vehicles, combined

EV/PHEV sales would arrive at around 34 million in 2030, compared to worldwide estimated vehicle sales of 120 million light-duty vehicles at the time. Other sources have also published estimates based on varying assumptions. McKinsey (2009) has tested the outcomes of three scenarios with a varying strong breakthrough of electric vehicles, that estimate vehicle sales ranging from 17 million (combined PHEV/EV) to 29 million in 2030.

Although the general trend for electric vehicle deployment is clearly more positive than in the past, unforeseen events, such as the worldwide economic crisis, can also be a set back in developments that are not taken into account in most forecasts. It seems also clear that to get a better picture the adoption behaviour of different world regions needs to be looked at more closely. This also holds for the grid perspective – basic conditions such as stability but also incorporation of RES-E differs heavily. Three scenarios for different world regions are discussed in paragraph 4.9.

Availability of vehicles is one of the key issues towards a broader market introduction. However the product range of electric and plug-in hybrid vehicles available is still very small. Most of the major automotive companies did neglect electric transport for quite some time and now rush to introduce new models. The range of vehicles that are available today are manufactured by small manufacturers with low volumes or niche specialisation (Aixam, Th!nk, Reva, Smith). Most of the established OEMs have announced electric vehicle sales across the board, led by Mitsubishi, Nissan-Renault, Toyota and Mercedes. Still, announced prices at market introduction are high, such as the Mitsubishi i-MiEV with a price tag of €32,000 or the GM Volt with US$ 40,000.

Unless such hard factors as battery cost and lifetime will be solved, mass-market introduction is still some time away, not to mention additional factors such as standardization and system integration. Automakers worldwide are joining with battery producers to improve the overall performance of the vehicles. From an innovation perspective electric transport has just left the R&D stage and is now in the position to demonstrate its abilities on a larger scale (see Figure 25).

On the technological development trajectory, demonstration projects represent the next important step before early markets can be entered. However, this shift towards larger production volumes is not easily achieved through demonstration projects alone and is only the start of a longer trajectory towards mass production. The next critical step is to bring the technology from a controlled environment to the early markets where electric vehicles have to compete with existing technologies.

On the technical side this step towards early markets has to make electric vehicles more cost competitive with conventional vehicles. To provide convenience of use, end-consumers need to be able to recharge their vehicles in public and heavily used spaces such as parking lots of large office buildings and supermarkets.

Important issues thus are cost reduction of the batteries and the build-up of the required infrastructure. To realize the full potential of the technology the policy needs to be targeted at the right point in development and should aim to reach mass market production. At the same time, the core vehicle technologies need to evolve alongside with other factors, including the (renewable) energy required to power these cars, the framework conditions, interface between the grid and the car, smart metering, and transparency over electricity and harmonized codes & standards.

Electric and plug-in hybrid vehicles are moving into the demonstration phase

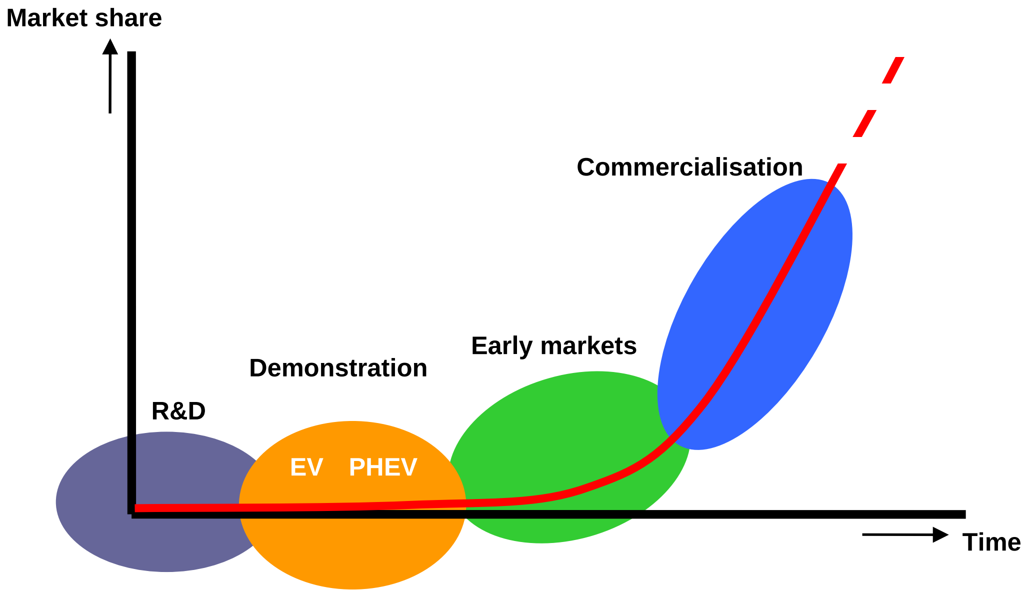

Figure 25 Position of electric transport in the technology development cycle

In order to allow the technology to make the next steps on the development trajectory the measures need to prepare the early markets for electric vehicles. Framework conditions for the reduction of additional vehicle cost (battery pack) and the support for deployment of vehicles e.g. via public procurement have to be ensured. At the same time recharging infrastructure has to be gradually build-up. Moreover, consumers need to be informed about the benefits and opportunities of the new technology and above all, the benefits of using renewable electricity.

In the following sections, policy instruments are presented that aim to tackle the barriers and specific problems associated with reaching the next phase along the development trajectory.

4.4 Policy options for stimulating the introduction of electric vehicles

This report focuses on the necessary measures to stimulate development and introduction of electric vehicles and infrastructure from the R&D phase to pilot projects and early commercialization.

In these phases the governmental support could specifically include supply-side measures, targeting the cost barriers for investments for the initial production of electric vehicles and recharging infrastructure to fuel demonstration projects and early markets. In the later stages, incentives could shift towards the demand side by providing financial measures to bridge the price difference with conventional vehicles for the end-consumer. Such measures may be implemented in a budget neutral way, e.g. by an additional (CO_2) tax on conventional cars. The development of the additional cost should be closely monitored in order to prevent over subsidising.

Governments could support the introduction of electric transport and the build-up of infrastructure through the following measures:

1. Supporting the set up of large-scale pilot projects;
2. Support further R&D to reduce cost or improve durability of key components;
3. Creating stable market conditions and long term prospects to enable car manufacturers to make the required R&D and market introduction investments, e.g. through vehicle standards.
4. Stimulating vehicle purchase and infrastructure build-up through e.g. fiscal measures;

4.4.1 Pilot projects

Currently little experience exists on integration and behaviour of electric vehicles and their users in the transport system. Demonstration projects involving electric vehicles can help to improve and harmonize the knowledge and visions of the automotive and the energy industry, suppliers and governments, and will help to come to a more reliable judgement about a realistic time frame when a mass-market introduction can be expected. Those projects should be accompanied by studies on the acceptance and environmental impact of electric vehicles and on benchmarking of vehicle performance. The focus here is the development of all key technologies of electric transport to market maturity. It also provides a testing ground for new connections between different partners from the vehicle side, infrastructure suppliers and electricity companies.

Since demonstration projects also create a recharging infrastructure with a low number of stations in the respective area, it is expected that those areas could later on serve as a starting point for early market applications, eventually growing larger and spreading out beyond the original area. Most projects aim to build charging facilities.

Table 3 Planned vehicle deployment in demonstration projects

Country/location	OEM	Deployment Plan	Timeline
France: Strasbourg France: Paris	Toyota/EDF	100 vehicles (Prius PHEV) 4,000 vehicles (autolib) 1,400 charging stations	2009-2013 2011
Germany: Berlin	Daimler/RWE	100 vehicles (Smart EV) 3,600 charging stations	2009
Japan: Tokyo	Mitsubishi, Subaru/Tepco	200 charging stations	2009
Spain: Sevilla, Barcelona, Madrid	various	2,000 vehicles 550 charging stations	2009-2011
Denmark	Better Place Gov.	500,000 charging stations 50 EV's /charging stations in 2009 150 EV/charging stations in 2012	2011
Ireland		10% of fleet electric (250,000 veh.) in 2020 1 M€ R&D and demo plan	2020
Israel	Better Place	100,000 charging stations	2010
Italy: Rome, Pisa	Daimler/Enel	100 vehicles(Smart EV) 400 charging stations	2009-2013
Netherlands: Amsterdam		10,000 vehicles to 40,000 vehicles	2015 2020
Canada: Vancouver	Mitsubishi	unknown (i-MiEV)	2009
USA: Arizona, California, Oregon, Tennessee, Washingthon	Nissan	up to 1,000 vehicles (Nissan Leaf) 12,750 charging stations	2010

Within the demonstration projects, local governmental institutions such as police and municipalities can act as lead customer and deploy an initial number of vehicles in their fleets. Other operators of vehicle fleets within urban areas such as car sharing, taxis and local delivery companies will be also very well suited to participate in those kinds of trials. These operators move only within a confined area and follow driving patterns that allow recharging over night. In addition, there is normally quite a high visibility of the vehicles which can contribute to the technology awareness among citizens. China has considered providing financial support for the purchase of electric vehicles by its governmental institutions and taxi fleets.

Currently several demonstration projects are established to scale up the technology further and to provide learning effects on how the vehicles interact within the system. In Table 3 a number of worldwide developments in demonstration projects are described.

Recommendation:

- Initiate and provide financial support for pilot projects
- Use public procurement for initial market deployment

4.4.2 Support R&D for batteries

The initially produced electric vehicles will be more expensive than comparable conventional vehicles. The main reasons for this are the high battery prices and low production volumes. Over time, vehicle costs are expected to go down fast due to ongoing R&D, learning effects and mass production. The IEA estimates that US$300-600/kWh could be an achievable target for battery costs by 2015 [IEA 2009c].

Lowering battery cost remains the most critical issue. Another issue is durability of the batteries. It is not clear how long the batteries will survive and what would be necessary to do in order to make them more durable. Therefore stimulating R&D, the support of research into novel batteries and the investment cost for new battery plants are of highest priority.

Recommendation:

- Encourage iterative and novel research and in the battery sector
- Provide incentives through investment support, zero-interest loans

4.4.3 Vehicle standards

Standards on the efficiency of the vehicles and/or the fuel production chain provide a general incentive for the industry to move to low-carbon alternatives. By setting a standard or mandate, industry can tailor their production to achieve the policy goals. If the standard is established with a clear long term objective, it creates the stable market conditions which are required for car manufacturers to make the R&D and market introduction investments.

The Californian low-carbon fuel standard (LCFS) and the EU CO_2 emission standard (130 gCO_2/km by 2015 and 95 gCO_2/km by 2020) for passenger cars are good examples. Standards that do not specifically point at electric vehicles are superior to those that specifically promote electric vehicles from a cost perspective. Such standards are beneficial for the introduction of electric vehicles, although also other alternatives will benefit. Standards also entail the danger of ‘picking the low-hanging fruit’, meaning that they stimulate incremental innovation over more disruptive options, as the cheapest option usually benefits.

As shown before in Figure 25, electric transport is still in a very early stage of development. Therefore standards should also be combined with accompanying and more technology-specific measures to facilitate market introduction such as lowering cost for the consumer or the installation of infrastructure.

4.4.4 Vehicle purchase or ownership

Due to the influence of high battery cost, the initial sales price of an electric vehicle will be much higher than the price of a conventional vehicle. The price of a small electric vehicle such as the Mitsubishi i-

MiEV is more than twice that of a comparable conventional vehicle (reportedly €32,000). Over time this price will go down but estimates vary how fast this might happen. Both further battery R&D and scale effects are necessary for this. Despite some early adopters (such as the government and fleet operators) that will be willing to purchase a more expensive vehicle, the general public is not easily going to pay more than they are used to. The vehicle price can be steered by policy instruments such as tax exemptions. Countries that have currently high vehicle taxation such as Denmark introduced tax-exemptions for EVs that already bring cost down significantly. External effects, such as a constant high oil price could make conventional cars less attractive and could support a switch to electric vehicles.

Financial support for initial vehicle production also provides support in terms of long-term prospects for the vehicle manufacturers In the case of electric transport the support should address both the vehicles and infrastructure.

Overall vehicle costs (total cost of ownership) need to be brought to a comparable level as for conventional vehicles. Additionally, consumers have a high discount rate, meaning that they value incentives at the time of purchase higher than incentives during the operation (consumer myopia) (Frederick, Loewenstein & O'Donoghue, 2002). Thus, instruments aiming at the purchase are also more effective in terms of influencing consumer purchasing behaviour. Governments are advised to provide a temporary financial relief for the additional vehicle cost to end-consumers. This can take the form of a fiscal incentive, such as reduced registration tax, subsidy on the battery cost (€/kWh) or the stimulation of alternative business models e.g. via battery leasing. This assumes that the battery remains in the ownership of e.g. a utility or a battery manufacturer that would also take care of the battery in the event of deteriorating performance and recycling. These types of business models require sophisticated billing systems (incl. roaming), to allow for example pay-as-you-drive systems for the user.

4.4.5 Infrastructure

Infrastructure aspects are of particular importance for the integration of electric vehicles. End-consumers will be hesitant to switch as long as a sufficient network of recharging stations does not exist. The government has therefore to ensure and/or coordinate a timely installation of sufficient infrastructure Although the costs for a recharging station are relatively low, first roll-out could be facilitated by governmental support for recharging infrastructure. As the current recharging structure has disadvantages in terms of time to recharge the battery, fast charging schemes should also be taken into account.

Table 4 summarizes a number of different financial instruments that can be applied around the purchase and the operation of vehicles.

Table 4 Policies impacting vehicle price and infrastructure build-up

Vehicle-fuel price related	Non-cost related
- Innovative finance models – e.g. battery leasing - Subsidy or registration tax reduction on the vehicle - No tax on electricity used for traction - Differentiated CO_2 taxes - Reductions in highway tolls and other vehicle fees - Incentives for providing recharging infrastructure - Subsidization of the cost of recharging infrastructure	- Free access for EV/PHEV to restricted areas within cities etc. - Use of dedicated lanes on highways (e.g. HOV in US), bus lanes in Europe - Guarantees for re-sale values - Additional credits under the regulatory system

4.5 Impact current policies on coupling electric vehicles and renewable electricity

The large scale introduction of electric vehicles will substantially increase the demand for renewable electricity (RES-E). Consequently, it is vital to develop policies that couple the growth of the electric vehicle fleet to additional RES-E. In addition, there is a need for coordination, because there are several new interlinkages between previously separate policy domains. In order to develop effective measures it is important to start with an overview of the impact of the current policies. This overview shows that the current policies generally involve a limited coupling between the growth of the electric vehicle fleet and RES-E. Therefore the next paragraph (4.6) provides new policy options, specifically aimed at a stronger coupling of electric vehicles and additional RES-E.

4.5.1 Feed-in tariffs or premiums – indirect incentive

Assuming a limited total budget for feed-in tariffs or premiums, increased electricity demand through electric vehicles is no direct incentive for RES-E. However, electric vehicles do provide an indirect incentive. Vehicle charging during the night, increases night-time electricity demand, thereby raising the relatively low electricity price for wind generated power during the night. Consequently, electric vehicles indirectly improve the profitability of wind power, implying that more capacity can be installed with a given total subsidy budget.

4.5.2 Obligations or renewable portfolio standards (RPS) – direct incentive

Targets for renewable electricity are usually formulated in relative terms, such as the RPS in several states in the US, or the targets set in the EU Renewable Energy Directive 2008. When electricity demand grows as a result of a large penetration of electric vehicles, the size of the target in absolute terms will also increase. This provides a direct incentive for additional production of RES-E when the electricity demand increases as a result of more electric vehicles.

4.5.3 Certificate systems – enabling role

Guarantees of origin or other (tradable) certificates can demonstrate the source of electricity to a prospective buyer. The certificate instrument in itself does not provide an incentive to additional RES-E production, because it may just induce a shift from existing RES-E production towards a new market. Nevertheless, a well-designed certificate system may be very important as it proves the electric vehicle owner whether the car is charged with renewable electricity.

4.5.4 Cap and trade systems – indirect incentive

A cap and trade system (Emission Trading Systems, ETS) also provides an incentive for additional RES-E production (or CCS) when the market share of electric vehicles increases. Under such a system in principle any additional demand for electricity has to be produced from carbon-neutral sources or has to be compensated by greenhouse gas reducing measures applied to other emitters that are part of the trading system. The additional demand for electricity by electric vehicles will lead to an increase in the price of emission credits, which will positively affect the business case of greenhouse gas reduction measures and renewable energy (see Figure 26).

In Europe the use of electric vehicles brings part of the transport sector's energy consumption under the EU-ETS

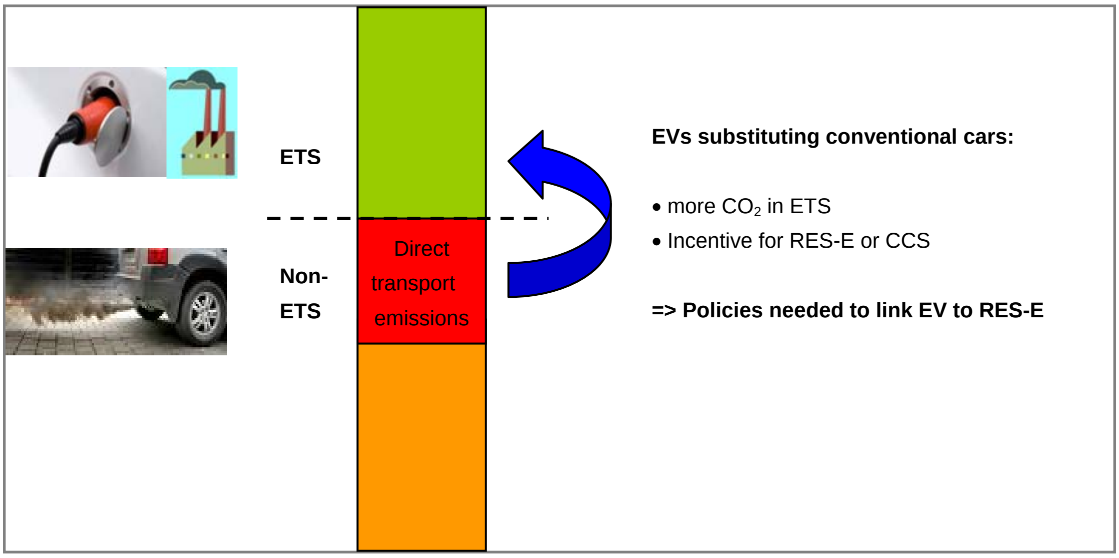

Figure 26 Electric vehicles in the context of the European CO_2 emission trading system EU-ETS.

4.5.5 Example of the impact of recent EU policies on renewable electricity for electric vehicles

Worldwide, governments develop regulations to promote renewable energy or to reduce CO_2 emissions. The EU has recently implemented several relevant regulations and thereby provides an example of how previously separate policy domains start to interact. Therefore this report briefly discusses three examples along with their interlinkages and impact on electric vehicles and additional RES-E.

- The CO_2 standards (EC regulation No. 443/2009) provide an *indirect incentive* for electric vehicles, because car manufacturers can promote electric vehicles as a way to reduce the average emissions of their car sales. Under the 130 gCO_2/km target for 2015, electric vehicles count as zero emission. For the subsequent 95 gCO_2/km target to be reached in 2020 it is still to be determined how electric vehicles and other alternatives are to be treated.
- The Renewable Energy Directive (RED, 2009/28/EG)[22] provides a *direct incentive* for electric vehicles through the subtarget of at least 10% renewable energy in transport in 2020. A small share of this subtarget could come from renewable electricity in electric vehicles. As these targets are formulated in relative terms, an increase in electricity demand will provide a direct incentive for additional RES-E production.[23]
- The EU Fuel Quality Directive (FQD, 2009/30/EG) obliges fuel suppliers to improve the well-to-wheel CO_2 emissions of their fuels by 6% in 2020. At the moment the FQD already provides a limited *direct incentive* for electric vehicles, but possibly in 2012 the directive will be extended with a mandatory 2% additional CO_2 reduction to be achieved by either RES-E, hydrogen, or CCS.

[22] The RED sets an overall target of 20% RES in final energy demand in 2020, distributed differentiated over EU member states, taking into account GDP, previously installed capacity and the potential for expanding the share of renewables. The overall target is further distributed over renewable electricity (RES-E), heating (RES-H) and transport fuels (RES-F). On average, it corresponds to some 35% RES-E in 2020, compared to 14,5% in 2006.

[23] The EU RED gives Member States the opportunity to calculate the RES-E contribution from EVs to the 10% subtarget in a somewhat flexible way, because they can either use their national share of RES-E or the EU average in the calculation. Furthermore, a factor of 2,5 may be used to reflect the higher efficiency of the electric engine compared to an ICE. This calculation does not apply to the overall 20% RES target.

It is clear that there are many potential interlinkages between the impacts of these policies in the changing context with a growth of EVs. The main point of attention concerns the way in which the emissions of electric vehicles are dealt with under different policy instruments. As mentioned before, the *well-to-wheel* emissions from electric vehicles are covered by the ETS because these take place in the power sector. However, the regulation regarding car CO2 standards only considers the *tank-to-wheel* perspective, at least in the short term, implying a possible adverse effect if the growing market penetration of EV allows other cars to emit more, while these car emissions are not covered by the ETS. However, the *well-to-tank* emissions of refineries are covered by the ETS, as well as subject to reduction targets under the FQD.

Another issue is that several decisions affecting the policy treatment of electric vehicles in the longer run are still to be taken. For example, the effectiveness of the ETS largely depends on the emission ceiling, which has been agreed for Phase II (until 2012), while the EU-wide cap for the ETS Phase III (2013-2020) is to be published in 2010. Also, the contribution of electric vehicles to the 2020 CO_2 standard is still to be determined, and in 2012 a decision will be taken regarding a further 2% emission reduction target in the FQD. Here, a coordinated policy approach is vital.

4.6 New policies to ensure a more direct linkage

As explained in the previous paragraph, the current policy framework does already involve a limited coupling between the growth of the electric vehicle fleet and RES-E. This increase in renewable electricity, however, can be considered as rather limited in view of the long term need for decarbonisation of the transport sector. Therefore policies towards charging of electric vehicles with renewable electricity should minimize the risk that renewable energy consumed in other sectors will be used in the capital intensive transport sector, thereby leading to less use of renewable energy in other sectors, to be substituted with other forms of electricity. Thus, in order to achieve substantial CO_2 emission reduction, the increasing electricity demand from the growing electric vehicle fleet, needs to be closely coupled to the simultaneous growth of *additional* RES-E. To this end we formulated the following recommendations, as listed below and visualized in Table 5:

Policy measures promoting the use of renewable energy by electric vehicles need to be targeted at the various stakeholders involved

	System stabilizing bonus	RES-E tax exemptions	Energy fund investing in new RES-E	Hard coupling EV electricity and absolute RES-E targets
Utilities			Invest (part of) energy revenues in new RES-E	
Consumers	✓	✓		
Grid operators	✓			
OEM			Allow to count EVs as ZEV in return for RES-E investments	
Governments		✓	Invest (part of) energy tax revenues in new RES-E	✓

Table 5 Policy options to promote additional renewable electricity through EVs

4.6.1 System stabilizing bonus

Controlling the charging of electric vehicle batteries has stabilizing benefits for the electricity system as is explained in detail in paragraph 3.2 to 3.4 of this report. This allows more fluctuating renewable energy sources to be integrated into electricity grids and a better voltage and frequency stability. To stimulate electric vehicle owners to allow this flexible charging, a bonus is required, which could be in the form of a reduced electricity tariff. A comparable bonus system already exists in some regions (e.g. Germany) for companies with a large but flexible energy consumption, that switch off for short time periods (order of minutes), at times of peak electricity demand. For those vehicle owners who want to be sure that only renewable electricity is being applied, green certificate systems can be used.
The advantages are:

- It provides an additional incentive for consumers to charge their car with renewable energy;
- It contributes to grid stabilization.

A condition is that it requires the implementation of smart metering solutions that recognize the connection to the vehicles.

4.6.2 RES-E tax exemptions

Another demand side measure is that EV users can be motivated to use RES-E for charging their vehicle by providing a price incentive towards RES-E electricity. This could be done via exemption from energy tax for RES-E, thus, making it less costly. This measure would also require smart metering.

The advantages are:

- Additional utilization of RES-E;
- Price advantage for RES-E, helping to build a level playing field with conventional energy.

A disadvantage is:

- Impact on governmental tax income, with increasing EV market share, needs to be balanced.

4.6.3 Dedicated energy fund investing in renewables

A supply side measure could be the set-up of a dedicated energy fund that invests in the physical build-up of additional RES-E. The energy fund would have the financial means to invest in large-scale projects that add extra RES-E to the system, e.g. through wind farms or solar energy installations. The fund could be set-up with support from the government. Preferably, an independent legal organization would monitor the developments on national level and plans the investments. It could be also set up as a private business model by the car manufacturers, but monitored by an independent certification body.

The fund would be financially equipped with contributions from two sectors: automotive and energy industry. Car manufacturers will be allowed to count electric vehicles as zero emission vehicles in the emission legislation framework, but only if they contribute to the RES-E fund per sold EV. The advantage for the car manufacturers would be that this system will lower their average fleet CO_2 emission (making it easier to meet the increasingly stringent EU car CO_2 legislation, and avoiding substantial penalties). The financial contribution could look like follows:

The payment could be based on current emission legislation:

- From 2015: €50 for each gram CO_2 above 130 gCO_2/km
- From 2020: €50 for each gram CO_2 above 95 CO_2/km

Another calculation option could be as follows: The car manufacturers pay an amount that is based on the investment (or at least the equity part) of a certain renewable technology (e.g. wind) or a technology mix. The energy generated by the capacity installed would have to cover the sum of the average driving distance of the EVs sold (using real data would be probably too complicated to monitor). The revenues of the sold energy could flow back to the fund, i.e. the car manufacturers.

The advantages are:
- Stimulates RES-E investments also from the tank-to-wheel perspective and not only well-to-wheel.

The disadvantages are:
- Possible rebound effect: Increase in high CO_2 emission cars;
- Additional investments for car manufacturers but with guaranteed revenues.

The second contribution to the energy fund may come from the energy companies themselves, especially if obliged by governmental policies. Part of their returns from sold electricity used for charging electric vehicles could be invested directly in *additional* RES-E, again through the RES-E fund. This requires smart metering and billing for electric vehicles, and a special electricity tariff for electric vehicles.

4.6.4 Hard coupling of EV electricity and RES-E targets

Currently, targets for the share of renewable energy in the energy system already exist (see the previous section). Nevertheless, there is not yet a direct link between the renewable electricity demand from EVs and the RES-E share in the energy system. A direct, 'hard coupling' between the EV market penetration and RES-E demand would ensure that with growing demand from EVs, the supply side would have to follow. For this measure to be effective, the share of EVs in the market would need to be monitored at least on an annual basis and timely decisions made to add extra RES-E capacity.

The advantages are:
- EVs can be 100% supplied with RES-E;
- A hard coupling communicates well to consumers and other stakeholders.

The disadvantages are:
- Care should be taken how the costs for the additional RES-E would be recovered. It would depend on the support scheme for RES-E whether the user of RES-E pays (for instance the electric vehicle driver), or society as a whole. The latter would probably be most beneficial for a fast uptake of electric driving.

Recommendations:

- Both demand and supply side for RES-E need to be stimulated to create additional demand and production of RES-E. The supply side should also address the tank-to-wheel side to contribute to the extension of the RES-E capacity.
- Stimulate the utilization of intermittent RES-E indirectly by providing a "system stabilizing bonus" for electric vehicle owners coupling their vehicle to the grid and/or by providing a competitive feed in tariff.
- Make RES-E cost competitive and stimulate the use through fiscal measures, e.g. energy tax exemption for RES-E used for charging EV
- Governments increase their existing RES-E targets proportionally with the growing energy demand from electric vehicles.
- Set-up of dedicated energy fund that invests in the physical build-up additional RES-E
- Financial contributions for the fund will be provided by automotive and energy industry

4.6.5 Policies to ensure a balanced grid development

What development is needed to accommodate an increasing number of electric vehicles, while providing opportunities for renewables at the same time? The policy analysis builds further on the stages of network integration that are elaborated in Table 6, in line with the stages of EV development presented in figures 24 and 30.

Table 6 Stages of network integration

I	No load management: the starting situation that involves very low levels of EV penetration.
↓	- Charging at conventional plugs - If day/night tariff structure and double metering at households already installed, Stage II will be reached more or less autonomously, otherwise, move on to Stage III
II	Shift load to night through the tariff structure, allowing charging from baseload power (coal, nuclear) and providing a market for excess supply of wind power at night.
↓	- Install smart grids and smart meters - Set up new intermediate organizations to introduce regulated charging o Introduce differentiated tariffs to encourage charging at low loads, preferential charging of wind power by making use of existing markets such as the balancing market and the market for reserve power - Introduce accounting system - Install (unidirectional) charging infrastructure
III	Active load management to integrate intermittent renewables
↓	- Use demand side management to promote 'load follows supply' - Introduce preferential charging of RES in times of surplus RES supply - Introduce time differentiated grid tariffs
IV	Active load management taking into account network requirements with a view to postponing grid reinforcement
↓	- Introduce bidirectional charging infrastructure - Introduce advanced system of financial incentives, an ICT communication structure and market organization
V	Renewables integration and local network optimisation (V2G)

The first stage is the starting point, and only feasible with a very low penetration of electric vehicles.

From stage I to II: When the number of electric vehicles increases, the capacity of the network does not allow simultaneous charging due to load constraints. The first level of load management is to induce a shift towards charging at night, when electricity demand is low. This can be stimulated through the tariff structure (passive load management) and does not impose many additional technical demands. Many households have a double meter (day/night tariffs) already. If households charge their car regularly (driving approximately 50 km each day) their electricity consumption may increase with some 50%. Therefore, low night tariffs may provide a substantial incentive towards charging at night. The benefits are a cost reduction through better utilization of base load power. In the short run, existing fossil power may be used (next to nuclear), in which case, CO_2 emissions may hardly be reduced. On the other hand, the competitiveness of wind power at night will improve.

From stage II to III: Smart meters are required to provide active control of charging patterns, driven by the integration of wind power, making use of existing markets such as the balancing market and the market for reserve power. Furthermore, new intermediate organizations are required to perform this active load management. New companies, such as Better Place, or the electricity suppliers may be candidates for this role. Currently, smart meters are in a demonstration phase.

From stage III to IV an optimization of network capacity is involved with a view on postponing grid reinforcement investments. Here, the network operator can use grid time differentiated tariffs to prevent the network from becoming too heavily used.

From stage IV to V is the final stage, representing a situation in which there is an optimal use of the grid, with a bi-directional power flow, both to charge vehicles and to use them as storage medium (V2G). This requires an advanced system of financial incentives, an ICT communication structure and market organization. There is still a large uncertainty both on the technical feasibility and on the business case – frequent charging/discharging cycles reduce the lifetime of the battery, for which the vehicle owner will need to be compensated.

Preventing unwanted effects

The flexibility in the demand offered by controlled (night-time) charging of electric vehicles could be ‘cannibalized’ by additional base-load coal power, at the cost of stabilizing capacity for intermittent renewable electricity sources. Therefore policies are required to prevent such unwanted effects, including further stimulation of priority access regulations for renewable electricity.

Recommendation:

- Stimulate policies that prioritize the access of electricity from intermittent renewable sources (such as included in the EU Renewable Energy Directive that provides either priority access or guaranteed access of renewable electricity to the grid.)
- Coordinate technical and institutional efforts to allow a timely introduction of smart grids and active load management

4.7 Action list by actor group

Making electric transport a success requires the involvement of two formerly un-associated sectors: the automotive and the power sector. Previously there was no immediate need for the two sectors to work closely together. However, the complete interface between the automotive and power industry needs to be reviewed, as there are important implications for both sectors if the increased use of electric vehicles is to co-develop with the increased use of renewable energy in transport. This could also mean a weakening of the current status of the automotive (and petroleum) industry and a rise of other sectors, namely the utilities and intermediaries. Key actions that have to be undertaken by different actors from automotive, power and governmental level are listed in the following, together with a number of framework conditions that need to be in place as well.

4.7.1 Automotive industry and system suppliers e.g. battery industry

Electric vehicles are both a threat and opportunity for incumbent car manufacturers. Most of them have focussed their value creation on the engine and transmission as most of the other parts of a car have been outsourced to suppliers. Therefore auto companies will be faced with a decision how to ensure their business model in a world that runs on electrons rather than hydrocarbons. Nevertheless, a gradual introduction of electric vehicles in the product portfolio is also a chance for the industry to comply with ever tightening emission regulations and avoidance of fines. To ensure that EVs will run on renewable electricity, consistent policies should also address the tank-to-wheel side as otherwise the automotive industry would disproportionally benefit from counting EVs as zero-emission vehicles.

The suppliers of the automotive industry will benefit most as they are possessing critical knowledge on future key components as electrical engines and batteries. Particularly the battery manufacturers will play a major role in rolling out electric vehicles, receiving an upgrade in esteem from the automotive companies. Nevertheless, most battery producers still struggle to find a way to mass manufacturing. What can be observed is an increase in strategic partnerships between first and second tier, e.g. Daimler and Evonik Industries, Nissan/NEC and Bosch/Samsung.

Actions:

- Roll-out of initial EV and PHEV population to feed demonstration projects;
- Overcome the range anxiety problem: range extension solutions (battery replacement, range extender) or simple regulatory solution: only de-charge battery for 50% max.;
- Development of cost-effective lithium recycling technologies;
- Increase R&D towards increased battery energy storage and cost reductions to allow for lower purchase prices;
- Target next generation of batteries that outperform current performance and avoid lifetime restrictions;
- All EVs are accounted as zero-emission vehicles, but a payment towards e.g. an energy fund is required per sold EV. The payment could orientate on the current emission legislation, for instance as follows:
  - Compared with the same vehicle model in the respective OEM fleet with the highest emissions;
  - From 2015: €50 for each gCO_2 above $130gCO_2/km$;
  - From 2020: €50 for each gCO_2 above $95gCO_2/km$.

4.7.2 Infrastructure providers

Companies from the electricity sector will be the suppliers of electrons as the necessary fuel of the future. This will create a large new market for them as vehicles will recharge from the grid, thereby offering a balance for the expected future reduction in overall power consumption per capita due to the effects of energy efficiency policies. Utilities will nevertheless depend on smart metering solutions that control the time of charging because recharging a vehicle is most beneficial for the utilities if done in off-peak hours. A stronger relationship needs to emerge between the utilities, car manufacturers and smart metering companies to ensure seamless operation of the vehicle for the customer. An example could be that if a new car is purchased, the car dealer would inform the responsible utility at the home address of the car user automatically. The utility would then take care that smart metering equipment is installed to the respective home and offer different tariff structures/packages in time.

Actions:

- TSO:
  - Develop plans for requirements for electricity system and recharging infrastructure
  - Develop and install technical requirements for smart grids
- DSO:
  - Set up accounting structure and allow customer to choose supplier
  - Start investments to accommodate recharging at strategic locations e.g. work/home/shopping – this may require completely new business models that may be assumed also by newly set up companies
  - Make green electricity transparent to the customer e.g. through labelling

4.7.3 Intermediaries: smart metering companies and IT

Companies that provide the technology for smart metering (i.e. meters that actively steer recharging processes and communicate with the utility) are key for the utilities to avoid additional peak demand and manage the charging process. This also means a stronger relationship between the technology supplier and the utility as they will struggle otherwise to make large-scale deployment of EVs feasible from a grid perspective (growing peak demand). Furthermore, new intermediate organizations are required to perform active load management and install the required accounting systems and tariff structures. Completely new companies that start to operate in this area by offering pay-as-you-drive solutions including battery leasing, but also established IT companies such as IBM or SAP may be candidates for this role.

Actions:
- Install smart metering solutions at private homes;
- Develop necessary accounting and billing structures together with DSO/TSO;
- Develop innovative business models that are based on €/km and not on initial high vehicle cost.

4.7.4 Research on consumers and implementation in society

Besides a group of innovators that always adopts new technologies easily, the broad public has certain expectations and habits with regard to their personal mobility. The role of the single consumer in the market introduction of EVs is not completely understood and more research is necessary towards daily driving behaviour and daily habits. Those parameters can help to understand which refinements are necessary with regard to the recharging infrastructure and at which places recharging opportunities need to be in place. This will also contribute to the overall planning of recharging infrastructure in cities. Other issues such as anxiety towards high-voltage recharging need to be considered.

Actions:
- More research into and understanding of driving behaviour
- Where are the vehicles located and where are they driven to?

4.7.5 Governments

On a political level, the regulatory authorities need to respond to the new situation. Depending on the level of liberalization of the power sector (DSO/TSO) in the respective country, governments need to actively steer the process and provide the possibilities for utilities to increase the use of renewable electricity. Timing is a key issue in initiating processes such as matching the increase of domestic renewable energy targets with the growing penetration of electrical vehicles.

Governments may also take the leading role to act as a moderator between these different stakeholder groups that all have their own economic interests in electric mobility. This should not only happen on a national level, but also internationally. A recent German joint position paper from the industry associations of the automotive, energy and supplier industry called for an orchestrated approach led by the government. Any support scheme should give a stable framework where the industry can base its decisions on. It must be closely monitored to avoid that tax payer's money is spent with limited effects. The recommendations for effective and efficient policy measures (see also the respective IEA reports) should be taken into account.

Actions:
- Define a long-term strategy for the co-evolution of the transport sector and the energy sector (see chapter 5).
- Provide R&D incentives for automotive and supplier industry (batteries, demonstration vehicles)
- Provide level playing field with conventional cars through legislation that encourages EV deployment such as stricter emission regulation
- Provide incentives to alleviate market entry barriers due to high initial EV vehicle cost
    - E.g. EV tax incentives at national level
    - E.g. subsidy on the additional vehicle cost compared to a conventional car; these subsidies could be provided for a certain period (e.g. 10 years) and decrease every year a certain percentage, for example with adjustments depending on market developments.

- Financial support for large-scale demonstration projects.
- Set up and manage energy fund that invests in additional RES-E (at national level)
- Provide a neutral discussion platform for EV stakeholders
- Define a way to organize national or supranational processes along the strategic lines ensuring the involvement of regional and local pilot projects. This process should not hinder the flexibility (so no completely centralized approach) but at the same time avoid wrong resource allocation.

4.8 Framework conditions

The move from conventional vehicles to a transport system that involves electric vehicles running on renewable electricity requires also changing framework conditions to make things work. Without those framework conditions in place, it might be substantially more difficult to achieve a system change. There are three main groups relevant to the development of electric vehicles.

4.8.1 Standardisation

For a barrier-free recharging of electric cars, the available infrastructure has to be compatible and standardized with the plugs that are used in the cars. Therefore the implementation of standards is essential to provide the interconnectivity of vehicles and the grid. In particular, the infrastructure needs priority standardization for the plugs, recharging protocol and public charging as they need to be able to absorb the upcoming different vehicle concepts. Furthermore, the vehicle-to-grid services require further standardization in order to enable charging and feeding with different energy suppliers. The voltage and power have to be standardized and safe and secure to use. This includes also the clear identification of charging points with a label.

4.8.2 Spatial planning incl. infrastructure

The possibility to charge electric vehicles at public spaces has to be taken into account in the spatial planning domain, especially with local governments. Places with a temporary or permanent high density of cars such as city centres and office locations should be equipped first with charging posts. Subsequently, also parking meters, that are more widely spread across cities can be either directly upgraded to charging posts or the meters receive a separate charging post in close proximity. The charging points should be clearly visible and allow easy and safe use for everyone. The early roll-out of this infrastructure is important to prevent ‘range anxiety’ among consumers related to a lack of charging possibilities and limitation of range. Deployment of electric vehicles in car-sharing schemes can support the broader spread of vehicles. On the other hand it should be considered that the first users of electric cars may not need a too sophisticated infrastructure because they may use the EV only for short distances and they may have charging facilities at home.

4.8.3 International collaboration

Development of electric transport is a global issue and is dominated by industry players from around the world. International collaboration in research, development and field testing reduces costs, increases learning and avoids double work. The newly founded International Renewable Energy Agency IRENA could be a platform for such international exchange.

A number of key areas should be defined and information should be made available on areas in which development is currently undertaken. Standardization is clearly one example where international collaboration will help to ensure that products and charging infrastructure will be operable worldwide. The international co-operation will also provide industry with long-term perspectives and reduce investment uncertainties. Also, the leading countries should at an early stage connect to followers from the emerging markets, e.g. the BRIC countries.

Recommendations:

- Coordination of standardisation issues related to the vehicle-grid connection, covering technical aspects of hardware (plugs) and software (vehicle-grid communication) but also aspects related to payment systems;
- Improve framework conditions such as spatial planning and permitting procedures;
- International collaboration.

4.9 Regional case studies

The level of overall grid development, its maturity, the current share of renewable electricity in the system and the readiness to integrate a higher share of renewable energy supply differs quite heavily around the world. The measures that have to be taken in order to accommodate electric vehicles and ensure the uptake of renewable energy in the grid have to be tailored towards the specific situation in different world regions. In order to provide a first impression on the necessary grid regulation this report estimated the impact on three regional case studies that have different grid situations that should be seen as representative.

4.9.1 First case: Robust grids, high availability of renewable energy in the grid (e.g. EU)

In the EU, there is generally a high level of network development, although there is a lot of variety among Member States and regions. The high voltage transmission grid is well developed, providing flexibility to match a large supply of intermittent wind power in one region with demand in another region. The exchange of RES-E surpluses across boarders is facilitated by agreements such as the Nord Pool (Nordic Electricity Market). In this way small countries like Denmark can balance their wind energy with hydro power from other Nordic countries. Furthermore, coming from a centrally planned situation, there was a tendency to invest in sufficient or overcapacity to prevent power outages, and still, the distribution system operators are subject to regulation in which power outages are discouraged.

The current EU policy framework already provides several incentives for renewables and/or for electric vehicles. The CO_2 standards for cars, Fuel Quality Directive, Renewable Energy Directive, and emission trading system are described in more detail in section 4.5.

There are large differences between member states with respect to the current share of renewable energy sources. The possibilities for electric vehicles to provide ancillary services are explained in Chapter 3. Several European countries have formulated (indicative) targets for electric vehicles, such as 1 million in Germany in 2020, 100.000 in France by 2012 and 200.000 in the Netherlands by 2020 [IEA 2009c] (see also table 3 in paragraph 4.4).

With respect to grid integration of electric vehicles, European distribution networks in their current state can probably deal with low penetrations of electric vehicles, especially when distributed over larger areas (stage I). In some countries, where double meters and day/night tariffs are implemented (the Netherlands, Spain), the shift to Stage II will take place more or less autonomously. If households charge their car regularly (driving approx. 40 km each day), their electricity consumption may increase with about 3000 kWh per year, so low night tariffs may provide a substantial incentive towards charging at night. This will accommodate the early growth in the electric vehicle market, by allowing the relative overcapacity in the network at night to be used. However, for all Member States, the step towards Stage III must be prepared already, because the passive load management in Stage II bears the risk that all cars will start charging at the same moment, e.g. at the time when the low tariff period starts, which is not desirable and stresses the grid more than without a day/night tariff differentiation. The benefits at Stage II are a cost reduction in electricity generation through better utilization of base load power. In the short run, existing coal power may be used (next to nuclear), in which case, CO_2 emissions may hardly be reduced. On the other hand, the competitiveness of wind power at night will improve.

Table 7 Electric vehicles and grid integration in the EU

			Level of EV penetration (●) **Low** **A**	**Moderate** **B**	**High** **C**
Grid requirements	**I**	No load management	● only very low penetration, depends on local/national network capacity		
	II	Shift load to night (passive)	● electricity tariff structure		
	III	Active load management to integrate intermittent RE		● smart meters, smart grids and intermediate organizations, ICT	
	IV	Active load management taking into account network capacity limits		● grid tariff structure	
	V	RE integration and local network optimisation (V2G)			● advanced ICT

Recommendation:

- Prepare for Stage III: smart grids, smart metering and intermediate organisations

4.9.2 Low-capacity grids with little availability of renewable electricity (e.g. US)

This scenario describes countries with electricity grids that have a low spare capacity at the moment for absorbing renewable electricity. The grids in those countries are ‘under stress’, supplying high population densities in urban areas and low demands in large geographical areas. Grids are local, i.e. little interconnectivity exists that could provide buffer capacity for raising shares of renewable electricity.

The US have been chosen as example, although also other large countries such as Japan and Canada could be included, but the conditions also differ widely between those countries with regard to the current situation of renewable electricity in the grid. Renewable electricity is often produced far away from the demand and has to be transported over long distances. In the US, electricity grids tend to be very local and cannot deal with high intermittent supply of renewables. Also transmission systems are not built to transmit beyond local or regional borders. No federal target exists to stimulate renewable electricity production in the US. At the state level, 29 states have mandated a share of renewable electricity through renewable portfolio standards (RPS). Nevertheless, the US recently experiences high growth rates for renewable energy in particular wind [REN21 2009].

Various states in the US have introduced standards to facilitate the emission reduction in transport, such as the low-carbon fuel standard and the zero-emission vehicle mandate (ZEV) in California.

The current network situation in the US is not suitable to supply electric vehicles with renewable electricity. In the US, local networks have to be generally upgraded since the overall technical standard is low. This also provides opportunities since it enables to directly move towards stage III and incorporate smart meters and active load management. This would also prepare the grid already for ancillary services such as vehicle to grid.

Table 8 EV and grid integration for a low capacity grid scenario

			Level of EV penetration (●)		
			Low **A**	**Moderate** **B**	**High** **C**
	I	No load management	● only very low penetration, depends on local/national network capacity		
Grid requirements	**II**	Shift load to night (passive)	● only if double meters already installed		
	III	Active load management to integrate intermittent RE	● smart meters and intermediate organisations		
	IV	Active load management taking into account network		● grid tariff structure	
	V	RE integration and local network optimisation (V2G)			● advanced ICT

Recommendations:

- Increase the interconnection capacity between the regions to allow higher share of intermittent resources.
- Introduce more ambitious long-term (relative) targets for renewable electricity
- Shift to stage III immediately.

4.9.3 Low to very low capacity in combination with a low stability (Developing Countries)

The electricity grid in the developing world is characterized by large differences. The grid capacity and stability varies enormously between countries and continents. In addition, urban and rural areas exhibit large differences in grid quality, traffic and population density. As those are initial drawbacks for the integration of electric vehicles, it could also pose a chance to facilitate their introduction along the upgrade of the whole energy system.

On average, the grid situation can be characterized by a low to very low capacity in combination with a low stability. Moreover, it should be noted that currently about 20% of the global population still has no access to the grid at all [IEA 2008a]. On the other hand, a number of countries with fast growing economies are developing grids with substantially better capacity characteristics, including several urban regions in China and Latin America. In addition several countries invest seriously in renewable electricity. India, for example, is expanding its electricity generation capacity and grid with large projects, not only including nuclear energy plants, but also renewable power, especially wind. However, at present, the electricity generation is seriously below peak demand and electrical power is unreliable in large areas and characterized by significant disruptions. In contrast, China has a much more stable and centrally organized electrical grid, while the country continues to invest strongly in the grid (ultra-high voltage transmission lines) and capacity (conventional and renewable). Wind power in China is booming [REN21 2009], although coal still dominates by far. Recently, China has announced ambitious CO_2 emission reductions for 2020 that will most likely increase the relative share of RES-E substantially.

It is highly likely that people wanting to purchase an EV in developing countries, do have access to the electricity grid, because: (1) income level is the main driver for passenger transport (see Figure 27) and vehicle ownership; and (2) as explained above, there is a strong relationship between the local economic situation and the electricity supply. The generally weak and unstable electricity grid in most developing countries does imply that the introduction of electric vehicles will start in the previously mentioned phase I (see table 5), with no load management, where the starting situation involves very low levels of EV penetration.

Passenger mobility strongly correlates with gross domestic product

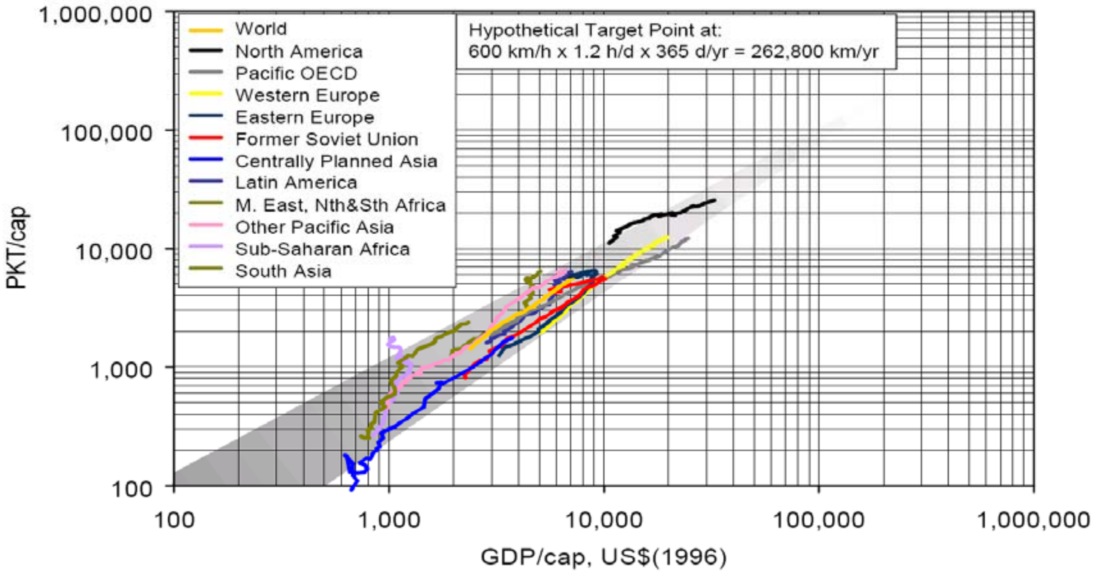

Figure 27 Relationship between income and passenger kilometres travelled [Schäfer 2005]

Window of opportunity?
Since the whole transportation sector in developing countries only recently started a booming growth, there is also a strong "window of opportunity" to introduce a large share of electric vehicles, since the vehicle market is far from saturated yet. In addition various countries or regions that do not have a centralized grid could "jump" that phase by introducing distributed energy supply with renewables that can be directly linked to EVs.

The successful introduction of (small) electric vehicles may be supported by the relatively low vehicle requirements of most people in the developing world (level of scooter performance), that generally matches with the specifications of relatively cheap small electric vehicles.

These opportunities are in line with the large ambitions of local manufacturers. Without a legacy of combustion engine supply chains and factories, Chinese and Indian companies might be able to deliver low cost, high quality electric vehicles to their national and global markets. For example the Chinese electric car and battery maker BYD expects to be a top supplier in governmental incentive programs to boost the use of electric cars in Chinese cities; similarly the Indian company TATA, which will soon bring its small mass market model Nano on the market in a relatively cheap plug-in version. Nevertheless, the introduction of electric vehicles might face other important issues that need to be solved first, such as general access to energy and other sustainability goals.

Recommendations:

- Use the window of opportunity to move towards a low carbon, electric vehicle stock in urban areas, distributed energy supply and align it with other sustainability goals.
- Thereby immediately shifting to stage III (Active load management to integrate intermittent renewables).

5 Conclusions and recommendations

5.1 Challenges for the transport sector

The transport sector is one of the major emitters of greenhouse gases and other pollutants. Due to the growth in vehicle numbers and kilometres driven energy demand and resulting greenhouse gas emissions from transport will continue to grow in the coming decades, despite efforts to make vehicles more energy efficient. A long term transition towards applying renewable energies in transport is necessary from different perspectives.

In the long term drastic GHG reductions will be required also from the transport sector in order to limit global warming to a maximum average temperature increase of 2 °C by the end of this century. By 2050 overall greenhouse gas emission reductions by industrialised countries of 80% or more compared to 1990 will be necessary to meet this goal. Furthermore the need to reduce the sector's dependence on imported oil and to improve security of supply is becoming more immanent. A shift towards using renewable energy sources will also help to reduce the adverse economic impacts of high oil prices and of the expected increasing volatility of the oil price.

Routes for creating a sustainable transport system

To reduce the greenhouse gas emissions from the transport sector and its dependence on imported oil to the levels as indicated above requires a true transition of the transport sector and its energy system. The main ingredients to realise such a transition are:

- reducing the energy demand of vehicles;
- shifting towards less carbon-intensive and carbon-neutral, renewable energy carriers;
- shifting towards more energy-efficient or less carbon-intensive modes of transport;
- curbing the growth of transport demand.

For the short term (2010-2020) energy efficiency improvements in fossil-fuelled vehicles will be the most important means of achieving intermediate GHG reduction goals. However, in order to start a transition towards a sustainable transport system that meets ambitious sustainability targets for the longer term (2030-2050), we do need to start the development and initial implementation in the short term of options that enable the use of renewable energies in transport.

The report explored possible synergetic effects between the evolution of road transport (electric and plug-in hybrid vehicles) and the increased uptake of renewable electricity. The deployment of electric and plug-in hybrid vehicles must be seen in the context of a wider evolution of power systems. In essence the energy system and transport systems must “co-evolve” to enable the transition to renewable energy supply for road transport. Suitable policy options are identified that can accelerate the transformation of road transport towards significantly lower carbon emissions through a higher uptake of energy from renewable sources.

5.2 Status and prospects of technology of vehicles and energy carriers

Important candidate technologies for applying renewable energy in the transport sector

- Vehicles with advanced combustion engines (including charge-sustaining hybrids) running on biofuels;
- Battery-electric vehicles using renewable electricity;
- Plug-in hybrid vehicles fuelled by conventional or biofuels in combination with renewable electricity;
- Fuel cell vehicles using hydrogen produced from renewable sources.

The above options are in different stages of maturity but none have reached full technical and market-readiness. All options have certain benefits but also challenges and uncertainties with respect to further technological development and introduction into the market.

First generation biofuels have the advantage that they can – to some extent – already be applied in the current vehicle stock (especially through blends with conventional fuels). In addition, biofuels may become an important option for greening heavy duty and long distance transport. The main issues with biofuels are related to their overall sustainability, specifically the high greenhouse gas emissions in the production chain (well-to-tank) of many first generation biofuels, generally derived from food crops. Second generation biofuels, derived from lignocellulosis and other woody biomass sources, promise higher chain efficiencies and lower well-to-tank emissions but are not yet ready for large scale industrial production. Production processes for these fuels still require technical development. Costs are still relatively high for all biofuels except ethanol from sugar cane.

Hydrogen fuel cell vehicles do not produce emissions during driving (zero tank-to-wheel emissions), and provide flexibility in the choice of the energy source to produce the hydrogen. Their driving range, and the time needed for refuelling are more comparable to conventional cars than those of electric vehicles. The main issues with fuel cell vehicles and hydrogen are associated with technical drawbacks of all presently available options for hydrogen storage on-board vehicles and the high costs of fuel cells. Furthermore production of hydrogen using electrolysis involves significant energy losses in the energy chain. Well-to-wheel greenhouse gasses and energy usage in general depend heavily on the method of hydrogen production. It is hard to achieve lower well-to-wheel emissions and energy usage than can be achieved with an electric vehicle.

Electric vehicles possible first candidate for harvesting synergy with increased use of renewables

Electric vehicles have no tank-to-wheel emissions and are flexible in choice of energy source, allowing the use of energy from various renewable sources. Battery-electric and plug-in hybrid vehicles are currently receiving much attention. Advances in lithium-ion battery technology allow for driving ranges in the order of 200 km (compared to 50-100 km some 10-15 years ago). Part of the current interest in electric vehicles is stemming from electricity companies looking for options to use electric vehicles to resolve challenges related to the foreseen increased use of intermittent renewable electricity production. Given the state-of-the-art of electric and plug-in vehicles on the one hand and the immanence of problems associated with large shares of wind energy production already occurring in some countries, this option is likely to be the first where the synergies emerging from a co-evolution of vehicles and energy system can be harvested.

Already with the present electricity generation mix in Europe, electric vehicles offer significant well-to-wheel greenhouse gas emission reductions compared to conventional vehicles. For the future the comparison is determined by various factors including developments of new base load power, increased share of renewables in electricity production, developments in the energy chain for conventional fuels, and developments in the efficiency of conventional and electric vehicles. Overall it is expected that the well-to-wheel greenhouse gas emission benefits of electric vehicles will further increase over time compared to conventional vehicles, predominantly resulting from the increasing share of renewable electricity.

The main challenges and uncertainties for the introduction of battery-electric and plug-in hybrid vehicles are the following:

Challenges regarding the grid:	**Challenges regarding vehicles:**
- Requirements for a new charging infrastructure, especially difficult to realise in densely populated urban areas. - Standardisation of charging infrastructure, plugs and grid-vehicle communication	- High initial costs of battery-electric vehicles, combined with uncertainties associated with battery lifetime. - Limited driving range combined with long recharging time.
Uncertainties regarding the viability of electric and plug-in hybrid vehicles: - Battery lifetime, to be proven in large scale field trials and battery safety issues. - Impact of fast charging on battery lifetime and energy efficiency. - Impact on battery lifetime of using electric vehicle batteries for vehicle-to-grid services. - Development of battery costs. - Material availability issues. - Development of future vehicle and energy tax regimes. How will these deal with battery costs and possible taxes on electricity?	

It should be noted that realising a charging infrastructure for electric vehicles is not so much a technical challenge as it is a political, institutional, economical and spatial planning challenge. The necessary technology for realizing the infrastructure is available.

The problem with driving range can in principle be largely overcome by means of fast charging or battery exchange. For battery exchange the economic case is not clear, and furthermore it requires levels of standardisation of vehicles and batteries that may be undesirable.

It is at present impossible to predict which technology or technologies will "win". Given the significant overall emission reductions to be achieved by 2050 and the uncertainties surrounding the various technologies, all options deserve stimulation for R&D and early market introduction.

Early market creation necessary to foster development of sustainable alternatives

Given the long lead times for large scale market introduction of all technologies for sustainable road transport, early action is required to have the necessary options ready for widespread implementation by 2030. R&D alone is insufficient to induce the desired technological developments and cost reductions. Creating an early market by means of large scale field trials and stable niche applications will enhance industrial investments in competitive R&D, and will foster learning effects and economies of scale in production leading to significant cost reductions.

Niche markets will be applications where users derive certain benefits from adopting EVs which outweigh possible disadvantages of the vehicles e.g. regarding costs or performance and where the realisation of the necessary charging infrastructure is relatively simple. Early niche market will comprise a number of professional applications in government and business fleets. Private consumers adopting EVs in the early phases of market introduction are expected to be mainly households with relatively high income, owning two cars and living in single-family houses with (reserved) parking facility on-site.

In the end the chances of successful market introduction of sustainable road vehicles depend on their cost compared to conventional vehicles and the real or perceived added value that these alternatives offer to the user. Added value in financial terms may be created by specific or more generic fiscal measures that promote the use of these alternatives. A payment received from the electricity company by users for making their electric vehicles available for storage of excess renewable electricity, would to some extent improve the economic business case for electric vehicles.

5.3 Synergy opportunities for the transport and the electricity sector through co-evolution

A **co-evolution of transport and electricity systems** enables electrical vehicles to support the uptake of renewable energy sources and profit from the provided services and from the CO_2 emission reduction.

Mainly, there are two roles for battery electric vehicles in relation to matching the supply of intermittent renewable energy sources:

- **Preferential charging:** using demand side management electric vehicles can be preferentially charged at moments when there is a large supply of renewable energy. The stored electricity is used for driving only;
- **Vehicle-to-grid services (V2G):** electric vehicles can also be used as buffers for renewable energy, charging at times of peak supply, and delivering electricity back to the grid at times of high demand. Furthermore electric vehicles may provide services in voltage and frequency stabilisation of the grid.

The first option already requires the introduction of smart grids where the grid is able to communicate with vehicles and other appliances and to control their electricity demand over time. The second option is more complex, and is not expected to be available soon. Among other things it requires batteries with a long lifetime (cycle life) and acceptable costs. Both options require an area-wide charging infrastructure.

Figure 28**Error! Reference source not found.** clarifies the different steps with respect to grid evolution for a coordinated uptake of renewable energy supply and electric and plug-in hybrid vehicles. There are four quadrants that represent different aspects that have to be considered:

1. Integration of renewable energy sources – Actions that have to be taken to ensure a high penetration rate of renewable energy sources into the electrical grid
2. Supporting RES with EV and PHEV – Steps for a co-evolution of the electrical grid and the electrical vehicles with the aim to reduce the impacts for the environment
3. Technical requirements for the grid support – How the grid has to be strengthened do ensure its reliability in the future.
4. Integration of EV and PHEV – Changes in the infrastructure to use EV and PHEV reasonably

Within each of the four quadrants the layers indicate consecutive steps towards a sustainable transport system based on electric vehicles and renewable electricity. Each level is necessary to reach the next. The required capacity or penetration rate of electrical vehicles for each step depends on the existing grid in every country. When the grid reserves are small the next steps have to be made earlier than in well developed grid structures. A universal approach can not be made. But it is important that technical development enables the grid and the vehicles to provide these services in the future.

Electric vehicles can be rewarded for the services they are providing. The exact amount of the revenue depends on the (value of the) provided service and the cost for the battery use. Costs of battery use and resulting possible lifetime reduction have only to be accounted for when energy is fed back into the grid. For all negative services (when the vehicle is charging from the grid) net revenues are always positive. The value of the revenues is around a few hundred Euros per year. As a matter of fact this revenue might not be high enough to finance the cost difference between a conventional and an electric vehicle. For plug-in hybrids, which generally have smaller batteries, this gap is much lower and can be reduced or closed by the value of possible grid related services, especially when battery prices fall in the future.

The energy market will change with the integration of electrical vehicles. How this will influence the prices or will change the existing market situation remains to be seen.

Overview of necessary steps for achieving a high penetration of renewable energy sources and electric vehicles

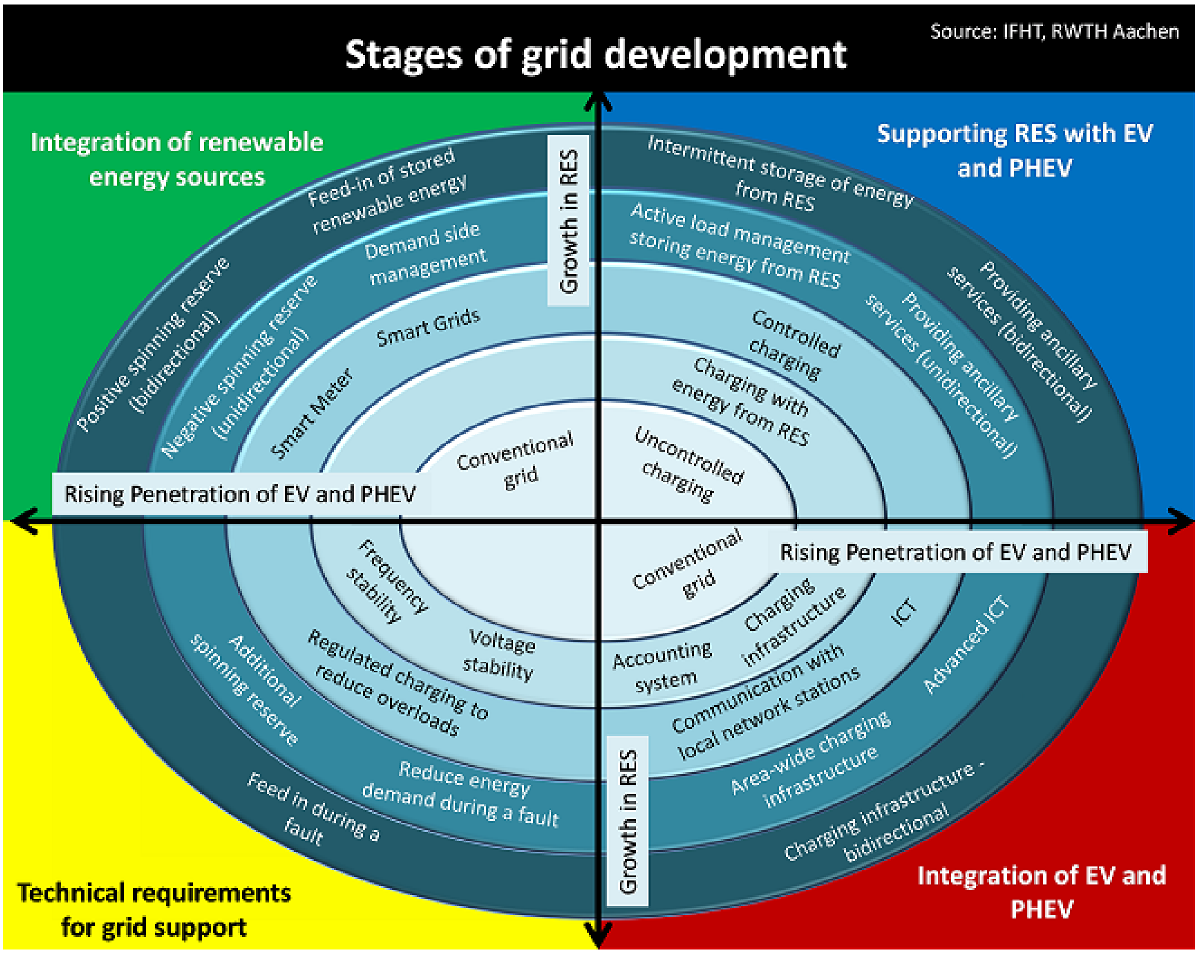

Figure 28 Four dimensions of EV introduction and additional RES-E [IFHT, RWTH Aachen]

5.4 Policy options

Design of a consistent package of policy measures for promoting the use of renewable electricity in transport

To achieve a successful introduction of large scale electric transport accompanied by an increase in renewable electricity use, a variety of different measures has to be applied. A clear, long-term policy framework provides security of investment for industry and underlines the serious ambition of governments to support the introduction of electric transport as low-carbon option. The planning of the automotive industry needs the perspective to reach a point in the market where returns on investments can be achieved.

Policy instruments will only be successful if they are applied at the right moment in time. Governments can provide favourable conditions but also other actors such as the transmission and distribution system operators (TSO/DSO) and the producers of renewable electricity need to be involved.

In general the roadmap for introducing electric vehicles consists of two phases. The first is market preparation, where the focus lies on the reduction of cost, achievement of learning effects and preparation for a future large integration through the establishment of favourable framework conditions e.g. on standardization. In the second phase the measures aim much more on the increased deployment and system integration. One of the first measures is to provide the ground for a future market to grow and provide the framework conditions. After first volumes of vehicles have been reached, vehicle costs will be further reduced through learning effects. Measures that promote the co-evolution of the transport system (through increased uptake of electric vehicles) and the energy system (through increased renewable energy generation) can be integrated in these two main phases:

Road map for synergetic co-evolution of transport and electricity sector

An integrated strategy is required that includes:

- Coordination between actors;
- A strong focus within the pilot projects on powering electric vehicles with renewable energy and on integration with smart grid developments;
- Pilot projects that work on different aspects within the overall strategy;
- Focus on niches in the first phase while preparing necessary pre-conditions for a large-scale roll out of electric vehicles in the second phase of market development;
- An integrated policy framework that provides investment security and creates an advantageous level playing field for electric vehicles, competing with other vehicles;
- Development of specific policy instruments to stimulate coordinated uptake of electric vehicles powered with renewable electricity, utilising the synergies of electric vehicles and renewable energies.

Until 2015, it is not expected that a large number of vehicles is appearing in the market place. From 2015 on, an increased supply of electric and plug-in hybrid vehicle models and a reduction in price will make the products more attractive for the consumers.

Parallel to the increase of electric vehicle shares, the production of renewable electricity is expected to continue to grow, due to targets and climate policies in many world regions. As discussed above, this imposes additional demands to the grid. Part of the ancillary services required to accommodate a large share of intermittent power may be provided by electric vehicles, if the grids evolve along the stages outlined in **Error! Reference source not found.**. The number of electric vehicles required largely depends on the condition of the networks and the share of renewable energy supply, and may therefore differ among regions.

In this report a number of suitable policy options have been identified for the three levels of electric and plug-in hybrid vehicle uptake, grid infrastructure, the uptake of additional renewable electricity and the influence on consumer behaviour. Those measures are structured by actors and presented along two timeframes in **Error! Reference source not found.**the following table:

Table 9 Policy roadmap for coordinated increase of the use of electric and plug-in hybrid vehicles and renewable electricity production

Actor	2010-2015	2015-2020
Government	- Set ambitious mid- and long term GHG reduction targets - Develop consistent framework for CO_2 emission standards for road vehicles - Stimulate R&D to increase battery energy density, lifetime and safety, decrease recharging time - Stimulate large scale demonstration projects to gain learning effects and reduce cost - Set up policy framework with sufficient incentives for consumers/manufacturers to begin moving toward EV/PHEV, focusing initially on early adopters and niche markets - Set-up energy fund financed from energy tax - Raise consumer awareness for electric vehicle - Incorporate EV infrastructure in spatial planning - Prioritize EV permitting procedures - Coordinate efforts to certain extent	- Monitor (fiscal) incentive framework and development of additional (battery) cost with a view to reducing the dependence on government incentives - Coordinate development of national recharging networks - Evaluate growth rate of vehicle penetration and adjust RES targets accordingly
Car manufacturer	- Initial roll-out of EV and PHEV models - Implementation of converter that could provide bidirectional charging - Define business models (e.g. energy fund) to ensure that EVs are counted as zero-emission vehicles - Define the target group of the first EVs: High end products in segments where image is more important than price may provide better margins and trigger development (e.g. Porsche vs. Golf)	- Increase production levels after further design optimization - Battery costs decline - Extension of the converter to provide decentralized grid support (frequency stability, voltage stability)
Battery manufacturer	- R&D to increase battery energy density, lifetime and safety, decrease recharging time - Improve reusage or recyclability of batteries and set of effective closed cycle systems	- Target a next generation set of batteries that outperform current generation considering environmental impacts
Regulator	- Change grid codes for the participation in the regulation markets - Participation for all kinds of ancillary services	- Preference for the ancillary services provided by EV to support RES.
RES-E operator/ supplier	- Provide electricity tariffs that are exclusively for RES, special tariff for EV and PHEV	- Extension of the tariffs and the energy offered, development of new RES

Actor	2010-2015	2015-2020
Transmission System Operator	- Develop plans for requirement for electricity system and recharging infrastructure - Develop and install smart grids	- Ensure full smart metering and smart grids coverage and adequate daytime charging coverage
Distribution System Operator	- Set up accounting structure, allowing EV driver to choose supplier - Begin investment to accommodate home charging and selected public locations, followed rollout of infrastructure for daytime / office charging, including fast charging - Install intelligent metering	- Make sure green electricity use is transparent for the customer
Standardi-zation bodies	- Common standards for plugs, recharging protocols in major regions - Include a possibility for communication	- Standards for systems allowing V2G

In addition to actions identified for the existing actors / stakeholders, also roles may be defined for new players on the market. Such new players may e.g. be:

- car hire or lease companies offering electric vehicles using new business models or in new mobility concepts;
- service providers that organise the pooling of individually owned vehicles in order to deliver vehicle-to-grid services;
- companies offering technical installations and services, which are focussing more and more on integral energy management of buildings and housing or industrial estates (Energy Service Companies – ESCOs), and which can implement local smart grids to facilitate the coupling of electric vehicles with locally produced renewable energy;
- local sustainable energy companies, which are currently being established in many cities to promote the implementation of energy conservation measures and local renewable energy production.

5.5 Conclusion

Given the many uncertainties still surrounding the long term perspectives of electric vehicles, full deployment of the potential for renewable electricity production should not be made dependent on the success of electric cars. Electric vehicles, on the other hand do need renewables to realise their full potential with respect to reducing greenhouse gas emissions and fossil energy dependence. The analysis presented in this report indicates that a co-evolution between the introduction of electric vehicles and increased renewable electricity production may provide a range of synergies which are worth exploring in more detail. The value of these synergies may on the one hand improve the business case for electric vehicles to some extent, and may on the other hand increase the speed of and potential for the uptake of renewable energy in the electricity sector. The synergies shown in the example of electric vehicles and "green" electricity may to some extent also be valid for other options such as biofuels and hydrogen that allow the use of renewable energy in transport.

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