Environmental impacts and impact on the electricity market of a large scale introduction of electric cars in Europe

- Critical Review of Literature -

ETC/ACC Technical Paper 2009/4
July 2009

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European Topic Centre
on Air and Climate Change

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1 Introduction

1.1 Context

Mobility is a major driver of economic growth and societal development. A large share of mobility relies on passenger car use – and the use of the passenger car is expected to continue to increase further, especially in developing and emerging countries. Today, transport is almost exclusively dominated by internal combustion vehicles – with approximately 95 % of transport reliant upon liquid carbon fuels derived from crude oil. There is no other sector which shows such a high level of dependence on one single source of primary energy.

Between 1990 and 2006, greenhouse gas (GHG) emissions from overall transport (including international aviation and marine) in EU-27 have much increased (+35.8%) while emissions from non transport sectors have decreased (-13.4%) over the same period. Road emissions in EU-27 have actually contributed to 61% of transport emissions increase and accounted for about 71% of overall transport emissions in 2006. Besides, international aviation and marine have shown the fastest growth over the same period (+73%), and weighted 23.5% of overall transport emissions in 2006 [EEA 2009, DELC 2009].

In light of climate change, urgent action is required to reduce global GHG emissions. The EU Council [EUCON 2007] and the European Parliament [EUPA 2008a] stated that developed countries should collectively reduce their GHG emissions by 60% to 80% by 2050 compared to 1990. Yet, the rate of growth of transport emissions has the potential to undermine the EU's efforts to meet these long-term GHG emission reduction targets if no action is taken to reduce them [EEA 2009, DELC 2009]. A challenge of such a scale requires all sectors, including road transport, to make urgent and substantial progress in reducing GHG emissions [KING 2007].

The two main drivers of transport emissions are the amount of kilometres travelled and the carbon intensity of these trips. Recognising the importance of increasing global mobility and economic growth and the associated increase in road transport use, large reductions in emissions have to be achieved, however this is also acknowledged as being particularly challenging for the transport sector. In this context, an increasing decarbonisation of the transport sector is essential. While the improvement of internal combustion engines still shows considerable potential to cut emissions, in particular in the short- and mid-term, reductions of GHG emissions in a range of more than 50 % will require new technological solutions.

Therefore, new propulsion systems gain increasing attraction in the context of long-term emission targets. Vehicles with electric propulsion are considered as an attractive option on the pathway towards low-emission vehicles that could enable the transport sector to reduce sectoral emissions by a significant degree.

Due to major progress in battery technology, vehicles with electric operation mode are expected to enter the market within the next few years. Electric vehicles are characterised by the highest engine efficiency of existing propulsion systems and zero tailpipe emissions. The use of electricity as an energy carrier for these vehicles offers the opportunity to broaden the range of primary energy sources in road transport. But it has to be kept in mind that well-to-wheel emissions of electric vehicles are strongly dependent on the carbon-intensity of power generation. If carbon emissions from electricity generation are fundamentally reduced over time, considerable emission reductions of the transport sector relying on a large share of electric vehicles could be achieved in the future.

1.2 Structure of the paper

Within the scope of this paper the potential environmental impacts and the impact on the electricity market of a large scale introduction of electric cars in Europe have been studied upon an extensive literature review. In light of the GHG emission reduction requirements mentioned above, the potential future contribution of the transport sector by the introduction of electric vehicles is addressed. In addition, further environmental concerns, such as local air pollutant and noise emissions and vehicle life cycle emissions were also examined on the basis of the findings in the reviewed literature.

Key factors which determine the environmental effect of a large-scale introduction of electric vehicles are:

- Total energy demand of electric vehicles on the market,
- GHG and further emissions of the electricity generation for electric vehicle energy supply.

In the scope of this technical paper, all relevant aspects influencing these key factors have been addressed based on the findings of available studies on electric vehicles, and aspects where further research is needed have been identified.

For the determination of the total energy demand of electric vehicles, information is needed with regard to the energy demand per state of the art EV, the mileage which can be substituted in electric driving mode, and the assumed future market penetration.

Energy demand per state of the art electric vehicle

The energy demand of electric vehicles depends mainly on the applied vehicle and propulsion concept. The in-use energy demand per vehicle is further dependent on the driving behaviour and external conditions.

An overview of the current status of electric vehicle development and potential future perspectives is given in Chapter 2, referring to already available technology and its projected development - in accordance with the literature. Starting from an overview of available battery system technologies and their characteristics (Section 2.1), the discussion of different vehicle concepts (Section 2.2) highlights the main fields of application (2.2.2) and properties of electric vehicles, including information on the energy consumption of different vehicle concepts (2.2.3).

In Section 2.3, an overview of the current and prospective market for EVs is given and major pilot schemes are illustrated.

Substitutable mileage

The total mileage which could be substituted by vehicles in electric operation mode is mainly influenced by the real-world driving and charging behaviour of electric vehicles, electric driving range and customer acceptance.

In Chapter 3, the potential for electric vehicles is discussed with regard to different business models (Section 3.1) and to average driving patterns, projected focus areas and applications and potential early target groups (Section 3.2) which have been derived from available driving data and early user's experience, documented in the literature.

Market penetration

In Section 3.3 an overview of market penetration scenarios which can be found in the literature is given and an assessment of its technological feasibility is documented. Section 3.4 discusses then the main market barriers and highlights fields of action, presenting a wide range of potential policy measures supporting the introduction of EVs which are discussed in the literature. Further, the current public engagement with regard to the deployment of electric vehicles is illustrated providing examples of governmental initiatives and policies which have already been implemented or have been announced in several countries – on a regional, national or continental level – with a major focus on the member states of the European Union.

Electricity and load demand

Chapter 4 reflects on the potential environmental impact of electric vehicles as discussed in the reviewed literature, focusing in particular on GHG emissions and the interaction of the energy demand of electric vehicles with the power sector.

Section 4.1 determines the GHG reduction potential of electric vehicles, assuming average emission factors for different present and future national grid mix scenarios, without considering further interactions with the power sector (this approach is widely applied in the available studies on this topic). In addition, an overview of the required additional energy demand under different EV penetration assumptions as stated in the reviewed literature is provided.

In Section 4.2, the impact on GHG emissions is evaluated taking into account the interactions of the energy and load demand by electric vehicles with the electricity market, assuming different strategies with regard to the development of the power sector and load management (regarding battery charging). Further consequences on electric vehicle related emissions, which result from interactions with current EU legislation, are illustrated in section 4.3 First findings with regard to the assumed impact of a large-scale introduction of electric vehicles on air quality and noise emissions are addressed in section 4.4.

Open issues

A further open question is related to general mobility patterns which could be influenced by an increasing deployment of small battery electric vehicles. On the one hand, due to zero tailpipe emissions, high efficiency and low operation costs of electric vehicles, passenger car use could become even more attractive and the vehicle miles travelled could continue to rise in the future. Thus, other important options related to sustainable transport policy such as demand reduction or the use of more environmentally friendly transport modes would become less attractive. On the other hand, an alternative scenario is imaginable as well, where the limitations of battery performance lead to a rethinking of established car concepts and mobility patterns. New vehicle concepts and mobility services could be established matching to individual mobility needs and transform mobility significantly versus car concepts and mobility patterns such as car sharing combined with public transport. Both scenarios are highly hypothetical but interesting questions in the context of a more sustainable mobility. These have not yet been addressed in literature as they reflect more fundamental aspects of future transport policy. But it should be kept in mind when discussing the subject of electro-mobility.

2 Electric vehicles

2.1 Energy storage systems

2.1.1 General considerations

The successful market introduction of vehicles with electric driving mode is highly dependent on the availability of a battery technology that allows reliable on-board storage of electric energy. Starting form the conventional lead-acid battery, a multitude of battery concepts have been developed over the last decade and already attained considerable progress in storing electric energy.

The high share and range of electric operation of plug-in hybrid and electric vehicles leads consequentially to increased requirements on battery systems for automotive application. Traction batteries for electric vehicles have to ensure a sufficient energy and power density without exceeding given battery weight and volume restrictions. Batteries need to offer a considerable electric driving range as well as an appropriate vehicle performance. Strong safety standards have to be assured due to the high amount of stored energy in mobile applications. The risk of sudden uncontrolled discharges in case of short-circuit, over-loading and overheating should be minimised to negligible levels. The life-time of traction batteries is determined by the expected average service life of the vehicle, and should be at least guaranteed for 8 to 10 years. In general, the original battery capacity decreases over the lifetime independently of the type of use, as well as depending on the number and type of discharge-cycles. The minimum number of discharge-recharge-cycles which has to be tolerated by the battery varies depending on the vehicle concept. Pure electric vehicles require at least 1,000 deep cycles, plug-in hybrid vehicles with a relevant electric driving range, require between 2,000 and 2,500 cycles during the vehicle's lifetime [CARB 2007, MIT 2007]. With regard to the characteristics of electric vehicles, traction batteries have variable dimensions in regard to power and energy capacity. In particular for pure electric vehicles, where the electric drive train represents the sole propulsion system, the battery has to be robust regardless of the external temperature and the battery's status of charge. The demand of performance and energy has to be ensured by the battery at all conditions.

Battery costs represent the main additional costs of plug-in hybrid and full electric vehicles. They are the determining factor of cost-effectiveness of electric vehicles [CARB 2007].

2.1.2 Overview of technology options for automotive application

Nickel-cadmium battery

Nickel-cadmium batteries have been widely applied in electric vehicles of the 1990s. In particular due to its high self-discharge rate and a low tolerance of frequent charging and discharging (low cycle life), the nickel-cadmium technologies has not been further developed [ENG 2007]. Besides a modest energy density (40 Wh/kg), a further drawback of this technology is the toxicity of cadmium [BONN 2009]. During the last decade costs of Ni-Cd-batteries have been significantly reduced. Further cost reductions are not expected as today's battery costs are mainly dominated by the raw material price of Nickel [MUNT 2007].

Sodium-nickel chloride (ZEBRA) battery

So called ZEBRA-batteries are based on a sodium-nickel chloride technology which operates at high temperature and which has been mainly tested in heavy-duty vehicles. ZEBRA-batteries are characterised by long life times, a particular robustness, and relatively high energy densities at moderate costs. The low power density of this technology (see Figure 1) does not meet the power requirements of hybrid electric and pure electric vehicles. ZEBRA batteries are therefore produced only in small volumes (1,500 per year). Possible fields of application are small battery electric vehicles (e.g. Smart ed in London) and hybrid electric heavy-duty vehicles and urban busses [CARB 2007].

Nickel-metal hydride battery

Nickel-metal hydride (NiMH) batteries represent the current standard technology for hybrid electric vehicles as well as for recent electric test vehicles. NiMH batteries are characterised by a relatively high power density, high cycle life and long lifetime and a high safety standard [CARB 2007, MIT 2007]. In Japan, mature high-performance NiMH batteries for automotive application are manufactured with a yearly production volume of 500,000. However, despite the large production volume, the costs of these battery systems remain at a high level. The actual status of NiMH technology has provided a basis for the production of first marketable hybrid electric vehicles such as the Toyota Prius. Mean-power/mean-energy batteries of the NiMH type would be applicable for plug-in hybrid vehicles with low electric ranges. High-energy NiMH batteries, which would be required for longer electric ranges, are still very costly. The NiMH battery is nearing fundamental technical limits, for example the energy density is expected at ~75 Wh/kg per pack, and further substantial technological progress is not expected [MIT 2007]. Experts on battery technology do not expect the application of NiMH-based battery systems for plug-in hybrid and electric vehicles with larger electric driving ranges, due to the inferior energy density of NiMH batteries compared to that of lithium-ion batteries and the low potential for further improvement [E.g. a passenger car with a electric range of 100-150 kilometres would require a battery of about 30 kWh energy capacity which would weight between 540 and 600 kilograms in case of the NiMH technology.] The main focus of NiMH battery development is a further cost reduction and its application for conventional hybrid electric vehicles with only short electric operation capability [CARB 2007]. Moreover, NiMH could be applied to low-performance electric vehicles of vehicles with lower electric driving range, requiring lower energy capacities that can be fulfilled by the NiMH technology. Due to the high raw material price for nickel and a nickel requirement of 5 to 10 kg/kWh for NiMH batteries, further cost reductions are rather challenging [ZSW 2009].

Lithium ion battery

Lithium ion batteries represent the most promising technology of electric energy storage at the moment and 'there is a widespread feeling that lithium-ion batteries will become the dominant chemistry for electrically-driven vehicles in the future' [MIT 2007]. Starting from the development of corresponding batteries for consumer electronics, an increased research and development of larger lithium ion battery systems for automotive applications can be observed during the last years. Lithium ion-type batteries achieve a much higher energy density due to the voltage of lithium ion cells that is significantly higher than that of the before mentioned technologies (see Figure 1). According to DEBA [2008], for a given weight or size, lithium ion batteries provide 1.4 to 2.0 times the power and energy, and have potential to significantly reduce cost compared with NiMH technology. Furthermore, this type of battery is characterised by relatively high cycle life and lifetime and only low self-discharging losses [MIT 2007, SAFT 2007, UNSA 2009].

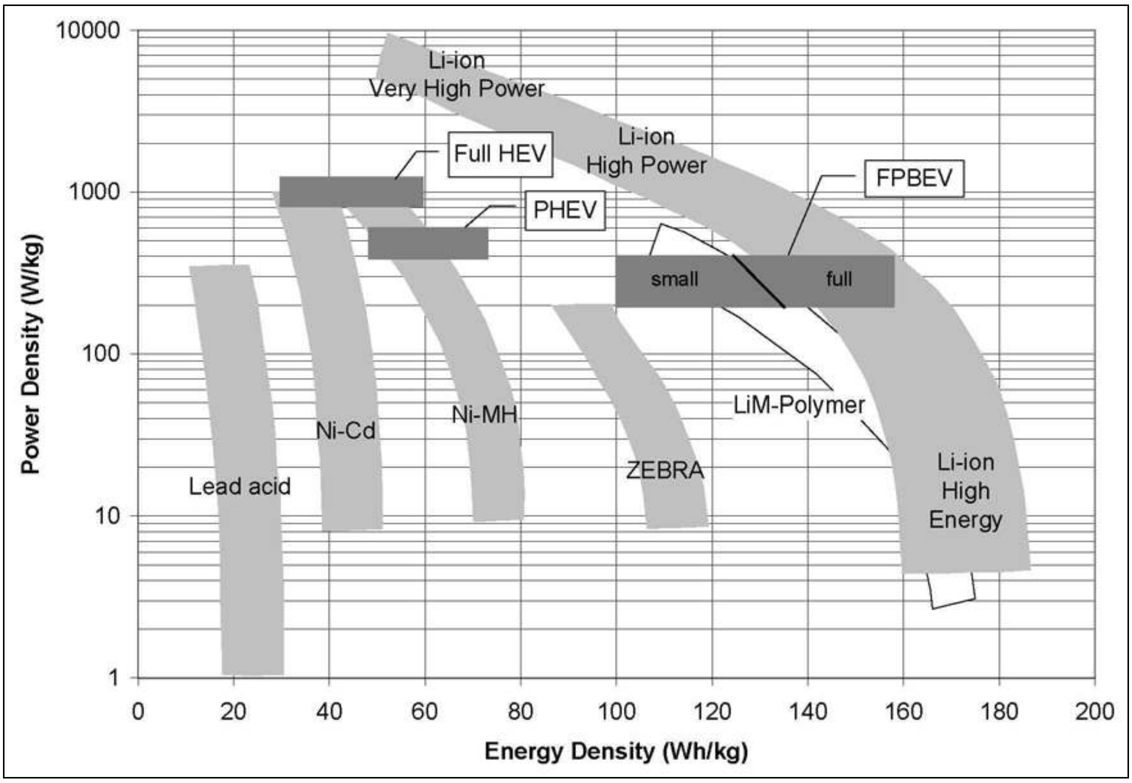

Figure 1: Power and energy density characteristics of different battery technologies for automotive application (Source: CARB 2007).

However, lithium ion cells are sensitive to overcharging. Safety issues in relation to electric, electrochemical, thermal and mechanical impacts are considered as manageable, but require a battery management system that monitors cell voltages and temperatures at any time [UNSA 2009]. The continuing improvement in material characteristics has already led to a considerable increase of battery safety [TECH 2008]. No noteworthy accident has occurred during the testing of about 200 pilot electric vehicles with lithium ion batteries [CARB 2007]. The currently available energy and power density of lithium ion technology fulfils already minimum battery requirements for small and medium size full electric vehicles and plug-in hybrid electric vehicles with low electric range. Furthermore, the additional weight of those storage systems is acceptable. It is expected that the adoption of modified materials (e.g. electrode materials) can further improve energy density, life time and safety of lithium ion batteries in the near future [CARB 2007, ZSW 2009].

The high production costs of lithium ion batteries are responsible for the delayed market entry and remain a main field of ongoing research and development. Today's prognoses on possible future cost reductions, subject to production volumes, vary widely among experts. Despite this remaining uncertainty, it is generally assumed that the lithium-ion technology offers the potential to lower costs as a result of the optimisations of manufacturing processes with economy of scale and the transition to alternative less expensive materials [MIT 2007, BERR 2008a]. Today, about 90% of battery research is done in the field of lithium batteries, but further R&D programs are essential for fast capacity building and subsequent production [ZSW 2009].

Other lithium-based battery technologies

In the long term, the lithium-sulphur battery is a candidate for a high-capacity energy storage system as it has the highest theoretical energy density among known battery systems. However, a market introduction of lithium-sulphur batteries is not expected in the near future because of the difficult manageability of metallic lithium, the danger of electrochemical cell discharge reactions, low cycling life and considerably high production costs [CARB 2007].

Lithium-ion polymer battery systems and the lithium iron phosphate battery are further battery technologies that are currently under development and could become available for automotive application in the near future [PBL 2009]. The first is flexible and even lighter than the conventional lithium-ion technology; the latter is characterized by a longer average life time and lower costs than other technological solutions.

Further energy storage concept

Researchers in the US and Japan recently developed a technology that stores energy in magnets rather than through chemical reaction [EUREK 2009]. This technology uses nano-magnets to induce electromotive force by the conversion of magnetic energy into electrical energy without a chemical reaction. This concept is still at an early stage of development but researchers assume that this new battery concept could be developed to power electric vehicles in the future.

Flywheels and ultracapacitors continue to improve and represent further non-electrochemical alternatives for future mobile energy storage that could be applied for electric vehicles in the long-term [EUREK 2009]. Ultracapacitors store electricity physically and allow therefore fast charging and discharging. Because of the relative low energy density, this technology remains however less suitable for electric vehicles [PBL 2009, DEBA 2008]. However, as stated in an unpublished working paper of the International Energy Agency (IEA), these alternative energy storage concepts should not be ignored and strong R&D programs should be established in order to develop "next-generation" energy storage systems beyond lithium ion batteries.

SUMMARY: BATTERY TECHNOLOGY OPTIONS

Results from literature

- The battery system represents the key technology of electric vehicles as it defines their electric range and performance characteristics.
- Electric vehicles with considerable electric driving range require a high energy and power density of the battery to allow its integration within the vehicle.
- Further criteria are safe and robust operation, sufficient cycle life and life-time.
- With regard to the economic attractiveness of electric vehicles, the battery system plays a decisive role. Only battery technologies that offer the future potential of a production at reasonable costs seem to be attractive for automotive applications.
- In view of the required energy and power density, the lithium-ion battery technology represents the most promising technology of the near future.
- Besides the high energy and power density compared to competing technologies, lithium-ion batteries show further favourable characteristics, such as low self-discharge rates, good life time and discharge cycle characteristics. Safety issues and the risk of overcharging are considered to be manageable.
- In contrast to other battery concepts, lithium-ion batteries are still in their infancy and large battery systems for automotive application have not achieved commercialisation yet.
- The remaining high costs of lithium-ion batteries are considered as major drawback, but future cost reduction is expected due to the replacement of high cost materials and economies of scales.
- Other options, such as flywheels, ultracapacitors and magnetic energy storage are not considered to be available for electric vehicle application in the near term, but should be further investigated in order to develop long-term alternatives.

2.1.3 Recent development of battery technology

During the last decade, battery technology for automotive application has achieved major progress that have been mainly driven by the development of reliable batteries for consumer electronic applications and the newly emerged market segment of hybrid electric vehicles. NiMH and lithium ion batteries will be the preferred energy storage technologies in the automotive sector in the near future, according to major OEM's opinion [CARB 2007]. It is assumed that the further development of NiMH batteries, which is orientated on the mass market of hybrid electric vehicle production, will focus on cost optimisation. High-power lithium ion batteries with modest energy capacity will be developed as an alternative storage technology for hybrid electric vehicles and will achieve market entry in the near future. High-energy lithium-ion batteries will be still dominated by high production costs which could hamper market introduction. Furthermore, as electric vehicles with long electric ranges are still at an experimental stage and as battery requirements are not clearly identified, only small production volumes of high-energy lithium ion batteries are currently planned. Nonetheless, lithium-ion batteries offer the potential for lower cost as the technology matures and production volume increase [MIT 2007].

The future development of battery technologies is highly dependent on the evolution of electric vehicle demand and production. In case of a significantly increasing demand of vehicles with electric propulsion, it is expected that higher investments would result in further technological improvements and cost reductions. From today's point of view, corresponding prognoses on the future development of battery technologies are associated with high uncertainty.

2.1.4 Minimum requirements for automotive application

Batteries as main energy storage units of vehicles with relevant electric driving ranges (PHEV and EV) need to comply with minimum requirements concerning the battery technology. Battery systems have to fulfil ambitious technical criteria in terms of power and energy capacity, life time and cycle life, safety issues and battery costs. Only the lithium-ion battery technology is considered an adequate technology, which could fulfil corresponding performance requirements in the near future, due to the particularly high energy capacity requirements that are needed allowing electric driving over longer distances [MIT 2007].

The following overview (Table 1) summarises the minimum requirements on traction batteries in terms of energy capacity, power and battery costs as stated in the reviewed literature for different vehicle concepts with varying electric range. The assumptions on the minimum power and energy density of the energy storage system are derived from the minimum requirements for specific types of electric vehicles. Only feasible technical applications of the batteries are taken into account. It is assumed, that the exceedance of the defined technical benchmarks would implicate a weight and volume of the battery that could hardly be integrated into the vehicle.

It is important to note that the stated specific costs of the battery (Table 1) do not represent current battery production costs, but values that are supposed to be achievable under the assumption of proceeding technological improvements and increasing demand of corresponding energy storage units. The cost values in brackets represent long-term cost targets, which could be achieved until the year 2030 and at a presumed minimum yearly production volume of 100,000 battery systems. It has to be further considered that the specific costs decrease with an increasing size of the battery system, because the share of production costs related to the housing and controlling of the battery decreases [CARB 2007]. Therefore, larger batteries for pure electric vehicles show lower costs per unit of stored energy than smaller batteries for hybrid electric vehicles with low electric range. At low production volumes, battery costs are mainly dominated by manufacturing costs. With increasing production volumes material costs become the main cost factor [MIT 2007]. In terms of the stated battery costs, a possible rise of raw material prices due to an increasing battery production is not considered here.

Table 1: Minimum battery requirements for battery-electric and plug-in hybrid vehicle application with varying electric driving range (literature review)

Source	Type of vehicle	Energy [kWh]	Power [kW]	Specific energy [Wh/kg]	Specific power [W/kg]	Specific costs [€/kWh]
MIT 2007	HEV	1.3	28	100	3000	550 (440)[1]
CARB 2007	PHEV-16	4	n.b.	110	1500	420-640 (290-440)[1]
MIT 2007	PHEV-16	3.2	43	110	-	310 (250)[1]
NREL 2007	PHEV-16	4.9	46	-	-	-
CARB 2007	PHEV-32	7	65	50	540	320-430 (220-300)[1]
MIT 2007	PHEV-48	10	40	135 (100-300)	750	310 (230)[1]
MIT 2007	PHEV-48	8.2	44	135	750	310 (230)[1]
CARB 2007	PHEV-64	14 (12)	50	75	400	280-320 (190-220)[1]
NREL 2007	PHEV-64	16.6	50	-	-	-
MIT 2007	PHEV-97	16.5	48	140	400	200 (160)[1]
MIT 2007	BEV-200	48	80	150	300	180 (150)[1]
CARB 2007	BEV-150	40	100	100	400	215 (150)[1]

[1]: long-term scenario (at high production volume and strong technological progress)

Whether the stated requirements related to energy capacity, power and costs of the traction battery are achievable in the near future is differently assessed by experts. However, all experts agree that the given targets represent an ambitious challenge for the development of battery technologies – in particular in regard to vehicles with high electric driving range.

2.1.5 Current status, limitations of battery technology and perspectives

Table 2 gives an overview of the energy and power performance of today's battery technologies. In contrast to the already mature NiMH-technology, lithium-ion cells are characterised by a considerably higher energy density and comparable power characteristics. However, it has to be recognised that automotive lithium-ion batteries differ greatly from the lithium-ion batteries currently used in consumer products, in terms of materials and cell shape. Therefore the procurement of additional resources and the introduction of new manufacturing equipment are required [TECH 2008]. The reliable coupling of lithium-ion cells to large robust battery systems for the automotive application is still under development and has not reached mass production. Large lithium-ion based battery systems would be able to achieve the minimum energy and power requirements for electric vehicles with considerable electric range if they could be successfully mass-produced.

Further requirements such as a sufficient cycle life, lifetime and safety standards seem to be achievable in the near future and are not considered as a major barrier for market introduction.

Table 2: Current status of battery technology (literature review)

Source	Type of battery	Specific energy [Wh/kg]	Specific power [W/kg]
VW 2008	NiMH for HEV (after METI)	40	1300
CONTI 2008	NiMH	40-50	1,300-1,800
IEA 2007	NiMH (high-energy battery)	60-80	200-600
BERG 2008	NiMH, today	60	-
ZSW 2007	Li-ion	70	2,000
VW 2008	Li-ion for HEV (after METI)	70	1,800
CONTI 2008	Li-ion, today	75-90	4,000
MIT 2007	Li-ion (high-energy battery)	150-180	-
MIT 2007	Li-ion	110-80	400-2,500
IEA 2007	Li-ion (high-energy battery)	110-220	200-600
BERG 2008	Li-ion (2010)	100	-
SYRO 2009	Li-ion	150-190	Up to 1,500
FFE 2007	Li-ion	150	300

Besides the remaining gap between performance requirements and the actual status of battery technologies, the high production costs of battery systems represent a major drawback of electric propulsion systems. Between 1991 and 2005, the price of lithium ion batteries per unit of stored energy decreased by a factor of ten. But it should be noted that this development did not take place in applications for electric vehicles but mainly for portable electric equipment; with regard to batteries used for electric driving, there is no historic knowledge [PBL 2009]. Today, high-energy batteries are only produced at very low production volumes and at particularly high costs. At current production costs for high-energy lithium-ion batteries (about 1,500 €/kWh) [BOST 2009, BASSI 2007], the additional costs of electric vehicles would – depending on the electric range – be dominated by battery costs of more than 10,000 €. This price premium is widely considered as prohibitive among experts for a considerable market penetration of electric vehicles with large electric driving range. Therefore, in order to reach the marketability of electric vehicles in the mid-term, cost reductions of high-energy batteries have to be achieved besides technical improvements. Key drivers of battery costs include cell materials (i.e. lithium, manganese, cobalt, nickel, graphite, electrolyte chemicals, copper foil), packaging, manufacturing, and electronics. The raw materials themselves typically only account for 15 to 20 % of the overall battery cost [DEBA 2008]. Table 3 summarises cost targets for high-energy batteries that are provided in literature. The estimations of future battery costs vary widely among the reviewed studies. This reflects the high uncertainty related to the further improvement of energy storage systems. The production volume represents the second major factor, besides necessary technological improvements, that influences battery cost. As a result of battery research high-cost materials might be replaced by lower cost materials and therefore overall battery costs might be reduced. The most significant element of lithium-ion cells is the cathode material, showing great potential for further cost reduction [BERR 2008a].The increasing demand of high-energy batteries and corresponding higher production volumes could further improve technological learning, optimise battery manufacturing and lead to decreasing costs.

Table 3: Cost targets [€/kWh] for automotive battery technology (literature review)

Source	Today	2010	2020	2030
CARB 2007	-	-	215-250	150-180
MIT 2007	-	-	-	150-200
VW 2008	-	660	-	-
IEA 2008a	-	650-800	-	240
BOST 2009	1,500	-	380-540	-
SAM 2009	770-1,500	500	-	-
BERG 2008	-	400	200	-
SYRO 2009	2,000	-	-	-
BASSI 2007	1,500	-	225	-
VW 2008	-	320	230	160

The stated cost targets are coupled to specific production volumes. For example the cost targets in CARB [2007] are assumed to be achievable at yearly production volumes of 20,000 and 100,000 battery systems, respectively until 2030. A long-term cost target of less than 150 $/kWh is extremely challenging and is widely regarded as unrealistic without a breakthrough in materials cost [MIT 2007]. It is unlikely that the price of lithium-ion batteries will fall significantly and that it will fall below $300 levels in the near term according to BERR [2008a]. Most cost estimations take further technological improvements and increasing production volumes into account. Raw material prices are not projected to increase with rising demand or it is assumed that increasing material costs are compensated by lower material-intensity of advanced battery systems.

According to a unpublished paper of the International Energy Agency, the coming years will be decisive for moving towards mass production of batteries for electric vehicles. If current battery technology is able to prove its reliability via in-use testing, battery manufacturers may be able to quickly go to mass production and to achieve considerable cost reductions. Further cost reduction could be achieved by supply chain optimization as battery supply chains and shipping can be very expensive.

In summary, despite the moderate optimistic estimation of battery cost development, it is assumed that battery costs pose the greatest long-term risk to commercialisation of electrically-driven vehicles [MIT 2007].

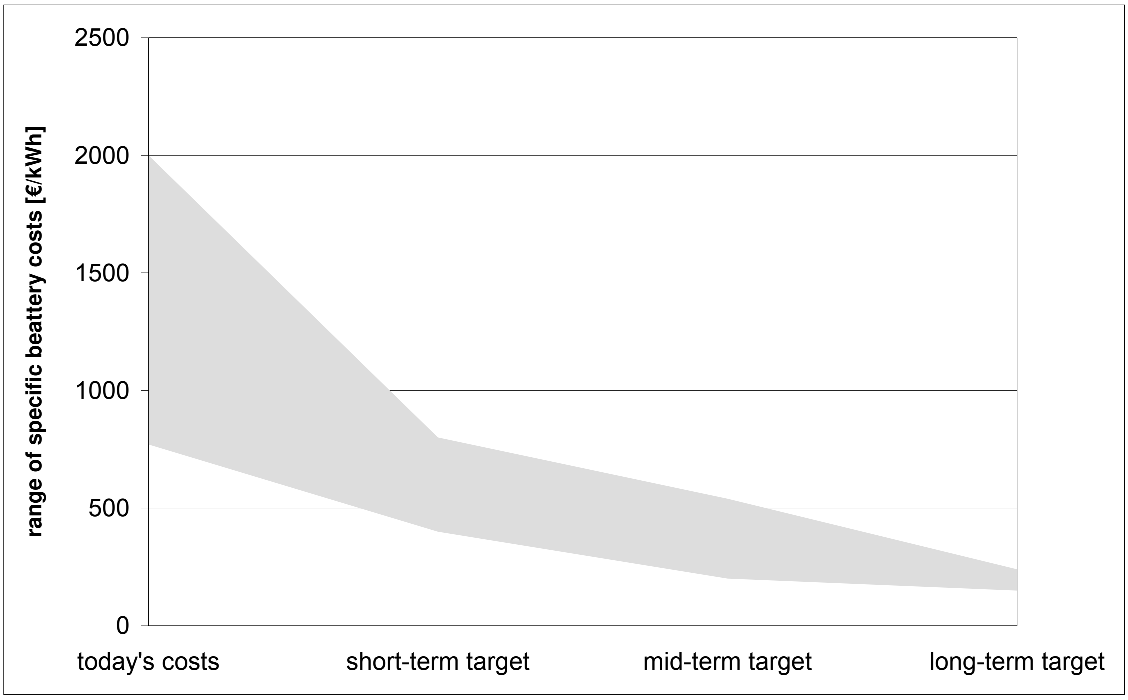

Figure 2: Range of today's specific cost and future cost targets for battery technology as stated in the literature.

SUMMARY: BATTERY REQUIREMENTS, STATUS AND PERSPECTIVES FOR AUTOMOTIVE APPLICATION

Results from literature

- Electric vehicles with an electric driving range of more than 100 kilometres require a high-energy battery of more than 20 kWh capacity.
- The specific energy density requirements stated in the reviewed literature are in the range of 100 to 150 Wh/kg. The specific power density is assumed to be about 400 W/kg.

- Corresponding battery characteristics are already achieved on the cell level for the lithium-ion technology and it is expected that corresponding battery systems will be available in the near future.
- The current production costs of batteries (about 1,500 €/kWh) are still considerably higher than cost targets and reflect the early status of battery development.
- While substantial cost reductions are likely to occur due to further technological improvement and economies of scales, a long-term target of 150-200 €/kWh is regarded to be very challenging.
- Battery cost reduction remains the main challenge and will be crucial for the economic attractiveness and the large-scale deployment of electric vehicles.

Discussion and recommendations

The lithium-ion technology shows promising characteristics with regard to an automotive application. While the development on the cell-level seems to be quite mature, the coupling of many cells to a large and reliable battery system required for EV use remains a major challenge, but is a prerequisite for the market introduction of electrically driven vehicles. Due to the early stage of technological development no long-term experiences with large lithium-ion batteries for vehicle use are available.

The major drawback of the available battery technology are the remaining high costs and – besides technological issues – a substantial cost reduction is needed to increase the attractiveness of EVs in order to achieve a relevant market share. Considerable cost reductions are assumed to be achievable by a further improvement of battery technology (e.g. replacement of high-cost materials) and by economies of scales. With regard to further research needs, the following points are important:

- The long-term reliability of energy storage systems for automotive use has to be further evaluated. Valuable information could be derived from announced fleet tests.
- Further cost reduction potentials of battery technology should be discussed with regard to an increasing demand of large battery systems. Potential impacts on raw material prices should be considered in this context.
- The future potential of alternative energy storage technologies (e.g. ultracapacitors, magnetic energy storage) should be discussed in greater detail.

2.1.6 Battery production, recycling & disposal

The electrification of the powertrain is related to a considerable modification of the vehicle's material composition which is mainly caused by the battery system. Therefore, an environmental assessment of electric propulsion systems has to consider life-cycle analysis of the battery systems in particular because of the expected additional demand of energy and resources. Today, different promising battery technologies are under development and the final composition of high-energy battery systems for electric vehicles and the resulting demand of raw materials can only roughly be estimated. Further, the total demand of resources for battery production will be dependent on the penetration rate of electric vehicles on the global scale which is hardly predictable from today's perspective.

Battery technology

Among experts it is assumed that "lithium-ion batteries are rapidly becoming the technology of choice for the next generation electric vehicles" [TAHI 2006] because of the most favourable energy density properties of all existing electrochemical storage systems as discussed in detail in section 2.1.2. Battery industry experts believe that nearly all of the new HEV and EV development programs amongst the global automakers will use lithium ion batteries [DEBA 2008]. Today, the key lithium-ion battery suppliers are developing cell technologies with different chemical set-ups [BERG 2008]. In contrast to NiMH batteries which are intrinsically tied to nickel and its high commodity price, the lithium-ion battery technology gives the opportunity to be made from a number of different fungible materials. "For example, the metal-oxide cathodes which are currently dominant can use not only cobalt, but also nickel, manganese, or aluminium" with a further strong potential to transition to even lower cost materials [MIT 2007]. Currently, a variety of different cathode materials are under development by battery manufacturers. Besides the traditional lithium-cobalt oxide cathode, new materials such as lithium-manganese oxide, lithium-iron phosphate or even so called three element designs, mixing cobalt, nickel and manganese, have emerged [VW 2008, TECH 2008].

Relevant construction materials

It is widely accepted that materials such as aluminium, iron, steel and copper pose no apparent material resource scarcity, although their shares and amounts are the largest. According to IPTS [2005] substances which need more attention are metals such as nickel, manganese, cobalt, lithium and rare earth extracts. Among them, global reserves of lithium could present the most limiting factor, while cobalt, nickel and manganese are not assumed to show shortages in supply with increasing demand for electric vehicles [ARG 2000a, OEKO 2009].

Table 4 gives a first estimation of the potential material composition of a lithium-ion battery system. However, it has to be considered that different battery technologies are currently under development showing varying anode and cathode materials as well as different electroytes (liquid or polymer) [ZSW 2009]. Correspondingly, the battery systems that are currently under development are characterised by a wide range of materials. Therefore, the final material composition of automotive batteries may differ from the data given in Table 4 and is likely to vary depending on the battery supplier and the applied chemical set-up.

Table 4: Estimated material composition of lithium-ion battery system for automotive use (according to DHIN 2001, IPTS 2005)

Material	Share
Aluminium	30.3 %
Copper	13.9 %
Manganese	11.7 %
Plastics	9.7 %
Steel	9.2 %
Ethylene oxide	6.2 %
Carbon dioxide	6.2 %
Others	6.0 %
Carbon	5.7 %
Lithium, lithium salt	0.9 %
N-Methyl-2-pyrrolidone	0.2 %
Polyvinyliden fluoride	0.1 %

Lithium

Lithium needs not to be produced in metallic form for use in lithium-ion batteries. The required raw material is lithium carbonate [ARG 2000a, IPTS 2005, DEBA 2008], which is manufactured in the form of lithium-metal oxide as cathode material and which is needed for the electrolyte [SUB 2005, TAHI 2006, TAHI 2007]. The amount of lithium varies depending on the size and type of battery. ARG [2000a] assumes a demand of 9.6 kilograms of lithium for a battery of an electric vehicle. TAHI [2006] & TAHI [2007] state an amount of 0.3 kilograms of lithium metal equivalent per kWh, or 1.5 kilograms of lithium-carbonate per kWh, which results in a total amount of about 9 kilograms lithium or 45 kilograms lithium-carbonate, respectively, for a 30 kWh-battery. DEBA [2008] assumes an average demand of lithium (carbonate) of 1.4 kg per kWh. The lithium demand given in OEKO [2009] for hybrid electric vehicles would result in a slightly higher amount when scaled up to the energy capacity required for electric vehicles. BERR [2008a] gives a lithium content of 1.75 % of the entire battery weight.

Supply & demand

The total reserve base in the earth's crust – including lithium reserves which are not extractable – is estimated to be about 11 million tonnes [USGS 2008]. Nearly one half of the worldwide lithium reserve base is assumed to be located in Bolivia, but no data on the extractable fraction is currently available [TAHI 2006]. EVAN [2008a] postulates even greater global reserves of lithium close to 30,000,000 tonnes. According to information given in [DEBA 2008], 15 million tons of lithium occur in brine resources and more than 2 million is in ore deposits.

The world reserves for lithium are estimated by the U.S. Geological Survey to 4,100,000 tonnes with a major share in Chile (73 %), followed by China (13 %) and Brazil (5 %) [OEKO 2009, USGS 2009]. The world reserves represent "that part of the reserve base which could be economically extracted or produced at the time of determination" [USGS 2008]. TAHI [2007] estimates the Bolivian lithium reserves with about 2,700,000 tonnes which would represent the largest national reserves world-wide and states global reserves of 6,800,000 tonnes.

Major gaps of the US Geological Survey estimates on lithium reserve base and reserves remain for Russia and Argentina, although considerable amounts of lithium are likely to be located within both countries [TAHI 2007].

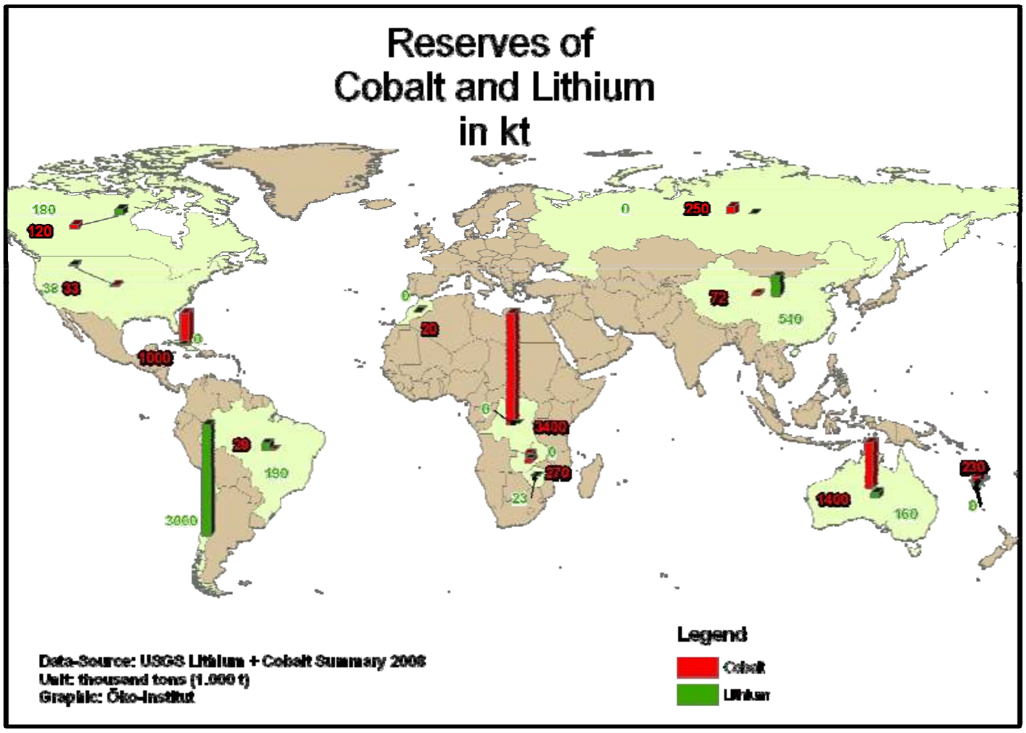

Figure 3: Global reserves of lithium and cobalt (Source: OEKO 2009).

Global mining of lithium amounts to 25,000 tonnes in 2007 with Chile as main producer. The global current demand is estimated to be about 17,500 tonnes of lithium per year [OEKO 2009]. Bolivia has already made a number of attempts to exploit its large lithium reserves according to TAHI [2006]. Until today, the political situation has been a strong disincentive for western mining companies to operate in Bolivia [TAHI 2006]. Based on announced capacity increases at various sites, DEBA [2008] belives production could increase by approximately 100 % from 2006 to 2010. Industry consultants estimate that the ultimate production of lithium from current sources (not including Bolivia) is approximately 200,000 tons per year, and that reserves in these locations total approximately 15 to 20 million tons [DEBA 2008].

The lithium demand has shown annual growth rates of 7.5 % over the last 10 years, driven by the increasing production of lithium-ion batteries for consumer electronic application, [OEKO 2009]. Today the battery market – with a share of 25 % – represents the leading end use for lithium [USGS 2008] and further growth of this sector is expected. Despite an observed increasing price over the last three decades lithium remains a low-price metal compared to other battery materials such as cobalt [OEKO 2009, DEBA 2008].

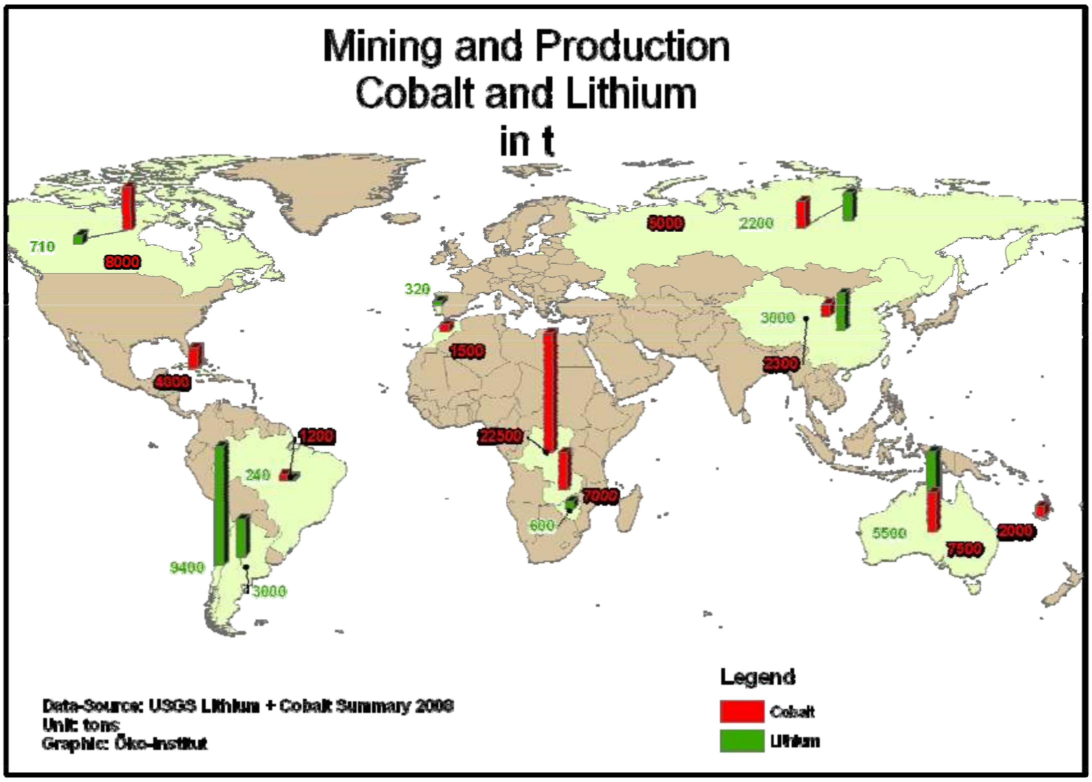

Figure 4: Global mining and production of lithium and cobalt (Source: OEKO 2009).

An increasing market penetration of plug-in hybrid electric and pure electric vehicles equipped with lithium-ion battery technology would lead to a considerable impact on the lithium market. Assuming an annual production of about 2.5 million electric vehicles, the additional demand of lithium carbonate would correspond to the current annual production volume. BONN [2009] assumes that the production of 10 million electric vehicles would result in a lithium demand of about 150,000 tonnes – exceeding the current annual production by far. TAHI [2007] estimates that 60 million electric vehicles with a small 8 kWh lithium-ion battery would consume 760,000 tonnes of lithium carbonate (about 134,000 tonnes of lithium metal equivalent) – nearly ten times current production. Pure electric vehicles with a 30 kWh battery would multiply the lithium requirement by a factor 4. Such a rapid increase of lithium demand due to an accelerated market penetration of electric vehicles would greatly exceed current capacity for lithium production. It is assumed, that such a ramp-up in production would be difficult to be sustained over multiple years [IPTS 2005].

Other aspects with regard to the long-term availability of lithium resources and to further impacts of a large-scale lithium production are discussed controversially among experts. Most experts refer to the fact that the world resources of lithium are expected to be quite large. They assume therefore that no long-term shortage of lithium supply will occur once lithium production is adequately adapted to the higher demand – even if electric vehicles will become an important share of the total global vehicle fleet of the future. A report cited in BERR [2008a] concludes that 'concerns regarding lithium availability for electric vehicles […] are unfounded'. A further study [BERR 2008a] calculates that the worlds reserves of lithium ore are enough to make batteries for 1.6 billion electric vehicles; slightly more than the number of vehicles in the world today. EVAN [2008a] points to the definition of reserves and argues that the share of economically extractable lithium will increase as raw material prices change over time and technologies is likely to improve. Further, EVAN [2008a] mentions other categories of geological resources such as hectorites, geothermal brines and oilfield brines that should be available in the near future for lithium extraction.

PBL [2009] points out that lithium is also used for other purposes (such as making glass, ceramics, synthetic rubber and lubricants), which could partly rely also on other materials in case of raw material shortage. PBL [2009] concludes that "it appears that there would be enough lithium available to supply all future vehicles with a lithium-ion battery" and refers to the possibility to recover secondary lithium from battery recycling after having established a corresponding recycling system.

Projections for automotive lithium ion cell production and growth assumptions for other markets, given in DEBA [2008], would result in an annual lithium production of 200,000 tons by 2017. The demand forecast assumes a continuation of 7 % annual growth for consumer electronics and other uses. DEBA [2008] assumes a further increase in the price of lithium. By 2017, additional mining sites may be discovered and new technologies may be developed to enable lithium mining from other types of sources, and a large-scale battery recycling will have been developed. Therefore, DEBA [2008] belives these factors will enable lithium to remain a viable, relatively abundant source of power for automobiles over the long-term.

In contrast TAHI [2006] & TAHI [2007] refer to a large difference between the physical reserves ('reserve base') and the considerably lower amount of economically extractable lithium using today's techniques. TAHI [2008] argues that many of the deposits catalogued could not be considered to be actual or potential lithium reserves and that the major economically recoverable lithium brine reserves would be lower than previously estimated at only 4 million tonnes of lithium. With regard to lithium extraction from seawater, TAHI [2007] & TAHI [2008] come to the conclusion that seawater would never be a viable source of supply due to the particularly low lithium concentration and the higher costs compared to existing extraction methods. TAHI [2006] & TAHI [2007] refer further to the risk of a new dependence on a few countries – similar to the dependence on the oil-producing Middle East today – because 75 to 80 % of global lithium reserves are located in South America.

In contrast to the large reserves in South-America and Asia, European lithium resources and other relevant resources for battery production are considered to be negligible. In Europe, some smaller lithium mineral deposits are located in Finland and Austria

[EVAN 2008]. A Norwegian mining groups plans to start lithium carbonate production at the Finnish site in 2010, although the production volume will remain at a rather modest level [TAHI 2008]. In summary, Europe is and will remain a net importer of all relevant materials in case of own battery production [IPTS 2005].

Extraction methods and environmental impacts

Further disagreement among experts can be found regarding the environmental impacts of a large-scale production of lithium. Today, lithium is extracted by two main methods: mining spodumene or petalite ore and using evaporation ponds on salt lakes (salar) [ECOL 2009, BERR 2008a]. The extraction from sea water could be an additional, but more energy-intensive option in the future [UNSA 2009], although it is controversially discussed (see: TAHI [2006] & TAHI [2007]). The hard mineral spodumene is a silicate or glass of lithium and aluminium. The soluble salts lithium carbonate and lithium chloride are derived from brine lakes and salt pans [TAHI 2006, TAHI 2007]. Currently, the majority of lithium is obtained from brine operation [DEBA 2008]. BERR [2008a] assumes that Bolivia and China could become the leading producers of brine-based lithium carbonate production by 2010. According to TAHI [2008], several extraction plants have been set up in recent time in China and Bolivia and both countries plan to significantly expand lithium production in the near future. DEBA [2008] refers to currently ongoing development of salt lake sites in China. In this context, TAHI [2006] is concerned about the local environmental impacts of lithium production, referring to the largest salt lake of Chile (Salar de Atacama), source of about 40 % of the world's lithium reserves, and characterised by a valuable natural ecosystem. According to TAHI [2006] & TAHI [2008], negative environmental impacts are likely to occur due to the construction of an adequate infrastructure, which would become necessary as most lithium reserves are located at remote areas. Other experts estimate the environmental impacts to be considerably lower [ECOL 2009, EVAN 2008a]. ECOL [2009] states the need of further research and a clearer scientific consensus considering the disagreement among experts with regard to the environmental impacts of lithium production.

Lithium supply for automotive battery application – a controversial issue

The global supply of lithium reserves for automotive battery application is discussed controversially in the reviewed literature. While most studies have a rather optimistic view on this issue, the Meridian Research Institute (W. Tahil) takes up a deviating position.

With regard to a large-scale introduction of electric vehicles based on the lithium-ion battery technology, experts agree that the current annual lithium production would be exceeded by far and a substantial increase of lithium production would be required.

Major disagreement among experts can be stated with regard to the following issues:

- the global reserve base of lithium,
- the reserves that are and will be physically and economically extractable at present and in the future,
- the maximum annual lithium production and the availability of lithium for automotive application in the context of other demands (e.g for portable electronic equipment),
- the global distribution of lithium reserves,
- potential environmental impacts of lithium extraction.

The geological knowledge on lithium resources seems still very imperfect as many areas of the globe have not been explored yet or corresponding data is not publicly available. Therefore, assumptions on the reserve base and the global distribution of lithium reserves, as well as statements on future lithium shortage should be regarded with caution, according to experts that were consulted.

The concept of “reserves” is highly dynamic as raw material market prices and extraction technologies change over time and are hardly predictable. Indeed, if the production of electric vehicles should rise steeply and if the lithium demand for consumer electronic battery should continue to rise, a strong increase of lithium production would be required and a supply crisis could occur over several years. However, this view should be tempered since production may be significantly adjusted and expanded in some countries (e.g. China or Bolivia) and since many junior mining companies seem to show growing interest in lithium.

Assuming a strong increase in lithium demand, raw material prices are likely to rise New extraction methods could become economically attractive and be used to exploit new reserves that are located outside of the current major extraction sites. In addition, lithium prices increase could also enable the development of new and competitive technology pathways for energy storage systems that do not rely on lithium.

Potential environmental impacts of lithium production are unlikely to be determined in advance as they are strongly related to the amount, the location and the applied method of lithium extraction; however this issue should be considered attentively in the context of electric vehicles with the overall intention to lower environmental damages.

Recycling and disposal

From the end-of-life disposal and recycling perspective the batteries of electric vehicles are of greatest concern. At present, the common lead acid batteries have a functioning disposal and recycling system, whereas recycling techniques for advanced battery systems, such as lithium-ion batteries, are still in their infancy [IPTS 2005]. The disposal of batteries for hybrid cars is already included in the EU Directive 2006/66/EC on batteries. The required minimum collection rate for all batteries is 45 % by 2016, but it is likely that much higher collection rates could be achieved through the currently established vehicle end of life route [BERR 2008a].

Post consumer lithium recycling is not common and until today a niche market. Main reasons are the low price of lithium and the low lithium concentration in current products and compounds. There are currently no recycling facilities in Europe which can recycle lithium for use in new batteries [BERR 2008a]. However, the first lithium-ion battery recycling plants are already announced and further activities of several companies are planned that would allow the dismantling, disposing and recycling of lithium-ion batteries from electric vehicles [IPTS 2005]. A French company developed recently a recycling method to recover about 40 kg of cobalt from 100 kg of lithium ion batteries [ADEM 2007a]. According to Sony, research by the Japan Battery Recycle Centre shows that between 56 and 61 % of the lithium in a battery can be reused in non-battery products [ECOL 2009]. Development of recycling legislations in many countries and further technical improvements could stimulate the lithium recycling activities, in particular considering the expected growth rates in battery applications and their size, Potentials of lithium recycling should however not be overestimated due to economic reasons [OEKO 2009]. The recovery of high-price materials such as cobalt makes battery recycling economically attractive [ARG 2000a].

It is assumed that only the most valuable materials (e.g. cobalt) will be recovered initially. Due to the large size of automotive batteries compared to small consumer cells, an increasing recycling could become technically feasible and economically attractive in the near future [ARG 2000a].

Energy demand and GHG emissions from battery production

There is no detailed information available with regard to the energy demand of the production of batteries for the automotive application due to the ongoing technological development and lack of mass-production of battery systems. MIT [2007] refers to estimates assuming a share of 18 % of total energy consumption which traces back to conventional vehicle production. In electric vehicle production, this share is assumed to rise by 4 to 8 % depending on the battery size. However, as this increase represents only a fraction of a fraction, the total effect is considered to remain rather small. Another study [ARG 2007b] examines the relative contribution of battery assembly and disposal on total pathway emissions of different vehicle configurations and comes to the conclusion that the share of total pathway emissions caused by batteries – of various types – remains rather small, even if the battery has to be replaced once in the vehicle's lifetime.

A life-cycle assessment determined the environmental impacts of different battery types for automotive application [MAT 2008]. The assessment considered the extraction of raw materials, processing activities of the material and compounds, the use phase of the battery, recycling and disposal. With regard to the lithium-ion technology, the study states a rather promising environmental performance and highlights further potential of improvement that could be achieved by a higher recycling rate. In general, [MAT 2008] concludes that the environmental impacts of automotive batteries are modest compared to the environmental burden caused by conventional vehicles during operation. The remaining impact could be compensated to a large extent, when the collection and recycling of the batteries would be efficient and performed on a large scale.

In general, only little data is available quantifying the amount of embodied carbon – resulting form the energy demand and related emissions in feedstock materials as well as data on energy demand from car assembly and distribution [ECOL 2009]. A comparison of the energy demand during production of conventional and electric vehicles would require data on the vehicle level.

Independent on the total amount of energy which is used for battery production increasing vehicle efficiency would increase the life-cycle share of energy consumption and related GHG-emissions related to vehicle production and disposal. As stated in KING [2008] production and disposal of current vehicles account for about 15 % of total life-cycle emissions. In case of an increase of vehicle efficiency by 50 % above current levels, the proportion of production/disposal emissions would rise to about 26 % of overall emissions. Considering the expected amount of energy for battery production, a higher share seems to be probable for electric vehicles.

According to BERR [2008a], the extraction of the battery materials would contribute with 13 % to the overall GHG emissions of electric vehicles. The assembly of the battery is assumed to add not more than 1 % to the whole life energy consumption. Compared to conventional vehicles, electric vehicles generate higher impacts on water use, aquatic ecotoxicity and waste generation which are mainly related to the extraction of raw materials for batteries.

BERR [2008a] states that there are a range of potential environmental issues associated with the production, use and disposal of lithium-ion batteries which require further investigation.

SUMMARY: BATTERY PRODUCTION, RECYCLING & DISPOSAL

Results from literature

- Large automotive battery systems cause major changes of raw material demand in vehicle production.
- Today, different battery set-ups are under development. Therefore, the final composition of lithium-ion batteries and the related demand of raw materials remain uncertain.

- Materials of particular concern are critical metals such as lithium which is considered to be the most limiting factor.
- The impact of a large-scale production of EVs on the global lithium supply is discussed controversially. The risk of a long-term lithium shortage is assumed by one author.
- Further issues of concern are the geographical distribution of lithium reserves and the potential negative environmental impacts of lithium production.
- A recycling and disposal system of lithium-ion batteries is not yet developed. Under current conditions, the recovery of lithium remains economically unattractive, but recycling activities could increase when large scale production of batteries for electric vehicles is reached.
- The energy demand of battery production is assumed to be significant, although no detailed data is available.
- The quantification of environmental impacts of battery production, recycling and disposal have not been investigated in greater detail as battery technology is still under research and no data on the final composition of automotive batteries is available.

Discussion and recommendations

As a result of the early stage of battery and electric vehicle development, great uncertainty remains about the final composition of automotive batteries and future deployment rates of electric vehicles. At the same time, the impact on global resources will be highly dependent on these factors.

A controversial debate on the long-term availability of lithium is led – but currently dominated by only few experts. The knowledge on global reserves of lithium is partly imperfect and prognosis on the future amount of economically extractable lithium varies greatly among the expert's estimations. While most experts assume that the worldwide lithium reserves do not indicate an urgent shortage, taking into account the amount of lithium needed for electric vehicle batteries, it is however mentioned that a fast demand increase could cause a short-term supply shortage.

Further, the influences of a substantial increase of lithium demand on market prices, production and extraction methods are only poorly studied and require further detailed consideration. Consistent information on potential environmental impacts of lithium production is not available and needs clarification in the context of a prospected increasing demand of lithium:

- The consequences of an increased market penetration of EVs on the global lithium supply are only poorly studied. Further research is needed that explores potential impacts on lithium supply under the assumption of different penetration scenarios and in the context of other battery applications (e.g. consumer electronics). Major topics that should be addressed are: lithium supply versus demand, the geographical distribution of lithium reserves and a potential dependence on few countries, potential production capacities and methods, as well as the evaluation of related environmental impacts.

- The long-term potential of automotive battery recycling to recover lithium and its potential to reduce the amount of required primary lithium in the long-term needs to be examined.
- As a consequence of the immature status of automotive battery systems, existing LCAs are based on rough estimates. Therefore, further research is needed which quantifies potential environmental impacts of battery production, recycling and disposal of the most probable battery technologies for electric vehicle applications.

2.2 Vehicle concepts

2.2.1 General characteristics

The electrification of vehicle propulsion systems comprises a wide range of technology options. Different vehicle concepts show variant degree of electrification. Besides fully electrified vehicles solely driven by an electric powertrain, hybrid electric vehicles combine a conventional internal combustion engine with an additional electric propulsion system to improve the overall efficiency of the vehicle's drive train.

Mild hybrid electric vehicle

On the electrification path towards an increasing electric driven powertrain, mild hybrid electric vehicles represent the first real step away from a purely combustion engine driven vehicle. In addition to the conventional internal combustion engine, mild hybrid systems include an engine start-stop system, regenerate braking energy by recharging the battery and utilise a small electric motor which provides acceleration assistance. Mild hybrid vehicles do not allow driving only on electric propulsion, due to the small size of the electric motor and the limited capacity of the battery. However, due to regenerative braking and the automatic engine start-stop system, mild hybrid vehicles achieve fuel efficiency gains in the range of 10 to 15 % compared to conventional internal combustion engine vehicles [BOST 2009].

The Honda Insight is a commercially available mild hybrid vehicle. Daimler announced the introduction of the Mercedes S 400 BlueHybrid to the market in 2009. This mild hybrid vehicle will be the first commercially available passenger car which will be equipped with a lithium-ion battery system [ADAC 2009].

Full hybrid electric vehicle

Compared to the mild hybrid system, full hybrid electric vehicles are characterised by a stronger emphasis on the electrification of the power train and an increase in fuel economy. The internal combustion engine remains the main propulsion system, but it is further complemented by a larger battery and a more powerful electric motor. This configuration allows a more efficient electric launching of the vehicle, electric acceleration assistance, and even pure-electric driving at low speeds and for a limited driving range is possible. The battery takes up energy from regenerative braking and is further recharged by the internal combustion engine; recharging from the power grid is not possible.

The size of the internal combustion engine can be significantly reduced (downsizing) because of the electric assistance in acceleration and low-speed driving situations. Torque and acceleration performance increase considerably in those situations. The dual powertrain allows the internal combustion engine to operate in more favourable and continuous conditions. The hybrid system seamlessly switches between the electric motor and the internal combustion engine depending on the power demand.

Full hybrid vehicles show the largest fuel savings in the stop-start cycle of urban driving because of maximum benefits of regenerative braking and zero idling, where conventional combustion engines operate particularly inefficient. With increasing speed and fewer start-stop and acceleration driving situations, the fuel efficiency gains of full hybrid vehicles decrease significantly. Full hybrid vehicles show fuel consumption benefits of about 25 to 30 % in standard test driving cycles, compared to conventional combustion engine vehicles [BOST 2009, UNSA 2009].

The hybrid-vehicle components can be arranged in a variety of ways.

In a **series hybrid** the electric motor drives the vehicle, whereas the combustion engine is not directly connected to the drive train. The internal combustion engine is used to drive an electric generator which provides electricity for the electric motor and charges the battery. Series hybrids are characterised by a powerful electric motor and a large capacity battery to guarantee sufficient vehicle performance. The combustion engine is considerably reduced in its size.

Parallel hybrid systems allow combined and individual propulsion of the vehicle by the electric motor and the internal combustion engine as they are both connected to the drive train.

The **split hybrid** combines both systems and allows therefore benefiting from the advantages of the parallel as well as those of the series concept. Currently it is the most common approach applied to hybrid vehicles.

The today’s most popular split hybrid vehicle is the Toyota Prius, which has been introduced to the market in 1997 [BERR 2008a].

Plug-in hybrid electric vehicle

The plug-in hybrid electric vehicle is an upgrade of the full hybrid allowing an increased proportion of electric driving. Besides a more powerful electric motor, a high-capacity battery and a correspondingly smaller combustion engine, the battery of the plug-in hybrid is not only charged by the on-board generator, but can also be charged with electricity from the power grid. Plug-in hybrid vehicles can be driven in electric mode over much longer distances. While its energy efficiency in conventional driving mode – where the combustion engine mainly drives the vehicle – corresponds approximately to that of a full hybrid, in the electric driving mode much higher energy efficiency gains can be acquired which are close to the energy consumption of battery electric vehicles.

The announced GM Chevrolet Volt is proposed with a particular high hybridisation rate and a series hybrid propulsion system. The electric driving range is high, due to a large traction battery, whereas the conventional engine, a so called ‘range extender’, mainly functions as generator in case of a low status of battery charge.

Due to the properties of the propulsion system, which uses electricity for short journeys and liquid fuels for long journeys, the plug-in hybrid concept represents a good compromise for vehicles which are used for a mix of long and short journeys [UNSA 2009].

Battery electric vehicle

The battery electric vehicle is entirely propelled by electricity stored in an on-board traction battery that is charged from the power grid. It is situated at the top of the electrification path. The conventional mechanical drive train and the combustion engine are replaced by an electric drive train with a powerful electric motor. Battery electric vehicles show the highest tank-to-wheel energy efficiency of all vehicle propulsion systems due to the particularly efficient operation of the electric motor and further efficiency gains through regenerative braking. In contrast to the favourable characteristics of electric propulsion it is limited with regard to performance and driving range by the battery technology's potentials.

SUMMARY: VEHICLE CONCEPTS

The electrification of the vehicle powertrain comprises a wide range of technological concepts:

- Mild and full hybrid electric vehicles still rely on conventional fuel and are mainly propelled by the conventional powertrain.
- Plug-in hybrid electric vehicles can be connected to the power grid to charge a larger battery system that allows pure electric driving over longer distances.
- Battery electric vehicles contain only the electric propulsion system which relies exclusively on electricity from the power grid.

In the scope of this study only plug-in hybrid and battery electric vehicles are further evaluated as these vehicle concepts are characterized by pure electric driving capability and charging from the power grid. Mild and full hybrid vehicles are rather considered as improved conventional vehicle concepts and are therefore not further evaluated.

2.2.2 Application of electric propulsion systems in road transport

Two-wheelers

The market of electric two-wheelers is highly dynamic. Its development is dominated by an increased demand of zero-emission two-wheelers in Asian metropolitan areas where conventional two-wheelers are outlawed in many major cities to reduce severe urban air pollution [WWF 2008]. A further increase of the demand and production of electric two-wheelers can therefore be expected.

Passenger cars

The application of electric propulsion systems is mainly discussed in the context of passenger cars. While hybrid electric passenger cars have already achieved early commercialisation, plug-in hybrid and fully electric vehicles have not yet achieved significant market penetration. Today, electric vehicles represent only a niche market, however an increased demand and corresponding activities of major OEMs to develop corresponding vehicles is expected and can be already observed.

Buses

The application of pure electric driven buses is limited by the availability of battery technologies and represents only a niche market. In contrast, hybrid electric buses have already been developed and tested in several cities as they offer considerable fuel economy benefits. First series-production plug-in vehicles have been recently introduced to the market.

Trucks and vans

Hybrid and electric propulsion systems do currently not represent a viable option for trucks and vans because of their high performance requirements and the high average mileage of heavy-duty vehicles [BERR 2008a]. However, hybrid electric and full electric delivery vehicles are under development and tested in several pilot schemes as they are well suited for fleets which operate relatively short-distance service cycles, typical of public transport, parcel couriers, and other urban delivery vehicles [WWF 2008]. The use of electric vehicles for these applications in urban areas seems particular beneficial because of short daily driving patterns with frequent stop/start operations and the opportunity of nightly battery charging at the depot [BERR 2008a].

2.2.3 Strengths and weaknesses of electric propulsion systems

The following general discussion gives an overview of the main strengths and weaknesses of electric propulsion systems. It concentrates on plug-in hybrid electric and full electric vehicles, as all other before mentioned stages of hybridisation (mild to full) do not represent a fundamental change of conventional propulsion systems. The use of electricity from the grid as single or additional energy source (besides conventional fuel) is the unique feature of plug-in hybrid and full electric vehicles and represents a fundamental difference to conventional vehicles with an internal combustion engine.

Energy efficiency

One main driver for the development of electric vehicles is the by far higher energy efficiency of the electric motor compared to a conventional combustion engine. The average energy efficiency of a conventional propulsion engine ranges between 15-20 % [EABEV 2009, WWF 2008, CONC 2007, MIT 2000, DEBA 2008] as the major part of the consumed energy is lost as waste heat and internal friction losses of the mechanical drive train. The electric drive train benefits from the highly efficient electric motor which converts electricity into kinetic energy by a factor of up to 90 % [EABEV 2009, ILEA 2005, MIT 2000]. The tank-to-wheel efficiency is stated in the reviewed literature to be in the range of 60 to 80 %, considering further energy losses, including charging losses and self-discharge of the traction battery. This tank-to-wheel efficiency outperforms the tank-to-wheel efficiency of conventional powertrains up to four times [EURE 2008]. However, with regard to the status of battery technology the amount of charging and self-discharging losses has to be regarded with precaution as only few long-term observations are available. High loss rates in practice might occur and could worsen the overall efficiency of electric vehicles.

Table 5: Energy efficiency of the electric propulsion system (plug-to-wheel)

Source	Charging losses	Self-discharge	Electric motor	Transmission	Energy distibution / electric resistance	Total efficiency (Tank-to-Wheel)
EABEV 2009	-10 to -12%	-5 to -15%	-5 to -10%	-	-2 to -4%	72%
ILEA 2005	-5%	-7%	-4%	-2%	-6%	76%
ENG 2007	-10 to -15%	-	-	-	-	-
MIT 2000	-	-5%	-8%	-5%	-	61,5% (urban) 58,8% (inter-urban)
ZSW 2007	-5%	-	-	-	-	-
ABERN 2006	-	-	-	-6%	-14%	80%
WWF 2008	-	-	-	-	-	65-76%
IEA 2005	- 11%	- 6%	-	- 11%	-	74%

The evaluation of the total energy efficiency has to consider the energy supply (well-to-tank) as well. The type of power plant which supplies electric energy for electric vehicles significantly influences the overall well-to-wheel energy efficiency and could even reduce its efficiency benefits to levels below conventional fuel-driven vehicles.

A detailed discussion of the interaction of electric vehicles and the power sector and its effects on the overall energy efficiency is carried out in chapter 4.

Energy consumption

As a result of the early status of electric vehicle development, only little data on the real-world energy consumption of electric and plug-in hybrid electric vehicles is available. The existing data is derived from first concept cars and small-scale produced EVs or vehicle simulations, and does in general not rely on a standardised fuel measurement driving cycle. The amount of energy needed for the operation of auxiliary equipment could be considerable, but is not documented in greater detail. SYRO [2008] assumes an additional power demand from auxiliaries of about 2.5 kW and up to 4 kW considering the additional energy consumption of an air conditioning system. The available data on energy consumption does not provide comprehensive information on the charging and discharging losses and the impact of the additional curb weight caused by the battery on vehicle efficiency. Table 6 gives a first overview of energy consumption for pure electric and plug-in hybrid vehicles. While the first exclusively rely on electric energy, the latter are fuelled from conventional fuel as well as electricity depending on the driving mode and the status of battery charge, respectively. Here, only the energy consumption during electric operation is provided, fuel consumption at the conventional hybrid driving mode is not considered. The considerable range reflects the different measurement and estimation approaches, as well as different vehicle concepts. Particularly, vehicle weight varies greatly among the reported vehicles and has a major impact on the average energy consumption. Generally, vehicles in electric driving mode show greatest energy savings at low-speed driving and during driving situations with frequently changing driving dynamics (e.g. in urban driving mode).

Table 6: Energy consumption of battery-electric and plug-in hybrid electric vehicles at different driving situations (literature review).

Source	Type of vehicle	Driving cycle	Energy consumption [kWh/100km]	Base
EABEV 2009	EV	average	11-14	available small-scale EVs and concept cars
UNSA 2008	EV	average	10-18	announced and available EVs
ENG 2007	EV – small / medium	urban	12 / 15	concept car
ENG 2007	EV - medium	inter-urban	18 / 20	concept car
CARB 2007	EV	average	20-25	U.S. concept cars of the 1990s
UNSA 2008	EV	average	14-34	U.S. concept cars of the 1990s
EDIS 1999	EV	urban	16-25	1999 concept car
EDIS 1999	EV	inter-urban	19-24	1999 concept car
MIT 2000	EV	average	12-16	simulation
BERR 2008a	EV	average	16	estimation
EURE 2007	EV	average	27	estimation
WWF 2009	EV	average	15-20	estimation
IFEU 2007	EV	average	20	estimation
KING 2007 / ETEC 2007	EV / PHEV	average	16	estimation
ARG 2008	PHEV	urban (US)	17-18	simulation
ARG 2008	PHEV	motorway (US)	18-19	simulation
IEA 2007	PHEV	urban (EU)	14-15	simulation
IEA 2007	PHEV	inter-urban (EU)	12-13	simulation
IEA 2007	PHEV	motorway (EU)	26-27	simulation
ENG 2007	PHEV	urban	14	concept car
ENG 2007	PHEV	inter-urban	20	concept car

Pilot schemes of recently developed electric vehicles that are announced for the near future are important with regard to the evaluation of real-world energy consumption of electric vehicles. As soon as corresponding measurements have been carried out, the available data should be critically reviewed.

Total GHG-emissions (Well-to-wheel-balance)

Electric driving is characterised by zero tailpipe emissions of greenhouse gases, whereas the combustion of fuel in conventional vehicles produces a considerable amount of direct GHG-emissions and other pollutants. However, on a well-to-wheel-balance electric vehicles account for GHG-emissions as well. The share of GHG-emissions from the refining of conventional fuels is relatively low compared to the total well-to-wheel emissions, while the total amount of GHG-emissions of electric vehicles are exclusively determined by the utilised power plant or power plant mix which supplies the electric energy. Therefore, the total amount of GHG-emissions of electric driven vehicles is strongly related to the structure of the power sector which finally determines the potential of electric vehicles to lower GHG-emissions compared to conventional fuel-driven vehicles. Thus the crucial point for assessing the potential for climate protection of electric vehicles is the deployed energy carrier. The electricity has to be generated by additional low-carbon energy sources in order to induce a substantial breakthrough for climate protection, even when significantly higher tank-to-wheel efficiency levels are achieved compared to conventional combustion engines.

The main interaction between the electricity demand of electric vehicles and the power sector as well as the impacts on GHG-emissions are discussed in chapter 4.

Local emissions

Electric vehicles and plug-in hybrid electric vehicles in electric driving mode are characterised by zero tailpipe emissions of harmful air pollutants such as particulates, nitrogen oxides and volatile organic compounds. In addition, electric vehicles greatly reduce noise emission in urban driving situations as the electric motor operates considerably more quietly than an internal combustion engines. Noise emissions of electric vehicles are mainly limited to noise from rolling and air resistance.

Further details on the impact of electric vehicles on air quality and noise are discussed in section 4.2.

Diversification of primary energy sources

Today, liquid hydrocarbon fuels derived from crude oil provide 95 % of the primary energy consumed in the transport sector worldwide [WWF 2008]. In the face of the need of a considerable reduction of GHG-emissions from the transport sector, the electrification of vehicle propulsion systems offers the opportunity of a diversification of the primary energy sources used in transport. The use of a wider range of primary energy sources is assessed in literature [WWF 2008, KING 2007] as an essential prerequisite to achieving the long-term goal of decarbonising the transport sector fuels. Furthermore, the broadening of potential energy sources for the transport sector offers security of energy supply and lowers the dependence on available oil resources.

Additional costs

The additional costs of electric propulsion systems represent a major drawback of electric vehicles. While fuel costs of electric vehicles may be significantly reduced due to a potential higher energy efficiency of the electric powertrain, the price premium of the electric propulsion technology as of today exceeds by far the fuel costs which could be saved over the entire time of vehicle operation (total-cost-of-ownership) [BOST 2009]. The major part of the supplementary costs of electric vehicles is determined by the expensive on-board energy storage system, while costs of further components such as the electric motor are compensated by cost savings due to a smaller or abolished combustion engine and mechanical drive train in plug-in hybrid or electric vehicles. The price premium of electric vehicles rises with increasing electric range as a larger battery system becomes necessary. Available conventional hybrid vehicles without plug-in capability show today a price premium of 3,000 to 5,000 € which corresponds to a 15 to 20 % higher purchase price [IPTS 2005]. Electric vehicles with an extended electric driving range would generate even higher costs due to the need of a larger battery system.

The future development of additional costs of electric vehicles highly depends on progresses in battery technology. It is expected that costs of battery systems can be significantly reduced over the next decades due to technological progress and economies of scales in light of an increasing market penetration of electric vehicles. However, a considerable price premium compared to conventional vehicles is likely to remain.

Figure 5 illustrates the range of potential price premiums of electric vehicles with electric driving range of about 100 kilometres assuming different battery cost targets. The estimation of additional battery costs relies on the assumption of a battery system with an energy capacity of 30 kWh and considers different cost assumptions provided in the reviewed literature (see also Table 3).

Today's battery costs are assumed to be in the range of 770 €/kWh (low) and 2,000 €/kWh (high), resulting in a price premium of 15,000 to 40,000 €. In the midterm, battery costs could decrease to less than 10,000 € if the stated cost targets would be achieved. Only if the most ambitious long-term cost reduction targets could be realised, the price premium of electric vehicles – caused by the additional battery costs – could fall below 5,000 €.

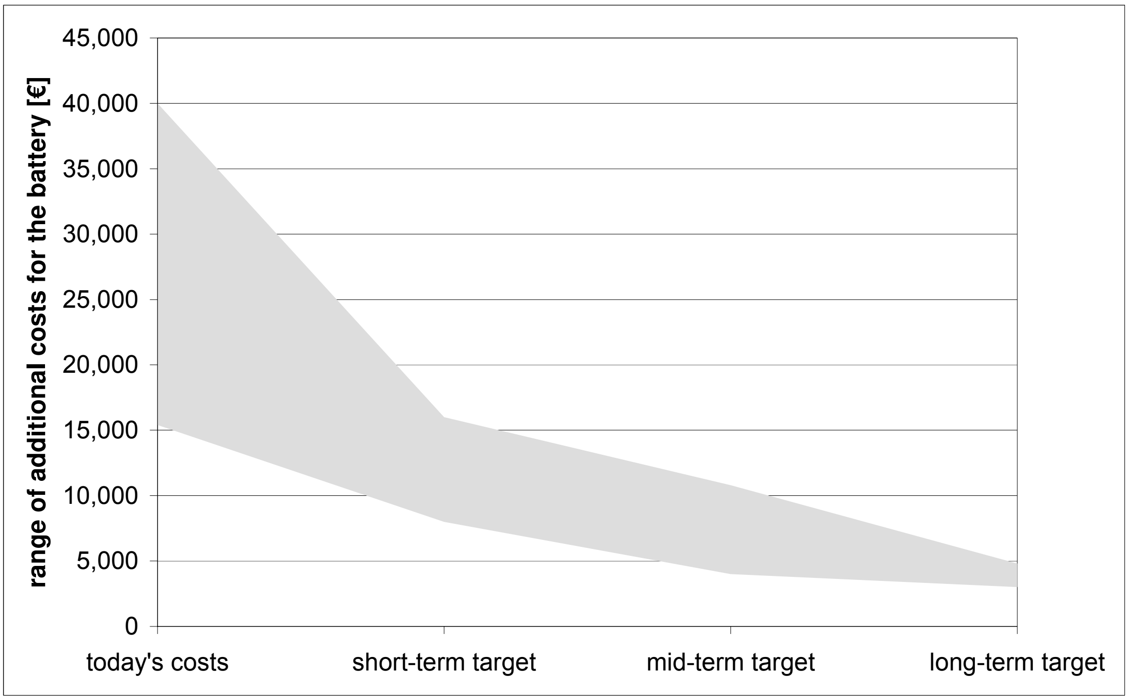

Figure 5: Range of the price premium of electric vehicles with 100 kilometres electric driving range (30 kWh battery) assuming different battery cost targets (based on literature review, own calculation).

Electric range and vehicle performance

To achieve a relevant market share, electric vehicles have to compete with conventional vehicles in terms of vehicle performance and driving range. While the electric driving range and performance of pure electric vehicles is sharply limited by the available battery technology, the overall driving range and performance characteristics of plug-in hybrid vehicles show considerably higher potential due to the availability of a secondary conventional propulsion system.

The electric range of electric vehicles is determined by the energy consumption per kilometre and the available energy stored in the battery. Despite the considerable higher tank-to-wheel energy efficiency of electric compared to conventional vehicles, the total electric range per full-charge is significantly lower. This is due to the restricted energy capacity of current battery systems caused by a specific energy density which is by a magnitude lower than that of conventional fuel [KING 2007].

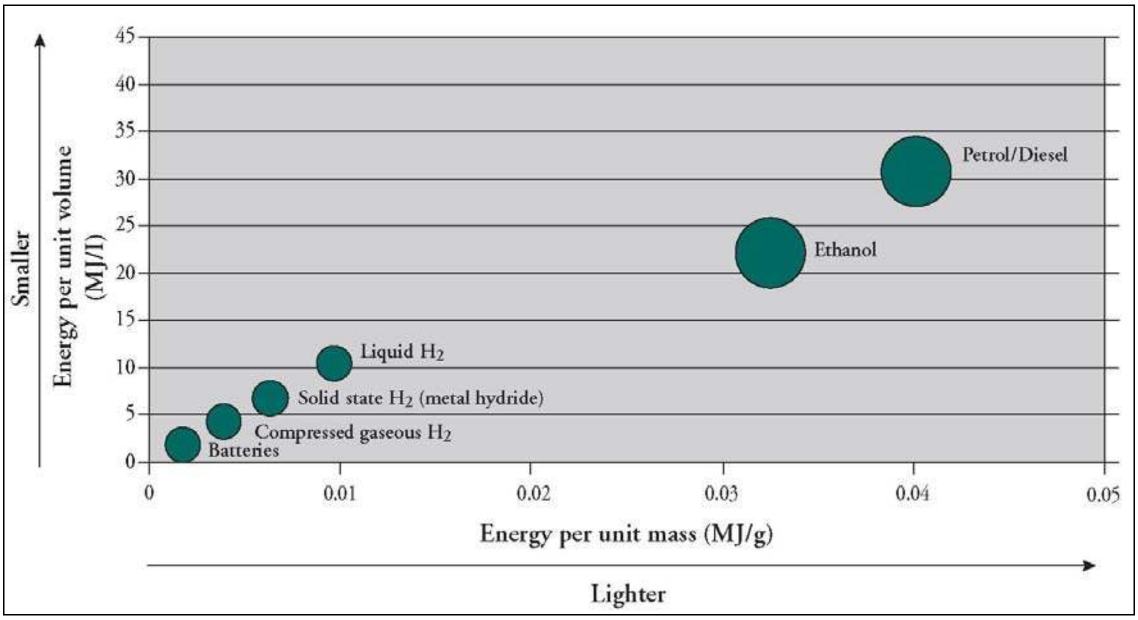

Figure 6: Energy density of some fuel types (Source: KING 2007).

The maximum speed performance of electric vehicles is also restricted by the power density of battery systems. The power density does not permit performance characteristics that are common for conventional vehicles without exceeding the implementable dimensions of an automotive battery.

On the basis of the currently available battery technology, the electric range of electric vehicles is limited to about up to 200 kilometres [UNSA 2009] (see Table 7). The maximum speed of electric vehicles varies depending on the vehicle concept, but on average it is lower than that of a corresponding conventional combustion engine vehicle.

Charging time and infrastructure

Due to the low energy capacity of battery systems and the limited electric driving range, more frequent charging is required to enable the same mileage that can be realised with conventional vehicles. While conventional vehicles can be refuelled within a few minutes, the recharge of a battery with a capacity which allows an electric range of 50 to over 100 kilometres takes several hours (3 to 8 hours) assuming conventional plugging to the electric grid [KING 2007].

Compared to the existing dense network of conventional filling stations, the existing electric power network is not adapted yet to the need of frequent recharging of electric vehicles. Besides the existing charging opportunities at private homes, a dense charging infrastructure would be needed in public spaces to permit recharging during daytime idle hours. In particular with regard to public charging polls safety and vandalism issues are of concern and need to be further considered.

High power fast charging stations could reduce the time of charging significantly to less than 30 minutes depending on the type and capacity of the battery [MIT 2007]. A corresponding network of fast charging stations would require considerable investments which could increase electricity prices. Further technical questions remain with regard to charging losses, heat development and negative impacts on the battery lifetime.

Weight and volume of battery

Traction batteries for pure electric driving are likely to be of considerable weight and volume because of the relatively low energy and power density of current battery systems. The fact that a higher vehicle weight increases energy consumption and that the available space for the propulsion system of a vehicle is limited, leads to restricted maximum dimensions of the battery, which finally determine the potential electric performance of the vehicle. A further increase of the battery would lower the efficiency of the electric powertrain and reduces the utility of the vehicle due to a reduction of the usable space.

Current battery technology increases the weight of vehicles with an electric range of about 100 kilometres by 250 to 300 kilograms, requires a considerable volume and significantly reduces the useable space compared to a conventional vehicle [UNSA 2009, BONN 2009]. MIT [2007] expects that the specific energy density of lithium-ion batteries could at most double in the next several decades, moving from 150 Wh/kg to 300 Wh/kg on the *cell*-level. SAFT [2007] gives an energy density of up to 120 Wh/kg which can be already achieved on a module level. VW [2008a] assumes that the technological development of current lithium-ion batteries could result in an energy density of up to 170 Wh/kg, whereas the introduction of new materials could result in a further increase up to 200 Wh/kg. Figure 7 illustrates the potential weight reduction of automotive battery systems, assuming an increase of energy density over time. The illustration relies on a 30 kWh battery system allowing an electric driving range of about 100 kilometres and assuming current, midterm and long-term energy densities of 100, 150 and 300 Wh/kg, respectively.

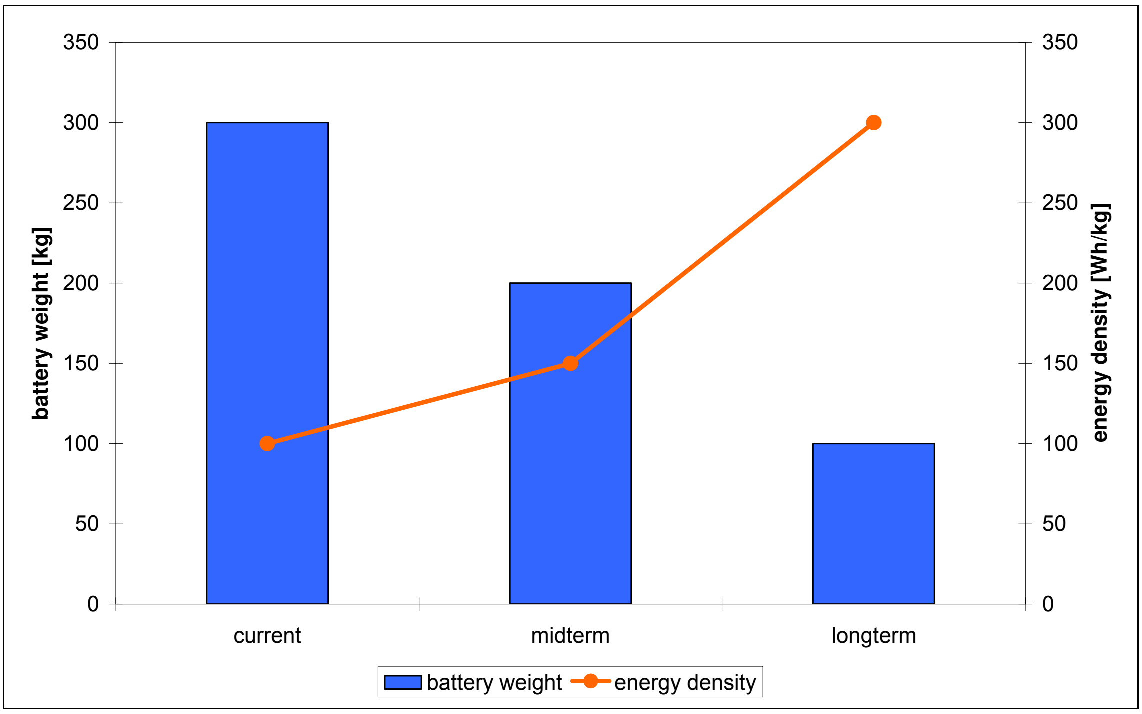

Figure 7: Impact of energy density characteristics of current and future (lithium-ion) battery technology on the total weight of batteries for automotive application (own calculations based on literature research).

Today's electric vehicles are largely based on conventional chassis which have not been developed explicitly for this specific use. Therefore, the large battery systems are often integrated into the trunk. More advanced concepts which are currently developed, foresee an under floor installation, which minimises the reduction of usable vehicle space.

The substitution of the internal combustion engine and the mechanical drive train by a lighter electric engine shows only little effect on the overall vehicle weight balance and can not compensate for the additional battery weight.

Demand on resources

The electrification of the powertrain considerably modifies the material composition of the entire vehicle. The electrochemical storage system, which includes critical metals such as lithium, has the largest impact on changes in material composition. It is difficult to assess future environmental and economic impacts of an increased demand of feedstock materials for traction batteries before electric vehicles have been introduced to the market in relevant numbers. Major impacts on the demand of certain raw materials, which today are only extracted in much lower volumes, can be expected in parallel with the expected market penetration of electric vehicles, (see also section 2.1.6).

SUMMARY: STRENGTHS AND WEAKNESSES OF ELECTRIC VEHICLES

Results from literature

- Vehicles with electric driving capability (EVs and PHEVs) are characterised by a high tank-to-wheel energy efficiency in the range of 60-80 %.
- The electrification of the powertrain allows a diversification of primary energy sources used in road transport and may decrease the dependence on crude oil.
- Local air pollutant emissions are completely avoided during electric driving and noise emissions are somewhat reduced using an electric propulsion system.
- The considerable price premium of electric vehicles – mainly caused by the high-cost battery system – remains the major drawback of electric vehicles. Only if considerable cost reductions can be achieved in the future, electric vehicles are likely to penetrate the automotive market at relevant production volumes.
- Due to the limited energy density of batteries, electric vehicles have a limited driving range and vehicle performance characteristics. A dense network of charging stations would be required to reduce driving limitations and to allow frequent charging.
- Further drawbacks are related to the high weight and large volume of automotive batteries that reduces the usable vehicle space and lowers the overall efficiency due to an increased vehicle curb weight.
- The available data on vehicle energy consumption varies to a large degree due to different vehicle types, driving cycles and measurement or simulation methods.

Discussion and recommendations

The considerable energy efficiency advantage of electric vehicles on a tank-to-wheel basis compared to conventional vehicles, the possibility to reduce oil dependence and zero local emissions are main advantages of the electric propulsion system.

The available data on energy efficiency and consumption of EVs on the vehicle level is derived from various sources and results from different approaches. Standardized data on the real-world energy consumption under different driving and external conditions is not available, but corresponding information is crucial for the determination of the overall impact of electric vehicles.

Further, a consistent comparison of different propulsion options, in particular with regard to energy efficiency and greenhouse gas emissions, should be carried out on a well-to-wheel basis and should comprise energy supply. In the case of electric vehicles the overall efficiency and related emissions are highly dependent on electricity production. In this context, uncertainty remains about the future electricity generation and its carbon-intensity, as well as the impact of EVs on the power sector that needs to be further investigated. The two main points are therefore:

- More detailed data on the real-world energy consumption of electric vehicles is necessary and may be gathered in the context of ongoing and announced pilot schemes.

- The potential of electric vehicles to reduce GHG emissions has to be evaluated on a well-to-wheel and life cycle basis, as emissions are mainly generated during electricity production and distribution. Depending on the energy supply, the total GHG emissions can vary in a wide range (see chapter 4.1).

2.3 Market overview EVs

Today's market of electric vehicles

Despite the recently growing interest on electrically driven vehicles, electric vehicles represent only a niche market in today's global vehicle fleet market. BERR [2008a] states that there is no electric car on the market at present which offers the capabilities of existing fully-homologated cars. According to an estimation of Electricité de France (EDF) today exist approximately 30,000 full electric vehicles, which represent 0.004 % of the total number of light vehicles (~800 million), [CARB 2007]. The International Energy Agency [IEA 2008b] states a total number of 150,000 electric vehicles for selected countries, which represent about half of the world's automotive population. The majority of those vehicles are electric two-wheelers. 2,000 electric vehicles (less than 0.005 % of the total fleet) and about 6,000 hybrid electric vehicles were registered in Germany in the year 2006 [WWF 2009]. BERR [2008a] states a number of 2,000 electric cars and 4,000 electric light-duty vehicles to be currently registered in the UK. The French population of electric vehicles is estimated to be higher (about 10,000 vehicles) due to a large number of electrically driven vehicles that were introduced in the mid 1990's and that are believed to be still in operation, primarily in the vehicle fleets of EDF [CARB 2007].

Even though the actual market penetration of pure electric vehicles is very low and mainly dominated by electric two-wheelers and low-performance electric four-wheelers, a major boost is expected from the emerged hybrid technology and the related development of battery systems with adequate performance characteristics. Hybrid electric vehicles (without grid-charging capability) have been introduced to the market in 1997 and have locally reached a relevant market penetration. Until 2005 more than 1 million hybrid electric vehicles have been sold worldwide, concentrated in the US and Japan [CARB 2007].

History of electric vehicle development

First electric vehicles have been on the road already in 1838 – 52 years before combustion engine vehicles entered the market [FRFR 2000]. In 1913, the production of electric vehicles started to decline and the starting mass-commercialisation of combustion engine vehicles has led quickly to road transport dominated by combustion engine technology. Until the 1960s, electric vehicle remained at an insignificant level. In the 1970, in the context of a rising environmental awareness and the oil crises, several prototypes of electric vehicles have been developed in Europe, Japan and the US and experts at that time have estimated a steeply rising deployment of electric vehicles. Finally, the production of electric vehicles remained at a negligible level during the 1980s [FRFR 2000].

A new boost of electric propulsion technology occurred in the mid-1990s, where several OEMs in Europe and the United States relaunched the development of electric vehicles. In the U.S., eight different electric vehicles were produced by six major OEMs. They were primarily developed in response to the September 1990 California ZEV (zero-emission vehicle) mandate, initially requiring by 2003 10 % of new cars sales to be ZEV [CARB 2007, MIT 2007]. In 1996, the California ZEV mandate has been postponed and the targets for zero-emission vehicles by 1998 and 2002 have been finally cancelled [FRFR 2000].

In Europe, electric vehicles with driving ranges of about 80 to 100 kilometres and maximum speeds of about 100 km/h, intended for urban use, were produced in the same period by several companies. Plug-in hybrid electric vehicles have been developed and tested since the 1980s. The first commercially produced PHEV is the Renault Kangoo Elect'road that has been in limited production since 2003 [BRAD 2009]. However, the developed vehicle concepts were commercially not successful at that time and have been only produced in low numbers. In particular the immature battery technology and the low driving range inhibited the market introduction of these vehicles. However, the research and development of electric propulsion systems in the 80s and 90s is considered the main technological groundwork for today's technological developments and the re-emergence of electric vehicles [CARB 2007].

Status quo and perspectives

Today, the small market of available electrically-driven vehicles is dominated by low-performance light electric vehicles and converted plug-in hybrid electric vehicles, produced by small vehicle manufacturers at small scales. The best selling inter-urban electric vehicle is the G-Wiz, which is produced by an Indian company and classified as a quadricycle rather than a car [WWF 2008]. Its production has been continuously expanded during the last years as it has experienced an increasing demand in metropolitan areas, such as London where it is exempted from congestion and parking charges [KING 2007]. Other electric vehicles that are already introduced to the market at small numbers are the French light-car Aixam Mega E-City and Th!nk City, a small electric city car produced by a Norwegian company as well as a U.S. high-performance sports car (Tesla Roadster), whose production started in 2008. Recently the Chinese manufacturer BYD started the production of a plug-in vehicle with 100 kilometre electric driving range. Further electric concept cars, such as the electrically powered smart ed have been recently introduced for testing.

A collaboration of UK's automotive engineering facilities recently developed a retro-fit hybrid conversion of a combustion engine vehicle [CRAN 2009]. The so called "Affordable Ad-on Zero Emissions Vehicle" (ADZEV) achieves an all electric range of over 20 kilometres. The technology is intended to convert existing vehicles from conventional to electric propulsion and may be scaled up for larger vans and even city buses according to the researcher's opinion.

Recently a considerable number of major OEMs announced the development and production of vehicles with electric operation capability, relying on improvements in battery technologies. Those developments of electric vehicles concentrate on small pure electric vehicles with electric driving ranges between 100 and 200 kilometres for urban applications and plug-in hybrid propulsion systems with electric driving capability that could propel larger vehicles [UNSA 2009].

An overview of electric and plug-in hybrid electric vehicles that are already available or announced to be introduced to the market within the next years is given in Table 7. An extended overview of further prototypes, concept cars, test fleet and small-scale produced vehicles as well as of converted hybrid-electric and battery electric vehicles is given in the appendix.

Table 7: Selection of available and announced plug-in hybrid and battery-electric vehicles (literature review).

	Manufacturer / Model	Type	Electric range [km]	Purchase price	Market introduction	Source
	Aixam Mega / Mega E-City	EV (light-car)	60	€ 17.950	available (small scale production)	MEGA 2009a NICE 2009a EMZE 2009
	Aixam Mega / Multitruck	EV (van)	60	£ 11,800 - 13,300	available (small scale production)	MEGA 2009b NICE 2009b
	BMW / E-mini	EV	240	-	test fleet	UNSA 2009
	Bolloré Pininfarina / Blue Car	EV	250	€ 330 /month (leasing)	2009 (small scale production)	PINI 2009 ABG 2009b
	BYD / E6	EV	400	-	2009 (in China)	BYD 2009b
	BYD / F3DM	PHEV	100	€ 16,000	available in China (small scale production)	BYD 2009a
	Daimler / Smart ed	EV	110	$ 36,000	test fleet	UNSA 2009
	General Motors / Volt	PHEV	65	< $ 40,000	2010/2011	AUZ 2009a
	Heuliez / Will	EV	150-400	-	2010 (small scale production)	SAAU 2009
	Mitsubishi / i-Miev	EV	160	€ 32,000	2010/11	UNSA 2009 TONA 2009
	MODEC / Modec	EV (van)	160	$ 52,000	available (small scale production)	UNSA 2009

	Nissan / E-Cube	EV	160	-	2010-2012	AUZ 2009b MAWI 2009
	Reva / G-Wiz	EV (light-car)	80	$ 18,000	available	UNSA 2009
	Subaru / R1e	EV	80	-	2009 (small scale production)	UNSA 2009
	Tesla Motors / Roadster	EV (sports car)	350	$ 109,000	available (small scale production)	UNSA 2009, TEMO 2009
	Th!nk / City	EV	180	€ 20,000	available (small scale production)	UNSA 2009
	VW / Twin Drive	PHEV	50	-	test fleet	AMS 2009a

Electric vehicles

Besides the already available electric light cars, such as the Reva G-Wiz, Mitsubishi developed a "city-like" car concept (Mitsubishi MiEV) with a range of 130 to 160 kilometres that is currently being tested. Its small scale series production and market introduction is expected for 2010/11. Daimler is currently developing a revised version of the smart ed with improved lithium-ion battery. Its former version was tested in London. Additional fleet tests are planned and the series production could start in 2011. A similar concept, the electric car 'E-mini' with about 200 kilometres of electric range, is realised by the BMW Group. It will be produced in a limited number of 500 vehicles and will be tested in metropolitan areas in the U.S. and in Germany [SPIE 2009]. Other small electric vehicles which are developed by major OEMs and which are likely to be available within the next years are the Subaru R1e and Nissan E-Cube. Several electric vehicles of the Nissan-Renault Alliance are announced to be developed within the Project Better Place cooperation until 2011. Initial models will be based on the Mégane [UNSA 2009]. Further electric concept cars were recently presented by several smaller vehicle manufacturers, such as Heuliez, Optimal Energy and Bolloré/Pininfarina, and small scale production is announced to begin within the next 2 years. With regard to the Asian market, emerging Chinese car manufacturers such as BYD and Geely announced several pure electric and plug-in hybrid vehicles that will be first marketed in China, with a planned expansion into the international market in the near future [BERG 2008]. BYD announced the introduction of its first EV to the Chinese market in 2009.

Plug-in hybrid electric vehicles

Plug-in hybrid electric vehicles with pure electric driving capability are limited to only few test vehicles. The recent improvements of battery performance have lead to increasing activities of several car manufacturers in the development of corresponding car concepts. The Chinese car manufacturer BYD started a small scale production of a plug-in hybrid car (BYD F3DM) at the end of the year 2009 in China. The production of the GM Volt, a plug-in hybrid vehicle with 65 kilometre electric driving range, is announced to start in 2010/11. The purchase price is targeted at less than 40,000 USD. The Swiss company Mindset develops a plug-in vehicle with 100 kilometre driving range and plans production at small volumes starting in 2009. Among the major OEMs, the Volkswagen Group recently started testing a fleet of plug-in hybrid electric vehicles (Golf TwinDrive) with an electric range of about 50 kilometres in Germany [VDIN 2008].

The most prominent hybrid vehicle, the Toyota Prius, supposes to be equipped with a larger battery that would enable pure electric driving over longer distances and the charging of the battery from the grid. Prototypes are currently tested in several pilot projects. The start of series production of the plug-in hybrid version of the Toyota Prius is not yet determined. Other plug-in concept cars that were recently presented by other OEMs such as the Volvo ReCharge may not be produced at larger scales in the coming years. Several Chinese car manufacturers announced the development of plug-in hybrid vehicles, which may be introduced to the market in the future [WWF 2008].

Electric delivery vans

Recently, a growing development of battery-electric delivery-vans can be observed, besides the emergence of electrically driven passenger cars. The major focus of the development activities are delivery-vans for urban areas with a limited daily driving range that can cope with lower performance characteristics including maximum speeds below 100 km/h Daimler is currently the only major OEM that develops and has already tested a plug-in hybrid electric delivery-van in the U.S. [SAUB 2008, FLOTT 2008, DAIM 2008]. Several small vehicle manufacturers started the small-scale production of pure and hybrid electric delivery-vans. Fleet tests are currently carried out in several countries with a main focus on delivery services in metropolitan areas [GREEN 2008].

Recent pilot projects and co operations

A considerable number of fleet tests of electric vehicles, including the installation of the required charging infrastructure, are carried out or have been announced in different countries (seeTable 8). Most of these pilot projects involve a cooperation of vehicle manufacturers and utility companies. While the first provide a considerable number of electric vehicles, the latter are in charge of the energy supply infrastructure. As a consequence, a limited number of charging polls will be established in the testing areas that will enable the frequent charging of the test vehicles. Those co operations reflect the altered stakeholders with regard to the available infrastructure and charging of electrically driven vehicles compared to conventional vehicles. The ongoing or announced fleet tests aim to prove the reliability and performance of the existing electric vehicle technologies, the battery systems and the energy supply infrastructure. The pilot tests with recharging stations at private and public places will provide evaluation data for the potential future need to extend the charging infrastructure in case of an increased demand of electrically driven vehicles. Furthermore, data on the customer acceptance of vehicles with low performance, limited driving range and the requirement of frequent recharging will be acquired in order to better evaluate the future market potential of electric vehicles. Valuable data will be collected from those pilot projects with regard to real-world energy consumption under different driving and external conditions, battery self-discharge losses and the energy demand of auxiliaries. Data on driving and charging behaviour could provide valuable information on the potential of electric vehicles to substitute conventionally driven mileage.

Table 8 provides an overview of current and announced pilot projects. Besides the London fleet test that has started in 2007, other pilot projects are announced to start within the next months in several countries with a major focus on urban areas. Most pilot projects receive considerable public financial support.

Several test fleets including pure electric and plug-in hybrid electric vehicles from different car manufacturer will operate in Berlin, Germany. Smaller fleets will be tested in other metropolitan areas. In France (Strasbourg) a 3-year test phase of plug-in hybrid vehicles has been recently announced. In the Paris region, a cooperation of the Renault-Nissan Alliance and EDF will carry out a large-scale electric vehicle test, starting in 2010. The car fleet will comprise passenger cars and light commercial vehicles for consumers, professionals and local government employees [REN 2009b]. The French post "La Poste" launched a plan in 2007 to integrate 500 electric vehicles within its commercial fleet and plans to increase the number of electric vehicles up to 10.000 within 5 years [GRLP 208]. The UK government recently announced to support field trials of electric passenger cars and light commercial vehicles in different locations for a minimum duration of 3 years [LOWC 2009, LOWC 2009a]. Fleet tests are further announced to be carried out in several larger cities in Italy and Spain, starting between the year 2009 and 2011. Smaller fleet tests will be carried out in Sweden and Finland. Corresponding activities are also announced in several US metropolitan areas and Japan, including the testing of different vehicle concepts and the installation of networks of charging polls.

Further plans have been recently announced in different countries including the development of a large scale charging infrastructures that would allow the operation of electric vehicles within a wider area. An overview of corresponding activities is discussed in greater detail in section 3.1.

The aim of the "Grid 4 Vehicles" project is to develop and demonstrate a master system which can predict, influence and handle the moving mobile customers. The project aims to prepare the pathway for an European wide common solution for a fully developed EV market. In 2008, a common OEM/utility standardisation initiative has been started to accelerate and improve standards definition. The research consortium comprises several international utilities and research institutes [RWE 2009, RWE 2009a].

Table 8: Selection of recently announced pilot projects and co operations between OEMs and utility companies (literature review).

Country / Location	**OEM / Utility**	**Start of pro-ject**	**Vehicle**	**Description**	**Financial support**	**Source**
Austria / Vorarlberg	various / VKW	2009	various	100 vehicles, 10 charging stations	4.7 million € by Austrian Climate and Energy Fund	VKW 2009 GRAU 2009a
Finland / Espoo	- / Fortum	Since 2008	-	10 to 15 PHEVs		FOR 2009
France / Paris	Renault-Nissan / EDF	2010	various	100 vehicles	By the Paris region	REN 2009b
France / Strasbourg	Toyota / EDF Energy	2009	Toyota Prius PHEV	100 vehicles	ADEME's research fund	WGA 2009a
Germany / Berlin	BMW / Vat-tenfall	2009	BMW e-mini	50 vehicles	Federal government	ATZ 2009
Germany / Berlin	Daimler / RWE	2009	Smart ed	100 vehicles, 500 charging stations	Federal government	DAIM 2009a RWE 2009a
Germany / Berlin, Wolfsburg	VW / E.on	2010	VW Twin-drive	20 PHEVs	Federal government	AMS 2009b
Italy / Rome, Milan, Pisa	Daimler / ENEL	2010	Smart ed	100 vehicles, 400 charging stations	-	DAIM 2009c
Italy / Mi-lan, Brescia	Renault-Nissan / A2A	2010	-	-	-	REN 2009c
Japan / Tokyo	- / Tepco	2009	-	300 EVs	-	GCC 2009b
Japan / Tokyo	Mitsubishi, Subaru / Tepco	2009	-	200 charging stations (1,000	-	ABG 2009d
Spain / Sevilla, Barcelona, Madrid	various / -	2009-2011	various	2,000 EVs, 550 charging stations	10 mio. € govern-mental support	TREE 2009b MOEL 2009 IDAE 2009
Sweden /	Volvo, Saab / Vattenfall	2009	-	10 PHEVs	5 million USD public subsidies	VATT 2009 GCC 2009a
Sweden / Öland	Th!nk	2008	Th!nk City	25 vehicles	360,000 by Swedish Energy Agency	TREE 2009a
Sweden / Stockholm	- / Fortum	2009	-	100 charging station	-	TREE 2009c
UK / London	Daimler	Since 2007	Smart ed	100 vehicles	-	DAIM 2009b

UK / London	BMW	2009	BMW e-mini	50 vehicles	-	FOL 2009a
UK / 8 different locations	Mini, Smart, Nissan	-	various	340 vehicles	25 million £ of governmental support	LOWC 2009
UK / 6 different locations	Ashwoods, Allied Vehicles, Smith, Modec	-	Various light commercial cehicles	-	20 million £ of governmental support	LOWC 2009a
USA / Los Angeles, New York, New Jersey	BMW	2009	BMW e-mini	500 vehicles	-	SPON 2009b WGA 2009b FOL 2009b

SUMMARY: MARKET OVERVIEW & PILOT SCHEMES

Results from literature

- Today electric vehicles represent a very small niche market which is dominated by low-performance light electric vehicles for particular applications.
- The first major activities of several OEMs were carried out in the 1990s and resulted in the development of several electric vehicles in the United States and Europe.
- A growing activity in electric vehicle development can be observed as a result of recent major advances of battery technologies.
- Some smaller manufacturers have already introduced electric vehicles at small production volumes into the market.
- Several major OEMs have announced the development and the commercialisation of electrically driven vehicles within the next years (see Table 7). The development activities comprise full electric and plug-in hybrid electric vehicle concepts and passenger cars as well as delivery vans.
- Some vehicle manufacturers started already a small scale production of electric vehicle prototypes that will be tested (Table 8). The pilot projects concentrate on urban areas and include the installation of charging infrastructure.

Discussion and recommendations

Major but also smaller manufacturers have announced recently a large number of EVs and PHEVs showing the increasing interest in electric vehicle propulsion. Despite the considerable number of electric vehicles that are presented in this review, their market introduction is still related to uncertainty. Most of these vehicles are planned to be introduced to the market at low production volumes and the market introduction of several vehicles has been postponed already several times. The major share of EVs that are already available are low-performance cars; a large number of presented EVs are concept cars that are not foreseen to be introduced to the market in the current configuration.

The further perspectives of the development and deployment of electric vehicles will be mainly determined by the further improvement of battery technology. The establishment of a corresponding charging infrastructure represents a further prerequisite for a large-scale operation of electric vehicles and is likely to be set up only if corresponding private activities are accompanied by public support.

Electric vehicles have to prove suitability for daily use and acceptance among consumers within the next years to achieve a relevant market share in the future and increase electric vehicle development. Electric and plug-in hybrid electric vehicles are likely to be introduced first to niche market.

At least 16 fleet tests have been announced around Europe and they are proposed to represent a valuable source of actual data to determine the status of technology and consumer acceptance. With regard to these fleet tests, the following recommendations can be drawn:

- It is essential to link the announced fleet tests with a broad accompanying research as these pilot projects will generate valuable "real-world" data with regard to charging behaviour, vehicle use pattern, substitutable mileage, long-term battery performance and real-world energy consumption.
- As these data are fundamental for reliable market penetration scenarios and an assessment of the environmental impact of EVs, a coordination between these initiatives and data compilation of all demonstration projects should be facilitated, e.g. by the establishment of a European data centre.

3 Market introduction of electric vehicles

3.1 Business models for the introduction and operation of electric cars

Considering the major challenges for the introduction and operation of electrically-driven vehicles, including the price premium caused by the expensive battery technology, the limited driving range, a reduced vehicle performance, as well as the need of a dense network of an electric charging infrastructure, new innovative business models are needed to assist in the transformation of automotive transport [WWF 2008]. BOST [2009] assumes that the commercialisation of electric vehicles may benefit from unconventional market models.

Price premium (of battery)

Other business models than ownership of electrically driven vehicles and their batteries by customers deserve consideration as a way of capturing the potential propulsion energy cost savings of electric EVs/PHEVs that would compensate prospective high costs of battery technologies [CARB 2007]. The electric utility ownership of batteries and lease-back to customers is one such model. Similar business models are situated at the interface of vehicle and grid including leasing concepts for batteries and life cycle cost sharing between the EV owner and the utility company [ERTRA 2009]. The ownership of the battery by the utility company could provide specific functions such as the availability of power and energy delivery to the grid as well as the use of batteries as energy storage subsystems [CARB 2007]. A further option could be that battery manufacturers own the battery over the entire life cycle to enable reuse, recycling and potential regaining of the captured values of their products.

The Norwegian company Think Global AS, manufacturer of the ‘Think City’ electric vehicle, offers already a battery leasing concept. In this business model, the used battery systems are not sold to the customer but remain in possession of the vehicle manufacturer [WWF 2009]. It guarantees the supply of the most advanced battery technology and its replacement in case of deteriorating performance.

Energy supply, charging infrastructure and charging time

The ‘fuelling’ of electric vehicles with electric energy requires major changes of the existing energy supply infrastructure in order to enable an adequate operation of these vehicles.

Charging infrastructure is considered to be a major factor in customer acceptability of electric vehicles [CARB 2007]. Due to the limited driving range and the long charging time of batteries, it will be essential to create pervasive public electric-charging infrastructure that ensures reliable charging capability. It will be difficult to make a business case for a public electric charging infrastructure because of high investment costs and high risks. If electric-power companies were to pay for the new infrastructure, the price of electricity for charging vehicles would have to rise significantly and the attractiveness of electric vehicles would decrease consequently [BOST 2009]. The installation of fast-charging infrastructure could improve the customer acceptability of electric vehicles, but create even higher investment needs. Therefore, it is expected that power companies will not invest in corresponding projects at a large scale without governmental subsidies and the perspective of a growing deployment of electric vehicles in the future [CARB 2007].

New business models could emerge at the interface of vehicle and electric grid. The implementation of smart systems for the interface vehicle-to-grid connection could allow an optimisation of battery charging which may become attractive for utility companies with regard to the management of the electric grid and the fluctuating supply and demand of energy. Smart power charging and metering capabilities of the batteries could provide functions such as spinning reserves, voltage regulation, emergency power and peak shaving or load levelling to power companies [CARB 2007, ERTRA 2009]. Corresponding vehicle-to-grid concepts are therefore discussed as potential future business models. Some OEMs have already built partnerships with third-party investors or directly with power companies (see Table 8) [BOST 2009].

The project Better Place, a U.S. start-up company, plans to build a dense network of battery charging and exchange stations for electric vehicles. The large number of charging stations would offer the opportunity of frequent recharging of the battery in public spaces during longer parking. As an additional option, depleted battery packs could be swapped at exchange stations for a fully charged one, allowing travelling longer distances without lengthy stops for battery recharging [BOST 2009]. In cooperation with the Renault-Nissan alliance, Better Place develops already prototypes of electric vehicles, suitable for battery exchange within only a few minutes [REN 2009]. The intended leasing scheme of Better Place would comprise the provision of the necessary battery system and the supply of energy. A subscription model, similar to that of mobile phones, would charge drivers of electric vehicles depending on the travel distances, whereas the initial price premium of the electric vehicle would be covered by Better Place. The Better Place approach may increase customer acceptance because high investment cost, long charging times, short driving ranges and the missing charging infrastructure could be overcome. However, a problem with this system would be that, in the short term, it would require much standardisation of the battery and its location within the vehicles. Several manufactures are sceptical with regard to this issue [PBL 2009].

First charging networks are announced to start in 2010/11 in Denmark, Israel and Portugal in cooperation with national power companies and supported by governments (see Table 9). More similar projects are planned in other countries, e.g. in the US (California and Hawaii), Canada (Ontario) and Australia [PBL 2009].

Table 9: Overview of large-scale charging infrastructure projects (literature review).

Country	Location	OEM / Utility	Start of project	Vehicle	Description	Source
Denmark	Country-wide	Renault-Nissan /DONG Energy / Better Place	2011	various	500,000 charging stations	BEPL 2009b EATE 2009
France	Paris	-	2010	-	‚Autolib': 4,000 vehicles, 1,400 charging stations	WGA 2009c
Israel	Starting with Haifa, Tel Aviv, Jerusalem	Renault-Nissan / - / Better Place	2010	various	100,000 charging stations	BEPL 2009a BEPL 2009c BUWI 2009
Portugal	-	Renault-Nissan / - / Better Place	2011	-	320 charging stations until 2010 (goal: 1,300 stations)	NISS 2009 NEUR 2009

Limited driving range

"When private citizens purchase cars, they tend to choose a vehicle which is capable of fulfilling all of their mobility needs, from the mundane – such as the weekly supermarket run, or the daily commute – to the exceptional" [WWF 2008]. Therefore, despite the fact that the average daily driving distance is far below 100 kilometres and the average urban vehicle occupancy rate in Europe is approximately 1.37 according to the International Energy Agency [WWF 2008], most vehicles exceed these daily requirements. They are expected to fulfil rarely occurring peak demands with longer driving ranges and the need of larger sized vehicles. Most vehicles are thus not adapted to the required lower demands during the vast majority of their lifetime and mostly operate in an inefficient mode.

With regard to the average use pattern of vehicles in terms of required size, range and performance, electric vehicle could represent a solution which could theoretically substitute a large number of conventionally powered vehicles, whereas the maximum requirements seems to be not achievable by electric vehicles in the foreseeable future. New business models, such as car sharing that provides personal mobility services rather than the ownership of a specific vehicle could foster this development. Participants in car sharing could use smaller electrically driven vehicles for their daily trips. Less frequent trips of longer distance could be carried out with an adequate vehicle with longer driving range and higher performance.

Another option of an integrated approach is the combination of car sharing with mass transit services which may extend the network coverage of public transport providers far beyond their traditional nodes. This could link the strengths of electric vehicles on short distances with the strength of mass transport modes for long-distance trips. Electric vehicles would be capable of completing the first and last few kilometres that are not well connected through public transport and improve thereby the attractiveness of public transport systems [WWF 2008].

A new approach for mobility as an alternative solution to the private passenger car is currently examined in the scope of different research projects. So called “Cybernetic Transport Systems” consist of small automated urban vehicles that are intended to form part of the public transportation system and complement mass transit and non-motorised transport [CYCA 2008]. This novel form of vehicle-sharing, based on automated vehicles shows particularly favourable conditions for the application of electric propulsion systems. At the moment, several international projects examine the future potentials of corresponding transportation systems for a large-scale implementation [CYMO 2009, CYBC 2009, CYBE 2009]. Among them, two new projects (CyberCars-2 & CityMobil) are funded by the European Commission [CYCA 2009].

A recent research among experts from the automotive industry comes to the conclusion that consumers are likely to become more open to flexible access to transport and less tied to their own car by 2020. People may want to purchase a small, efficient car, with a certain access to alternative transport facilities included in the price, such as public transport or larger rental vehicles [PBL 2009].

Recently, the Paris city authorities announced plans to establish until 2010 a large-scale so called ‘Autolib’ electric car-sharing scheme (see Table 9) [CLIM 2009]. The ‘Autolib’ system will comprise 4,000 electric vehicles which will be placed in Paris and its outskirts to enable participants to cover short journeys [GUAR 2008]. In contrast to existing car-sharing, the Autolib concept will allow to start a journey at one of 700 public pick-up points and to leave the vehicle at another station. Tariffs have not been set yet, but the Paris authorities mentioned a monthly subscription charge which could range between 15 and 20 € and between 5 and 4 € charge for every 30 minutes of vehicle usage [MAIR 2008]. [GRLP 208] estimates the potential of an expansion of the Autolib concept to other major European cities with about 70,000 electric vehicles.

First experiences with a fleet of electric cars available in self-service mode in a limited area have already been made in the 1990s within the “Praxitele Project” in a city close to Paris [MALA 1999]. The purpose of this project was to establish a new mode of transport between public mass transportation and the private automobile. The survey that has accompanied the pilot project showed a very high level of satisfaction among participants.

Other European capitals are already thinking about similar activities. The London authorities are considering the introduction of a similar electric car hire scheme and the replacement of at least half of the vehicle fleet owned by the Greater London Authority by electric vehicles [GUAR 2009].

<u>SUMMARY</u>: BUSINESS MODELS

Results from literature

- New business models could foster the commercial success of electric vehicles.
- New leasing concepts could help to cope with the considerable high investment costs which are related to the battery.
- The expensive build-up of a dense charging station network would likely require public and private investments.
- At the vehicle to grid interface new business models may emerge as utilities are interested in grid management strategies through grid-connected automotive batteries.
- In consideration of the need of frequent charging and long charging times, charging infrastructure as well as battery exchange stations are discussed as a viable option (e.g. Better Place Project).
- Other concepts including car sharing clubs and the combination of electric vehicle use with mass transit services (e.g. AutoLib) take advantage of the limited driving range of electric vehicles.
- In the long-term new mobility concepts such as Cybernetic Transport Systems could be particularly favourable for the application of electric propulsion systems.

Discussion and recommendations

Due to the fundamentally different characteristics of EVs compared to conventional vehicles new business models and mobility concepts are likely to be required for achieving a relevant market share of electric vehicles. Major barriers that have to be tackled are the price premium, the required charging infrastructure and the limited driving range. In this context, different business models are under discussion. Business models that are not ultimately tied to electric vehicles – such as car sharing clubs – represent currently only a niche market. The mentioned business models that are related to electric vehicle use would be associated with large financial investments and high economic risks. The economical attractiveness of these business models for investors will be highly dependent on the consumer's acceptance, but corresponding knowledge is still very limited and can only be derived from few niche applications:

- The evaluation of experiences from new business models in niche markets could help to evaluate further potentials.
- Testing of different business models and feasibility studies are important to deliver information as a basis for valuable market penetration scenarios.

3.2 EV potential with regard to use pattern and charging schemes

The potential of electric vehicles to substitute conventional vehicles has to consider their lower driving range, the need of frequent and long-time charging. Therefore it is assumed that general changes in driving behaviour and vehicle purchase criteria would have to be established. The identification of future potentials of electrically driven vehicles such as battery-electric and plug-in hybrid electric vehicles requires the analysis of vehicle use patterns and the (charging) infrastructure. The determination of possible energy and GHG savings due to electrically substituted mileage requires reliable travel data with a focus on daily driving distances and the charging behaviour of electric car owners. Several analysis which focus on the future EV potential with regard to use pattern and charging schemes have been already carried out.

Driving pattern

Several times, the National Personal Transportation Survey (NPTS) collected data on the US vehicle daily mileage. Distribution shows, that the majority of daily trips are relatively short, with 50 % of the trips being less than 50 kilometres [NREL 2006a]. 80 % of all daily trips are below a mileage of 80 kilometres (50 miles). The 2007 edition of the Transportation Energy Data Book reports that the average household vehicle trip length and the average daily vehicle miles rose only slightly since the 1990s. Therefore, a similar daily mileage distribution as reported for the year 1995 can be assumed for today, although no more recent data is available [WWF 2008]. The European Commission's statistics agency Eurostat published passenger mobility data for Europe that is in good accordance with the US data. A summary of most recent national travel surveys of several European countries depicts an average daily total trip length of 30 to 40 kilometres across all modes of transport and an average daily distance of 27 kilometres by car [DEBA 2008]. In the UK, the daily car travel length is 38.9 km and 94 % of the car trips are less than 25 miles (40 km) [DFT 2007, DEBA 2008]. The German Mobility Panel (MOP) surveys passenger travel behavior in Germany. According to MOP (www.mobilitaetspanel.de), the daily car travel length is 20.7 km in Germany and 90.9 % of all car trips have a length below 40 km. In France, the daily car travel length was 35.9 km in 2006 [MEED 2006] and 80 % of French commuters drove less than 50 km per day in 2004 [INSEE 2004].

In metropolitan areas, the share of short trips is particularly high. On average, 84 % of all car trips in London are less than 20 kilometres and 95 % less than a total of 75 kilometres per day [MAYO 2009]. Similar driving pattern can be observed in other European metropolitan areas.

[PBL 2009] states a usual driving pattern of occasional longer trips, combined with mostly short trips. Worldwide, most commuter trips are below 50 kilometres as well as a large part of other daily trips. It is thought that more than 99 % of passenger cars cover less than 300 kilometres per day.

At a first glance (see Figure 8) one could suggest that there is a large potential of vehicle trips that could be substituted by electrically driven cars. Electric vehicles, equipped with current battery technology, have a driving range of 100 to 200 kilometres and could be used for the large majority of the daily vehicle trips. However, the deployment of electric vehicles is confronted to established vehicle purchase criteria that are based on the maximum demand on vehicle performance and range and that can not be fulfilled completely by the electric propulsion system. Plug-in hybrid electric vehicles that overcome the range restrictions of the battery by additionally employing conventional propulsion power besides the opportunity of pure electric driving could therefore present a viable alternative. Other options like EVs with range extenders, batteries swap stations and dense networks of charging spots are other viable solutions. Secondly, long car trips – which represent a very small fraction the annual car trips for most Europeans – could be made with other modes of transport and could be fostered by new mobility concepts (see 3.1).

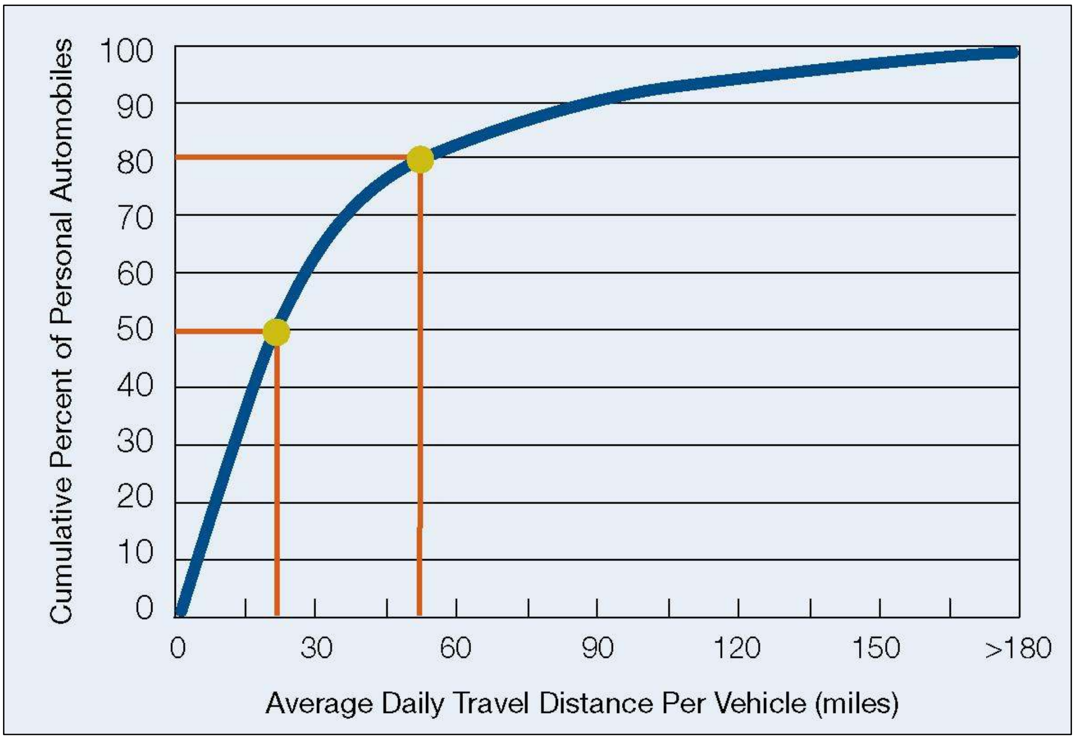

Figure 8: American driving patterns. Average daily travel distance per vehicle, based on nationwide travel data (Source: WWF 2008).

Focus areas and applications

The greatest potential of electric vehicle operation is found in urban areas, where the average speeds and the maximum lengths of vehicle trips are particularly low [EABEV 2009]. PBL [2009] argues that electric vehicles appear to be most suited for short and medium-range distances, because of the weight and purchase price of the battery. BASSI [2007] mentions urban profiles of certain users, including craftsmen, local office services and tourist transfers, with particularly favourable conditions for the use of electric cars with restricted driving range. [GRPL 208] refers to the large potential of electric vehicle application within commercial vehicle fleets. The electrification of commercial fleets seems particularly favourable as a range restriction and long charging cycles are not major constraints for many commercial applications. The analysis of FFE [2007] identifies an additional potential with commuters that are regularly travelling the same distance, often repeatedly with the same start and end points. Moreover, the attractiveness of an electric vehicle may rise if a second car is available within the same household that would be suitable for the more occasionally occurring long-distance trips [PBL 2009]. EABEV [2009] refer to the high potential of electric vehicles as a light, small and low-power second car that is used for daily commuting and short trips, while the fuel car would be used for week-end trips and holidays. The potentials for substituting conventional cars by electric vehicles with different user types, including commuter, other private and company vehicles, is evaluated in FFE [2007] in two scenario analysis. The pessimistic scenario achieves substitution rates of 0 to 10 % depending on the vehicle use. The optimistic scenario results in substitution rates between 10 to 50 %. A recent study by the American Council for Energy Efficiency Economy (ACEEE), focusing on plug-in hybrid electric vehicles, demonstrated that an all-electric range of about 50 kilometres should be sufficient to cover 50 % of trips, on average [WWF 2008]. With regard to Germany, an electric range of 40 kilometres could substitute 50 % of the average annual distance travelled [IFEU 2007].

Charging opportunity and infrastructure

The deployment of electrically driven vehicles is highly dependent on the availability of battery recharging infrastructure that would allow frequent recharging of the traction battery. It can be assumed that only a small number of public charging stations will be available at the beginning of electric vehicle deployment, with a concentration in urban areas. Therefore, early marketing of electric vehicles need to focused on car owners with the opportunity of charging at their homes. IEA [2007] expects this market to be mainly on the edges of dense city centres, in residential areas where higher income residents are found and where the highest percentage of single family detached dwelling units are found disposing of a garage to park and charge the vehicle overnight. The analysis of ARG [2009] evaluated the potential of electric vehicles on the basis of the 2005 American Housing Survey (AHS). According to AHS, 63 % of all occupied housing units in the United States have access to a garage or a carport. In contrast, far fewer Europeans own a garage or carport for recharging their vehicle (about 20 % in France) [IEA 2007]. However, it is assumed to be desirable to start the market by targeting those households with available plugs at their homes as public charging will not be a common option for early markets.

Other valuable information can be derived from studies which report early users' experiences with plug-in hybrid and electric vehicles. ITS [2008a] found that 59.5 % of plug-in hybrid vehicle users in California had at least one viable recharge location within their 24-hour daily routine. 52.4 % could charge their vehicle at home, 4.8 % found outlets at work and more than 10 % at other locations. Another report finds that frequent daily recharging among early PHEV drivers is common and that the majority of vehicles (80 %) were recharged in multiple locations such as their workplaces and homes [ITS 2009]. While most studies assessing the impact of electric vehicles on the power grid assume charging during off-peak hours, the study from ITS [2009] reports that all vehicles were regularly charged during daytime business hours. This study shows that an unregulated battery recharging could result in an increased power demand during peak-periods, although, these documented first experiences relied on a small number of early users of vehicles with grid-charging capability that may not be representative of the average electric car user of the future. The need for a constrained recharging scheme may arise as an increasing number of grid-connected electric vehicles would have a considerable impact on load demand.

SUMMARY: EV POTENTIAL WITH REGARD TO DRIVING AND CHARGING BEHAVIOUR

Results from literature

- Despite an average driving pattern with a high share of short trips that is perfectly suited for EVs, vehicle purchase is still rather determined by maximum range and performance requirements that can not be completely fulfilled by EVs.
- Urban and suburban areas are assumed to be the most promising early target markets for electric vehicles due to driving range restrictions and the need of frequent recharging.
- The use of electric vehicles is expected to be particularly suitable for households with private overnight charging capabilities because the early market is likely to be confronted with only poor public charging infrastructure.
- Electric vehicles seem especially interesting for repeated driving patterns such as commuting and for vehicle fleets with low daily driving ranges and charging stations at their depot.
- Because of the limited driving range, it is assumed that EVs may mainly be used as second cars for short distances, whereas a supplementary conventional vehicle would assure to cope with longer distances.
- Plug-in hybrid vehicles can also cope with long-distance travelling which could extend the early market to other target groups.

Discussion and recommendations

The discussion of potential areas of EV application is mainly based on information from theoretical analysis of statistical data on driving behaviour and other relevant parameters (e.g. charging opportunity). The few data that is available from state-of-the-art electric vehicle use in practise is of limited significance as it is based on an only small number of vehicle users (so called “early adopters”) that might be not representative for a large-scale introduction and should therefore be considered only with caution when drawing general conclusions.

Under the assumption that vehicle purchase criteria and general mobility concepts do not change dramatically, the analysis of average driving pattern is only partly useful to determine potential fields of application for EVs. An improved investigation of potential target markets should comprise further factors that are relevant for vehicle purchase and use (e.g. investment costs, resale value, infrastructure) and additional information from current fleet tests should be considered.

In the context of current investigations new mobility concepts and offers as well as the assumption of a modification in consumer behaviour and mobility pattern are not considered when determining future EV potentials, due to the lack of practical experiences and the difficulty of corresponding projections. However, it is imaginable that the use of electric vehicles could become much more attractive when assuming major changes of traditional mobility concepts.

Further mobility concepts such as "Personal Rapid Transit" or "Cybernetic Transport" schemes could emerge in the long term in the context of an increasing electrification of road transport [RAWA 2008, EUCO 2009]. Although a detailed discussion of these alternative mobility concepts is beyond the scope of this report.

Considering uncertainties of the vehicle characteristics of forthcoming EVs, future driving and charging behaviours can only be estimated. However, this information is essential for the assessment of the environmental impact of EVs (substitutable mileage, charging pattern etc.):

- The announced pilot projects are valuable sources of data that should be evaluated with regard to driving and charging behaviour and the potential to substitute conventional car trips.
- The rethinking of conventional mobility concepts seems to be of particular usefulness in the context of the deployment of electric vehicles. The further discussion of future perspectives of electric vehicles should comprise the consideration of alternative linkages between vehicle use and other modes of transport.

3.3 Overview of market penetration scenarios for electric vehicles

Until today only grid-independent hybrid electric vehicles have already achieved a relevant market share of new sales in the range of about 1 % in most European countries and up to 2.2 % in the United States [IEA 2008]. The progress in battery technologies and the successful introduction of hybrid electric vehicles have lead to an increased engagement of major OEMs in the development of electrically driven vehicles. The introduction of electric vehicles is further supported by various governmental programs and international efforts to reduce greenhouse gas emissions in the transport sector.

The prediction of the future development and market penetration of electrically driven vehicles includes great uncertainties and depends on a multitude of influencing factors. The electric propulsion system represents an innovative technology that has not yet achieved technological maturity and mass commercialisation, due to remaining technological and economic barriers. Besides the need of further improvement of the battery technology, the commercialisation of electric-vehicles will be particularly influenced by general framework conditions, such as the energy prices, regulatory and other governmental measures, which can be hardly predicted. DEBA [2008] assumes that penetration levels for EVs will depend on the extent to which governments provide incentives for zero-emission vehicles and zero-petroleum vehicles, or the extent to which new business models emerge which eliminate the upfront cost of the battery, and spread this cost into the per mile cost of fuel.

Market penetration and early markets

The range of conceivable market penetration scenarios varies widely among the reviewed studies. While several studies focus on the global market developments for electrically driven vehicles, others differentiate further between different countries and world regions and identify potential lead markets.

The Boston Consulting Group analysis [BOST 2009] of the automotive propulsion market for the four largest automotive markets – Western Europe, North America, Japan, and China – considered 3 scenarios from 2008 to 2020 that applied different oil prices and governmental regulations. Under all scenarios, the internal combustion engine remains the dominant technology in 2020. Cars with alternative propulsion technologies achieve between 12 to 45 % of new car sales – with a maximum share of 16 % electric vehicles. It is estimated that fully electric vehicles are most likely to be introduced in the city car segment, whereas the hybrid electric propulsions systems are mainly applied in larger vehicles. Counted in units, 1.5 million (2.7 % market share) fully electric vehicles and 1.5 million plug-in hybrid electric vehicles are expected to be sold in 2020 in the main markets.

The International Energy Agency analysed the deployment of electric vehicles in three scenarios [IEA 2008a]. The ACT Map scenario is based on cost-efficient and already available technologies; the BLUE Map scenario comprises also future and high-cost technologies that would achieve higher emission reductions (50 % GHG-emission reduction by 2050). Within the ACT Map scenario the market share of sold plug-in hybrid electric vehicles rises to 5 to 10 % by 2030 and 15 to 25 % by 2050 while the electric range increases simultaneously. The BLUE scenario is characterised by a significant decarbonisation of the transport sector, driven by a higher share of PHEV with longer electric driving ranges (20 to 33 % in 2030, 50 to 67 % in 2050) and includes 20 % of fully electric vehicles by 2050. A further BLUE EV success scenario describes an even greater success of electric propulsion systems, resulting in a share of sales of 50 % and 90 % fully electric vehicles in 2030 and 2050, respectively [IEA 2008a].

A revision of the IEA BLUE Map scenario has been carried out recently by an IEA expert group on EV/PHEV. It takes into account the current global economic crisis and assumes therefore relatively low EV sales through 2010 (maximum share of new sales of 0.1 % (EVs) and 0.4 % (PHEVs)). Between 2010 and 2020 an increasing number of electric vehicles is expected, resulting in market shares of up to 3 % (EVs) and 10 % in lead markets by 2020 and average global sale rates of 2.5 % (EVs) and 6.1 % (PHEVs).

The global annual production of EVs and PHEVs is assumed to reach about 31 million light duty vehicles by 2030 and 105 million vehicles by 2050.

BERG [2008] sees a number of OEMs and new market players that successfully provide the first attractive EVs and the necessary infrastructures in key metropolitan areas of the world by 2011. It is expected that plug-in hybrid electric and fully electric vehicles could attain a 10 % global market share of new car sales by 2020, with regional variations depending on the level of governmental and infrastructure support. Europe is considered as one lead market with a market penetration of EVs of up to 25 % in 2020. Other markets with high potentials of early introduction and market penetration of electric vehicles are China, Japan and the United States.

In contrast, the vehicle projections of the California Air Resources Board (CARB) panel are rather pessimistic with regard to the prospects of electrically driven vehicles [CARB 2007]. CARB assumes that PHEV are likely to become available in the near future (within the next 5 to 10 years) and that a rapid growth of plug-in hybrid electric vehicles leads to mass commercialisation (100,000 vehicles/year) within 5 years thereafter. However, mass market production is not expected in the foreseeable future for full electric vehicles, due to the high price premium and limited customer acceptance with regard to range and recharging times. A continuous growth of full electric vehicles is expected that could result in a commercialisation at low production volumes (10,000 vehicles/year) after 2015.

BERR [2008a] discusses three EV penetration scenarios. In a mid-range scenario, it is assumed that 2.5 % of all cars by 2020 and 11.7 % by 2030 are connected to the grid. A high-range scenario concludes with 4.9 % (2020) and 32 % EVs (2030). In an extreme range scenario penetration rates of 10 % in 2020 and 60 % in 2030 are achieved. Besides these hypothetical scenarios, [BERR 2008a] assumes that plug-in hybrid and battery-electric vehicles will reach high volume production by 2014, assuming that a mass market new vehicle product takes between four to six years to develop. An overview of the EV technologies which are likely to be developed over the next 20 years for the global vehicle market according to [BERR 2008a] is given in Figure 9.

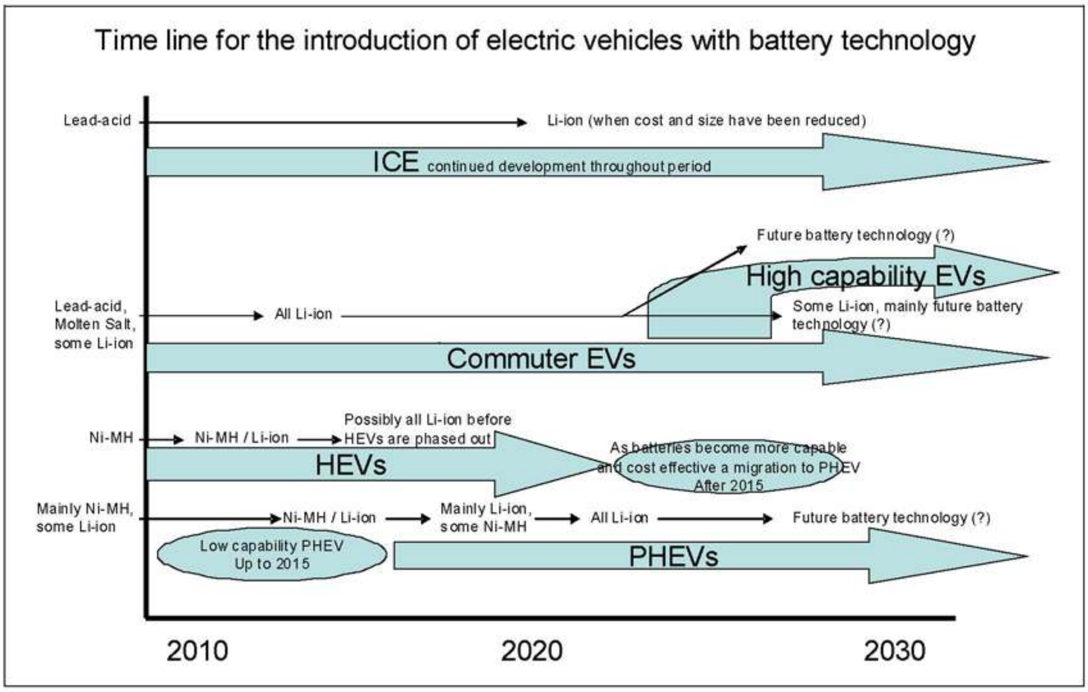

Figure 9: Overview of EV and battery technologies and their potential market introduction (Source: BERR 2008a).

The King Review [KING 2007] expects an increasing penetration and use of hybrid electric and fully electric vehicles after 2030. At long-term, an almost complete decarbonisation of the transport sector, based on electrically driven vehicles, is thought to be possible by 2050.

EPRI [2007] analysed the environmental impacts of three plug-in hybrid electric adoption scenarios which would lead to a new vehicle market share of 20 %, 62 % and 80 %, respectively, in 2050. Eurelectric [AVER 2007] expects that the market share of PHEV will reach 8 to 20 % by 2030 in Europe. The research firm LECG estimates that the number of PHEV could rise to more than 68 million vehicles in 2036, representing about 17 % of the estimated total U.S. cars at that time [TIME 2008]. A recent study of McKinsey [MCKIN 2009] assumes a sale number of 42 million hybrid vehicles (including plug-in vehicles) by 2030 – about 40 % of all new car sales. The latest publication of McKinsey [MCKIN 2009a] considers two potential development paths for the automotive sector that involve the deployment of electric vehicles. The lower penetration scenario (mixed technology) assumes a new vehicle sales share of 1 % and 5 % for electric and plug-in hybrid vehicles in 2020, and 3 % and 16 % in 2030, respectively. In the more ambitious scenario electric and plug-in vehicles attain 2 % and 6 % by 2020 and 8 % and 24 % by 2030. The most optimistic scenario by the French Environmental Agency [ADEM 2007] predicts 80 to 100 % of plug-in hybrid electric and fully electric vehicles by 2050 at a global scale. MIT [2007] assumes that PHEV enter the vehicle market in 2012 and could achieve a 25 % new sales market share by 2050. PriceWaterhouseCoopers estimates that a production volume of about 1.5 million full electric vehicles could be realised by 2020 [PWC 2008].

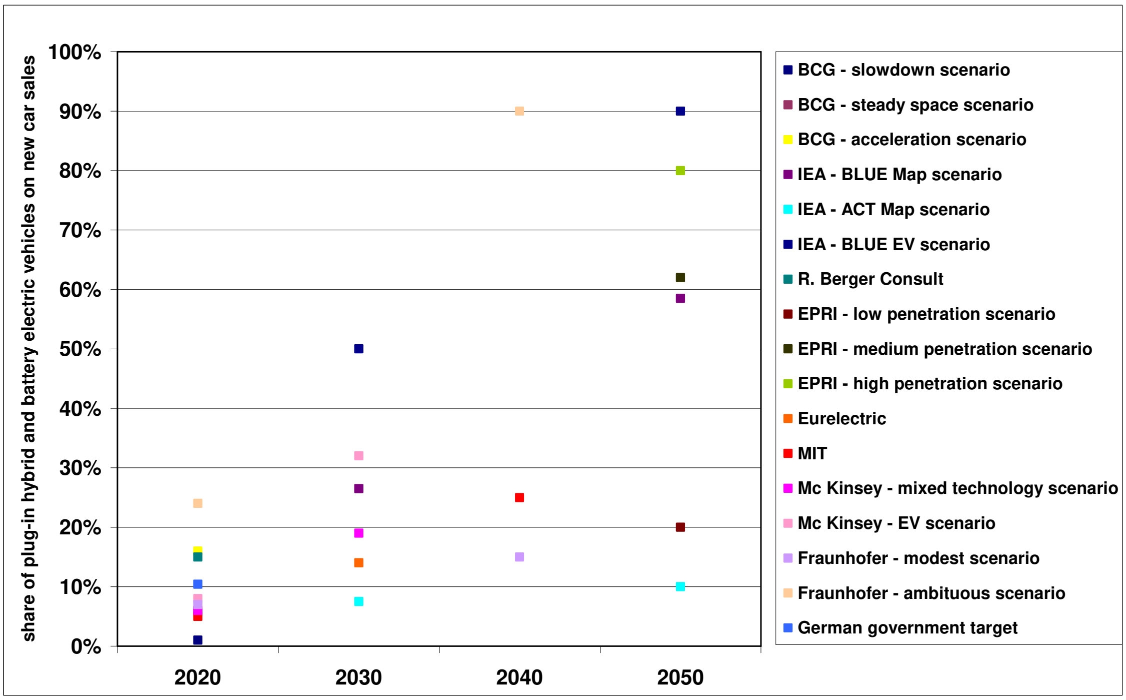

Figure 10: Market penetration scenarios – share of plug-in hybrid and battery electric vehicles on new car sales (literature review).

A recent study by the Fraunhofer Institute of Systems and Innovation Research imagines two roadmaps towards electric powered vehicles in Germany. In the more modest scenario the national amount of PHEVs and EVs rises from a share of less than 0.3 % after 2010 to about 7 % by 2030 and 15 % by 2050. A more ambitious scenario is characterised by an even stronger growth of electric vehicle sales. Here, PHEVs remain dominant until 2030 (24 % of vehicle fleet), then a total market share of about 90 % in 2050 is equally distributed between PHEV and EV due to a strong growth of EV sales after 2030 [WIET 2008]. Another scenario by a German utility company in conjunction with a major OEM projects 1.25 million EV/PHEVs in Germany by 2015 (2.6 % market share) which rises to 15 million vehicles and a market share of about 31 % by 2030.

A forecast of Deutsche Bank Securities Inc. [DEBA 2008] assumes a market share of EVs and PHEVs of 1 % and 2 %, respectively on the US and European market by 2015 and expects a further increase leading to a market share of 2 % (EVs) and 5 % (PHEVs) by 2020 for the US and 3 % (EVs) and 2 % (PHEVs) for the European market.

Recently, several European governments have announced national targets for the deployment of electric vehicles. The German government targets 1 million electric vehicles by 2020 (2.1 % market share) and more than 5 million EVs by 2030 (10.4 %) [BUND 2008]. The Spanish government announced an objective of having 1 million electric and hybrid vehicles operating in Spain by 2014 as part of a set of energy efficiency measures [BOST 2009].

Penetration rate and fleet turnover

With regard to the market penetration scenarios which are cited above, the question arises whether the mentioned steeply growing penetration rates are realistic within the prospected time frame. In this context, it is useful to consider the needed development stages for new vehicle technologies to penetrate the vehicle fleet in large numbers. First, the technologies must become market ready to allow small scale production. Once the new technologies are in production, market penetration increases slowly as it takes time to optimise production scales and to build consumer confidence. Even when the new technology comprises a sizeable fraction of new vehicle sales, the fleet must turn over before this market penetration is reflected in the mix of in-use vehicles. This could take about one decade [MIT 2007]. In vehicle history, the penetration of new powertrain technology took considerable time before the ultimate market shares could be achieved [ARG 2009]. Generally it is assumed, that a new vehicle technology takes 10 to 20 years to comprise 5 % of new sales. However it could be expected, that a faster market penetration could be realised with a combination of competitive technologies and strong policy incentives or governmental regulations. Besides, it has to be considered that for radically new technologies – such as the electric propulsion system – the available historic data on the market penetration of new technologies is only partly applicable as the related magnitude of change in terms of vehicle technology can not rely on corresponding data from recent history.

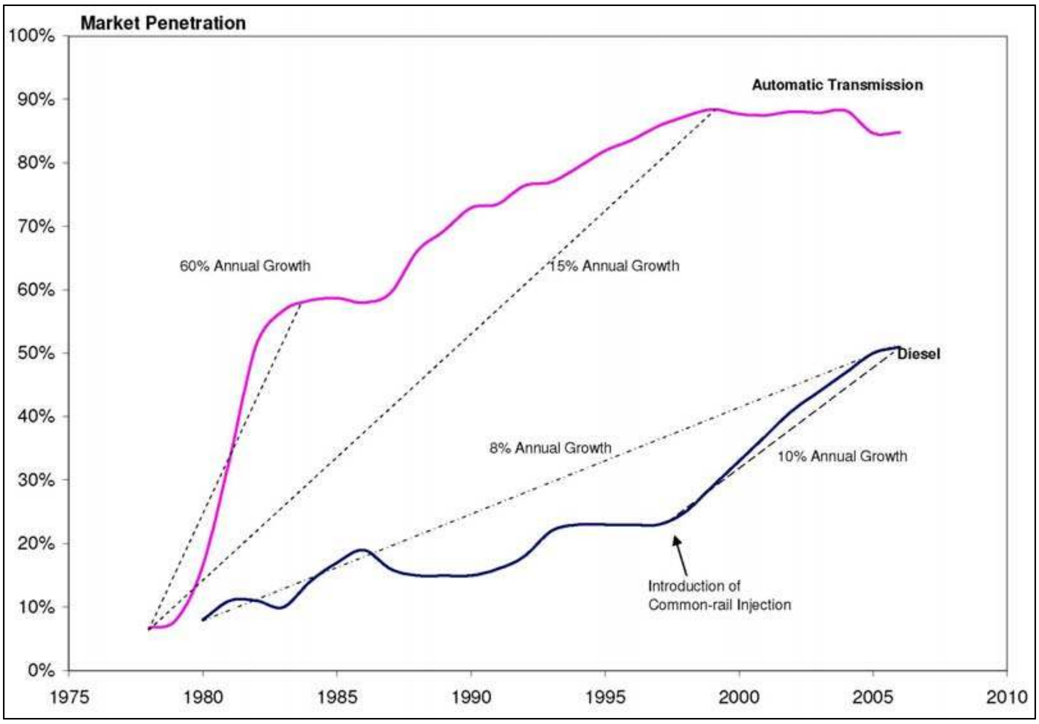

Figure 11: Market penetration rates of different vehicle technologies during the last decades (Source: MIT 2007).

The plausibility analysis of targeted market penetration scenarios carried out by MIT [2007], shows that market penetration rates between 25 and 75 % could be achieved by 2040 at reasonable annual growth rates between 6 to 11 %, if the corresponding technology manages to reach sale rates of 5 % already by 2010/15. For existing hybrid technologies a 5 % sales rate is estimated to be realisable; advanced plug-in hybrid and fully electric vehicles are expected to achieve a 5 % sales share after 2015. A market penetration of 25 % by 2040 would be still in the range of plausible growth rates (8 to 11 % p.a.) if advanced hybrids reach a 5 % share of new car sales in 2025, while higher targeted market penetrations or a further delay of market introduction would require annual growth rates of 12 to 31 %. Long-term growth rates of more than 15 % have not been observed during the last decades for the considered technologies. This illustrates the challenging nature of a corresponding development. In order to achieve high market shares, major changes in the deployment of new automotive technologies would have to occur.

Scepticism with regard to the future potential of electric vehicles

The current re-emergence of electric vehicles in the public debate and the related activities of industry let assume that electric vehicles will become of increasing importance within the transport sector in the coming years.

In contrast to a large number of experts that assume an increasing market penetration of electric vehicles, FRFR [2000] refers to the history of electric vehicle development over the last century and illustrates that electric propulsion technology has been considered several times in history as a very promising technology that could replace combustion engine vehicles and achieve a large market share within the following decades. [FRFR 2000] states that every time such prognosis have been made and first prototypes have been developed, the technology failed after only a short time.

Although the main supporting arguments for electric vehicle use remained over time, such as high efficiency, zero local emissions and a driving range that suites well to a large share of vehicle distance travelled, FRFR [2000] identifies multiple causes that inhibited finally the non-substitution of conventional by electric vehicles.

The considerable price premium – mainly caused by the high costs of the battery – is seen as a major inhibiting factor for the purchase of an electric vehicle. [FRFR 2000] refers to several surveys that identified a maximum price premium of 15 % that would be accepted by consumers. Further, he argues that the purchase of a vehicle is not determined by the average use characteristics, but by exceptional usages. Therefore, statistics on driving behaviour should be treated with caution, when drawing conclusion on the market potential of electric vehicles. With regard to the automobile and maintenance industry, FRFR [2000] explains the rather low investments and activities in the field of electric propulsion technology with the major economic importance of combustion engines for these industries. In contrast electric propulsion technology could reduce the benefits and could lower the need of car maintenance.

Further barriers, mentioned by FRFR [2000] are the lack of a corresponding charging infrastructure and the general challenge of a new technology to enter a market that is mainly dominated by a single technology, such as the transport sector by the internal combustion engine technology.

According to [FRFR 2000] important factors that could inhibit a new failure of electric vehicles would be a major improvement of battery technology, a modified perception of electric propulsion technology, the integration of electric vehicles in new mobility concepts and a stronger focus on the complementarity of electric vehicle use than on the intention of a complete substitution of conventional vehicles, the establishment of the infrastructure needed and strong public support.

SUMMARY: MARKET PENETRATION SCENARIOS FOR EVs

Results from literature

- Although electric vehicles have not yet achieved mass commercialisation, it is widely assumed that electrically driven vehicles could achieve considerable market penetration in the future.
- Due to a multitude of influencing factors and remaining barriers, estimations on the future development and deployment of electric vehicles come with great uncertainties. Therefore, conceivable pathways are illustrated in various penetration scenarios that reflect different framework conditions.
- Optimistic scenarios: assumption of an early market introduction of EVs and PHEVs leads to a share of new sales of 20 % in 2020, up to 50 % in 2030 and more than 80 % in 2050.
- Moderate scenarios: delayed market introduction, sales share of 5 to 30 % in 2030 and around 60 % in 2050.
- Pessimistic scenarios: market introduction not before 2015, sales share of 5 to 10 % in 2030 and not more than 25 % in 2050.
- Potential lead markets: United States, Europe and Asia – with particular focus on China.
- An analysis of penetration rates of earlier innovative technologies in road transport suggests that a global fleet penetration of electric vehicles of more than 25 % by 2050 could hardly be achieved under moderate growth assumptions.
- A higher market share would imply annual sales growth rates of electric vehicles exceeding typical penetration rates that have been historically observed with new automotive technologies.
- However, since the electric propulsion system represents a radically new vehicle concept, historic data may be of limited applicability; higher growth rates could be imagined – in particular when assuming strong policy incentives and public support with regard to the deployment of electric vehicles.
- Regarding the history of electric vehicle development it can be stated that the electric propulsion technology has been already considered several times as the most

promising technology for vehicle propulsion, but has every time failed to achieve a significant market penetration.

Discussion and recommendations

The illustrated market penetration scenarios are no prognosis. Due to considerable uncertainty that is related to the technological development and future consumer behaviour, a large range of potential pathways reflects the difficulty of reliable predictions from today's perspective. Electric vehicle propulsion represents a radical new technology within road transport that is highly dominated by internal combustion engine technology. Therefore it is difficult also to draw conclusions from historic data concerning technological diffusion rates to determine the future market penetration potential of electric vehicles.

With regard to the history of electric vehicle development it must be stated that the shortly occurring breakthrough of electric propulsion has been predicted already several times within the last decades. However, with regard to the major improvement of battery technology and increasing public support at different levels, it seems likely that the currently increasing activities will result in a more sustainable success of electric propulsion technology within the transport sector and will achieve a relevant market share at the long term.

Based on information from the announced pilot projects, more reliable market penetration scenarios taking into account the acceptance of EVs and their use patterns can be developed.

3.4 Policy issues

In contrast to incremental innovations which are characterised by the continuous improvements of existing products, the development of the electric propulsion system represents a radical innovation, as it leads to a significant departure from previous technological concepts and production methods [STER 2006].

The electric propulsion system is confronted to a couple of persisting barriers that inhibit a larger market penetration at the current conditions. Several shortcomings of the technology, presented in this study exemplify the immature status of a developing technology that has not achieved commercialisation yet. Other barriers are a fragmented infrastructure, missing standards and regulations and remaining scepticism of consumers towards an emerging technology. Thus, further measures would be needed to enable the successful market introduction of electric propulsion technology.

The following section provides an overview of possible policies that tend to stimulate the development and deployment of electrically driven vehicles. Furthermore, an overview of policies that are already implemented or announced on the regional, national or international level is given.

The innovation process

Innovation is more than only invention, but a process over time that involves generating new technological possibilities, their initial successful market commercialisation, and subsequent widespread market diffusion [ETEC 2007]. The success relies on the coming together of a variety of players, including suppliers, customers, universities, research and technology organisations and other intermediaries. This process of innovation can be influenced by governments, investors, academia and business [KING 2008]. The innovation process stages are basic and applied R&D, followed by demonstration programmes of early prototypes. The pre-commercial level is intended to capture a fairly broad stage of research and development and includes the focus on technology niche markets. The supported commercialisation period is followed by the completely unsupported competition of the commercial technologies within the broader regulatory framework [ETEC 2007]. In contrast to this idealised theoretical innovation process, several barriers are likely to occur along the innovation chain that finally could delay or even inhibit the commercialisation of new technologies. As mentioned in [ETEC 2007], in addition to the potential lack of market demand, there may be systems failure in innovation systems which prevents technologies successfully moving along the chain

Barriers for innovative technologies

While it is generally assumed that the private sector is best placed to make judgements on the appropriate level of investments in R&D due to their understanding of the relevant market, in particular with regard to early stage technologies private R&D investments are characterised by a number of barriers. In case of a high uncertainty related to the future demand and adoption of the new technology by consumers, uncertainty about the future policy environment or infrastructure development, private investment is more unlikely due to the inherent risk. With regard to new technologies, such as alternative propulsion systems, the necessary infrastructure requirements may constitute a further barrier for private sector engagement as long as the question of supporting infrastructure remains unsolved. A main challenge with regard to technology development and R&D investment represents the gap between the long-term benefits of many technological breakthroughs and the shorter-term returns on investments which are expected in the private sector [KING 2008]. Therefore, private investments more likely concentrate on the least-cost short-term opportunities, despite the possibility that higher cost technologies may deliver return on investments in the long term [STER 2006]. The fact, that information is a public good may further limit innovation processes in the private sector. In general, the individual company which has created new information can not capture the full economic benefit of its investment in innovation due to knowledge externalities (or spillovers). While an adapted intellectually property regime could act as an incentive to the innovator, the granting of a certain property right could also slow the dissemination of technological progress [STER 2006].

In the context of the development of low carbon alternatives the so-called technology “lock-in” is a phenomenon which hampers their market introduction due to an already existing technology which dominates the relevant sector. In this case, the dominant technology (e.g. the internal combustion engine) improves over time, reaches economies of scales, benefits form societal preferences, subsidies and incentives. As a consequence, the technology position is reinforced and subsequent alternatives have difficulties to enter the market as they compete with a mature technology, their optimised supply chains and infrastructures [KING 2008, WWF 2008]. These factors may have locked-in the hydrocarbon mobility systems. The development of low carbon transport requires both the development of vehicle technologies and new infrastructures, but also innovation in the institutional framework of rules, regulations, skills and behaviours which support them [ETEC 2007].

Low carbon technologies are characterised by a smaller market pull based on limited consumer demand. Therefore innovation systems for low carbon technologies have often included a higher degree of intervention from governments, which may also be required for the deployment of the electric mobility technologies [ETEC 2007].

Policy categories and fields of action

In the reviewed literature a wide range of policies is discussed which illustrates potential fields of action for governmental engagement.

<u>Monetary incentives</u>

Electric vehicles are characterised by a considerable price premium which represents a major economic barrier for market introduction. However, as long as production volumes do not increase it remains difficult to achieve cost reductions. To break this vicious circle, monetary incentives are one option to lower the original price premium and to increase the attractiveness of electric vehicle purchases. Governmental monetary incentives comprise direct subsidies and fiscal measures such as tax incentives. Tax incentives could be realised by reduced purchase, circulation or fuel taxes for electric vehicles or potentially by the use of CO_2-emissions as the standard tax base.

The public (financial) support of the private sector for R&D, demonstration projects and early stage commercialisation investments could further foster the deployment of electric vehicles [STER 2006]. Public procurement policies can play a major role for early markets as long as the electric propulsion systems are not able to compete with the dominating established technology. Public sector organisations could establish a first market for electric vehicles with procurement policies for public fleets. Additionally, the private sector procurement could be encouraged to consider electric vehicles within their fleets through incentives. Dedicated procurement targets could provide investment certainty for manufacturers that otherwise may hesitate to invest in production capacity for new automotive technologies. Economies of scale could be achieved more quickly [WWF 2008].

Other incentives that focus on the usage of the vehicle, in particular in urban areas, are the exemption of EVs from road tolls, congestion charges and reduced parking fees [IEA 2008, EURE 2008].

<u>Non-monetary incentives</u>

Besides monetary incentives which increase the economic competitiveness of electric vehicles, an increased attractiveness could be achieved by non-monetary incentives.

Possible measures under discussion are reserved parking lots with plugs for vehicle charging, the allowance to use taxi and bus lanes and entry rules for certain areas which favour low-emission vehicles [IEA 2008, EURE 2008].

Regulation

Regulative approaches represent a viable instrument to stimulate the development and deployment of EVs. As stated in IEA [2008a], the barriers to new technology deployment are not always economic and it is therefore assumed, that carefully designed regulations and standards may be the most effective policy measures.

The establishment of directives for stringent emission levels for new vehicles reward the production and demand of low-emission and low carbon vehicles. They are considered as an essential element to accelerate the market introduction of low-emission vehicles. Any policy framework and its time frame should be clearly defined and predictable in order to give all stakeholders planning security to reduce the risks for investments. Policy target schemes may also be introduced with a focus on specific technologies, besides regulative approaches that target the entire vehicle fleet with the introduction of specific standards. Targeted policy schemes can foster expensive technologies that are associated with high investment risks, if they promise large benefits in the future. Fixed target schemes for new technologies have lead to an increased investment and development in other examples. Vehicles mandates are discussed and already partly implemented in selected countries to promote the market introduction of low-emission technologies.

Infrastructure

As already discussed before, infrastructure aspects are of particular importance for the deployment of electric vehicles. A dense network of charging or/and battery exchange stations is a prerequisite for a successful market penetration and the reliable operation of EVs, but comes with large investment costs. Early governmental coordination and financial support is needed to compensate the fairly long lead time and the uncertainties associated with the prospects of electrically driven vehicles.

Standardisation

Today's road transport is nearly exclusively based on hydrocarbons and internal combustion engines and all relevant standards and regulations are configured accordingly. Standards and regulations may need to be adapted to the different nature of the electric propulsion system. The implementation of standards is essential for the successful development and deployment of electric vehicles as it provides a framework for vehicle and infrastructure building and aims to assure the compatibility of infrastructure and vehicles.

Fuel economy or CO_2 emissions standards are an effective way of overcoming the aversion to investing in fuel economy that stems form the inherent instability of oil prices [GLOB 2009]. Today, the Unites States, the European Union and Japan dispose of such standards, while China is the only non-OECD county that has introduced comparable regulations. In order to further improve vehicle efficiency, it will be important to renew and tighten such standards over time [GLOB 2009].

Existing fuel consumption test cycles are designed for conventional internal combustion vehicles. The standardised determination of the energy efficiency of EVs as well as of PHEV, requires the adaptation of test cycles that recognises the energy consumption under different driving conditions. The reporting procedures have to consider that PHEVs employ two different primary energy sources in two distinct driving modes. Standard methodologies for estimating the relation of gasoline-fuelled and electric driven kilometres have to be established [NREL 2006, MIT 2007].

Due to the fact, that electric vehicles rely on an energy carrier which can show widely varying CO_2 emissions with regard to its supply, an adequate standard has to be established which is able to account for the well-to-wheel emissions and which allows a comparison with conventional vehicle’s emissions. An emission accounting which is limited to the tank-to-wheel emissions would neglect the fact that electric vehicles generate emissions during energy production, while the emissions generated by conventional vehicles are mainly produced by the internal combustion process during driving.

Furthermore, safety standards have to be adapted to the electric propulsion system including the large traction battery.

The charging infrastructure requires an early standardisation for example regarding plug types, recharging protocols and regulations for public recharging to assure the compatibility of different vehicle concepts and charging station providers. The vehicle to grid connection requires further standardisation to simplify the charging and accounting from different energy suppliers.

Existing end of life vehicles regulations do not explicitly take the specifics of electric propulsion systems into account. New recycling and disposal standards have to be established that guarantee an economically and environmentally friendly recycling or disposal of vehicle components, in particular the large battery systems.

Planning and licensing regulations are of considerable importance to promote the set up of the energy distribution infrastructures. Planning regulations may significantly increase costs or, in some cases, prevent investments taking place [STER 2006]. Therefore, global or national concerns have to be traded off against local concerns. In particular at an early stage of market introduction, lower planning and licensing restrictions could reduce the barriers for investment.

International collaboration

Today’s vehicle and energy market is dominated by international networks. International collaboration seems important to abate climate change and to develop energy-efficient technologies. The development and deployment of electric vehicles could benefit from international collaboration at different levels. Common research topics such as the availability of raw materials, the development of battery technologies and their recycling could be addressed by international collaboration. Those would in the long run accelerate technological breakthroughs. Sharing best practices could help to optimise policies and avoid repeating mistakes on the national level.

As already mentioned, standardisation is needed for the charging infrastructure, the vehicle to grid connection, safety standards and test cycles. Those too should be addressed at the global or at least continental level.

The international alignment of fuel economy testing, tax incentives and labelling systems could provide increasingly global markets with consistent signals for product development and marketing [GLOB 2009]. Furthermore, international standards would reduce the uncertainty for car producers and energy providers and could lead to higher investments and an accelerated market penetration of electric vehicles.

Consumer behaviour

The increasing environmental awareness in societies has not yet resulted in a large share of highly efficient vehicles, including energy efficient conventional vehicles, hybrid-electric and full electric vehicles. A lack of confidence in electric powered vehicles can still be observed due to battery problems of the past [IEA 2008]. The image of electric vehicles is still dominated by the idea of a low performing and unsound technology or in contrast, considered as gadgets such as futuristic concept cars that are far from commercialization [GRLP 2008]. The vehicle purchase behaviour and mobility expectations are mainly determined by the characteristics of internal combustion engines, which have dominated the road transport sector over the last century. Since the electric propulsion systems represent a new technology with considerably different driving characteristics, the successful market entry of EVs is highly dependent on the perception by consumers. In this context, governmental information programmes could help to heighten the public awareness and sensitivity to environmental issues and to promote the purchase of low-emission vehicles [IEA 2008]. [IEA 2008a] requires that government need to give a lead to public opinion, making the connection between the urgent need of lowering GHG-emissions and specific actions required, such as the deployment of low-carbon vehicles.

Overview of initiatives / policies in different countries

National initiatives to accelerate the development and deployment of electrically-driven vehicles have been started in the 1990s in Europe and the United States. As a consequence of the re-emergence of the electric propulsion technology during the last years, new governmental policies and public activities have been launched or are announced for the near future at the local, national and international level. The following discussion gives a sample of major activities which are related to the deployment of electric vehicles in different countries.

Austria

In Austria the fuel consumption tax is CO_2 based. As a result alternative fuelled vehicles attract a € 500 bonus whereas cars emitting more than 180 g/km pay a penalty of € 25 for each gram emitted in excess of 180 g/km (160 g/km as from 1st January 2010) [ACEA 2009]. Some electro mobility pilot projects include access to the so called “mobility card”, car leasing and maintenance and free charging for individuals using these cars [KLFO 2008].

The “e-connected” initative (www.e-connected) is a project funded by the Climate and Energy Fund of the Ministry of Transport, Innovation and Technology and aims to link different stakeholders and to provide information on ongoing projects and initiatives in the context of e-mobility. E-connected comprises several expert panels with representatives from research institutes, industry and NGOs in order to identify and eliminate obstacles to facilitate the deployment of EVs in Austria [LUG 2009].

Belgium

Tax incentives are granted to private persons purchasing a “green” car. Cars emitting less than 105 g/km get a reduction of 15 % of the purchase price up to a maximum of € 4,540 and cars emitting between 105 and 115 g/km receive 3 % of the purchase price up to a maximum of € 850.

In the Walloon Region a bonus-malus system is in placed paying up to € 1,000 for cars below 105 g/km and charging a penalty of up to € 1,000 for cars emitting more than 195 g/km [ACEA 2009]. Furthermore the Transport Minister in Wallonia made available € 2 million for municipalities that plan to buy electric vehicles (cars, cycles, vans).

Cyprus

In Cyprus the rates of the registration tax and the rates of the annual circulation tax are CO_2 based. For cars emitting less than 120 g/km there is a 30 % reduction in registration tax. Also the annual circulation tax gets reduced by 15 % for cars emitting less than 150 g/km. Furthermore, there is a discount of € 683 for purchases of new electric cars [ACEA 2009].

Denmark

The Danish Government has released a National Energy Plan onwards 2025 where clean cars are freed of all taxes. Considering the particularly high car registration tax of 180 % and a VAT of 25 %, the announced tax exemption represents a considerable subsidy for EVs [AVER 2007].

Electric cars in Denmark qualify for free parking [BERR 2008a].

The Danish energy corporation DONG and the American company Better Place are planning to invest € 100 million ($ 135 million) to build up infrastructure in the country for electric cars. The idea is to make it just as fast to charge up a battery as it is to fill up a tank of gas and to grow the numbers of electric cars up to 100,000 within two years [DEWE 2009, XU 2009]. The EDISON R&D project on intelligent integration of EVs and their optimal interaction with wind power is carried out by an international consortium and comprises a budget of 5.6 million €. A 4 millon € EV fleet trial programm is funded by the Danish Energy Authorities [XU 2009].

France

With regard to the average CO_2-emissions of passenger cars, the French Government recently set up a yearly eco-label [CLBZ 2006] on new vehicles with an auto-financed bonus-malus system which favours low-emission vehicles. The national bonus/malus scheme sets tax deductions (bonus) and tax penalties (malus) at the purchase of new vehicles on the basis of their tank-to-wheel CO_2 emissions. The scheme applies to cars new cars sold on the French market since January 2008. Since 2009, the scheme sets a new bonus of € 5,000 bonus for new cars and now new light commercial vehicles emitting less than 60 g CO2/km (covering hence full electric vehicles). It will be applicable till 2012 for the first 100 000 low carbon vehicles purchased [PDLR 2009, CHAT 2009].

France's progressive company car tax is based on CO_2 emissions. Tax rates vary from € 2 for each gram emitted for cars emitting 100g/ km or less to € 19 for each gram emitted for cars emitting more than 250 g/km [ACEA 2009].

Furthermore, the France government promised to dedicate € 400 million for R&D and demonstration projects over 2008-2012 on low carbon vehicles. This budget covers many R&D and demonstration activities for the development of vehicles and charging infrastructure [ENER 2008, CHAT 2009]. Part of this budget (57 million €) was recently attributed for 11 projects; another call is about to be launch and will be followed by another set of funded projects for an additional 50 million € [MESR 2009]. The research on electric vehicle technology is funded by 90 million €. Two national research platforms on the development of battery technology and electric and hybrid vehicles will be financed by an interministerial fund [CHAT 2009].

In February 2009 a specific working group was installed by the government in order to coordinate installation of a standardised national charging network for plug-in hybrid electric vehicles and battery powered EVs [CARN 2009, CHAT 2009]. The strategy already foresees the following provisions: local governments will be empowered to set up public charging infrastructure; a quota of parking areas in work places and shopping areas will have to be set for electric vehicles and charging spots; builders of collective residences will be obliged to set up charging facilities at parking places upon request of inhabitants; local governments will be obliged to equip public parking areas with charging facilities [CHAT 2009]. Free parking spaces for EVs (equipped with charging apparatus) are also being reviewed [BERR 2008a].

A 2008 public procurement programme includes a mass ordering of 5,000 hybrid and fully-electric vehicles [AVER 2007]. The French government plans to set-up a public-private procurement plan that coordinates the demand of electric vehicles for public and private vehicle fleets. In this context, the French post plans to procure 10,000 electric vehicles by 2012 [CHAT 2008].

Germany

The German Government announced at the “Nationale Strategiekonferenz Elektromobilität” in November 2008 in Berlin a national target of 1 million electric vehicles by 2020 and 5 million electric vehicles by [BUND 2008].

As part of a national economic stimulus package, a 500 million € programme has been set up to accelerate the development and deployment of electric vehicles within the next years. The money is dedicated to several pilot projects and to major German manufacturers of cars and battery systems as well as to utilities and scientific institutes to do the accompanying research [WWF 2009]. It covers research and development of battery technologies and electric vehicles, as well as the financial support of several demonstration projects with electric vehicles that will be launched in 2009 in several German cities. As part of these projects first tests with small electric vehicle fleets will be conducted by BMW and Daimler together with energy suppliers like Vattenfall and RWE [FOCUS 2008, TAGS 2009]. By the end of the year RWE and Daimler plan to install 500 charging stations in Berlin [TAGS 2009].

The lithium ion battery research programme (LIB 2015) is funded by the German government with 60 million € between 2008 and 2015 and complemented by further investments of 360 million € by an industy consortium [BMU 2009, BMBF 2009]

From July 2009 a new vehicle tax system will be implemented. The annual car tax will consist of a base tax and a CO_2 tax. The CO_2 tax will be linear at € 2 per g CO_2 per km. Cars with CO_2 emissions below 120 g//km will be exempt from taxation [ACEA 2009] as well as EVs in the first five years after purchase [COIN 2009, TAGE 2009].

In terms of infrastructure and industry standards, some of the major energy and automotive companies announced the development of a common plug standard in March 2009. The plug has a capacity of 400 voltage and 63 ampere, can be applied European wide and was presented at Hannover trade fare end of April [WELT 2009].

<u>Greece</u>

In Greece electric and hybrid cars are exempted from the special consumption tax and from the yearly circulation taxes. Furthermore they are excluded from circulation restriction in metroploitain areas, where these are applied. [HIEV 2009]

<u>Ireland</u>

By 2020 the Irish government aims for 10 % of the national fleet (250,000 cars and vans) to be electric, with the first significant number shall hit the road within the next two years. It has signed a deal with Renault-Nissan accordingly. The Government hopes that by boosting renewable energies, like wind, and improving the electricity grid, the introduction of electric cars will lead to a significant drop in carbon emissions in the transport sector (RTÉ 2009).

The registration tax is based on CO_2 emissions. Rates vary from 14 % of the purchase price for cars with CO_2 emissions of up to 120 g/km to 36 % for cars with CO_2 emissions above 225 g/km. Hybrid and flexible fuel vehicles benefit from a tax relief of maximum of € 2,500 [ACEA 2009]. EVs are exempt from vehicle registration tax until December 31st 2010 [BERR 2008a]. The annual circulation tax is also based on CO_2 emissions. Rates vary from € 104 (up to 120 g/km) to € 2,100 (above 225 g/km) [ACEA 2009].

<u>Norway</u>

Electric cars are exempted from registration tax, VAT and annual car tax [MAYO 2009]. Furthermore drivers of electric cars are allowed to use bus-lanes. Also they are exempted from congestion charges and parking fees on public parking places. Norway planes to enable the free use of ferryboats, connecting national roads by 2009 [OEN 2009].

Portugal

Electric cars and other alternative energy propulsion systems are planned to be exempt from circulation and registration tax [DOMB 2008, IMPO 2007]. Furthermore, people buying a new car emitting less than 140 g CO/km receive a bonus of up to € 1,000 [ACEA 2009]. Portugal plans to have 320 charging stations by 2010 and 1,300 by 2011 [GCC 2008].

Sweden

Electric and hybrid cars are covered by a green car rebate which allocates SEK 10,000 to individuals who buy a new green car [SWE 2007]. Furthermore the taxation system is CO_2 based. The annual circulation tax consists of a SEK 360 base rate plus SEK 15 for each gram CO_2 emitted above 100 g/km. This sum is multiplied by 3.15 for diesel cars bought in 2008 or later or by 3.3 for other diesel cars. For alternative fuel vehicles, the tax is SEK 10 per gram emitted above 100g/km [ACEA 2009].

The Stockholm congestion charge exempts hybrid and electric vehicles [ABERN 2006].

Spain

The government is committed to have one million electric or hybrid cars on the Spanish roads by 2014 [BUGR 2008]. One measure to achieve this goal is to provide consumers who buy an electric car in Spain with a rebate of 15 % of the price of the vehicle [BERR 2008a].

Additionally the registration tax is based on CO_2 emissions and all cars with emissions below 120 CO_2 g/km are exempted from such a charge. Cars with between 121 and 161 CO_2 g/km benefit from a reduced tax of 4.75 %, while those with between 161 and 200 CO_2 g/km pay 9.75 %. Vehicles with more than 201 CO_2 g/km must pay a registration tax of 14.75%. [ETAP 2009]. A pilot project to introduce 2000 electric cars and install 500 recharging points in 2009 and 2010 (called MOVELE) has already started by the IDAE (Institute for Energy's Diversification and Saving, belongs to Ministry of Industry) [IDAE 2009a].

United Kingdom

The British government outlined its ambition to be a world low carbon transport leader in its *Ultra-Low Carbon Vehicles in the UK: The Challenge*. There the UK announces a £ 400 million commitment to encourage development and support of ultra-low-emission vehicles [BERR 2009b]. As part of this effort a demonstration project with 100 electric vehicles will be launched in several UK towns and cities to gather first practical experiences with electrically driven cars. The demonstration project is funded with £ 10 million by the British government. At the same time, up to £ 20 million has been dedicated to UK research into improving electric vehicle technologies and the infrastructure needed. These activities will be coordinated by the Government-funded Technology Strategy Board [DFT 2008, BERR 2009b].

Furthermore, the British government announced a commitment to promote electric vehicles, to facilitate the roll-out of charging infrastructure through the planning system and to collaborate with other countries in the development of international standards and [DFT 2008].A £ 20 million procurement programme supports the demonstration and use of low carbon vehicles in the public sector with the aim to encourage the mass production of electric vans [DFT 2008].

The British government unveiled the plan of an electric car incentive program. Motorists will be offered subsidies of £ 2,000 to £ 5,000 encourage them to buy electric or plug-in hybrid cars. The program is planned to start in 2011 and is part of the government's € 250 million plan to promote low carbon transport over the next five years [BBC 2009, DFT 2009, BERR 2009b].

The UK tax system for vehicles is based on CO_2 and is in favour of cars emitting less than 100 g/km. The annual circulation for example is £0 for cars below this value but can augment up to £ 400 for cars emitting more than 225 g/km [ACEA 2009].

With regard to the local level, the London congestion charge requires car drivers to pay £ 8 for each day they travel in central London. 'Alternatively fueled' vehicles, including electric vehicles, are exempt from paying the charge. Foreseeable revisions of the scheme likely increase the charges for high emission vehicles [KING 2008, WWF 2008]. Also London Mayor Boris Johnson advocates electric cars and said he wants to make the city the European capital for electric vehicles by delivering 25,000 charging points in London's workplaces, retail outlets, streets, in public and station car parks by 2015. The estimated cost of this program is €60 million [EDIE 2009].The company car tax scheme provides financial incentives for employers and company car drivers that choose a low carbon vehicle [ETEC 2007]. In the London Borough of Richmond and in Manchester, the costs of parking permits are related to the vehicle's emission level. Electric vehicles are exempted from parking fees [KING 2008].

<u>European Union</u>

The European Green Cars initiative is one of the three private and public partnerships (PPP) included in the Commission's recovery package. Several coordinated calls for research proposals should be launched in July 2009. It includes three streams of action: 1) R&D, mainly through FP7 grants for research on greening road transport (budget: € 1 billion, of which € 500 million from the Commission, matched by € 500 million from industry and Member States); 2) Support to industrial innovation through EIB loans (budget: € 4 billion in addition to existing loans); 3) Demand side measures & public procurement, such as reduction of circulation and registration taxes for low-CO2 cars. Under the Green Cars Initiative, the research topics notably target research on electric and hybrid vehicles, including research on high density batteries; electric engines and smart electricity grids and their interfaces with vehicles [EUCO 2009b, EURO 2009, COM 2009].

Furthermore, the European Commission supports projects on urban mobility which include demonstration of all-electric transport systems in urban settings [EURO 2009].

The Strategic Energy Technology (SET) Plan of the European Commission aims to establish a new energy research agenda for Europe with a main focus on the accelerated development and deployment of low carbon technologies. This plan comprises a better use of and increases in financial and human resources within low-carbon technology research and development [EURO 2007].

In the recently published Second Strategic Energy Review of the Commission, a vision of the future energy system is given, including the decarbonisation of the European energy supply as well as an ending oil dependence of the transport sector [EURO 2009a].

United States (California)

In 1990, the California Air Resources Board (CARB) introduced a zero-emission vehicle (ZEV) mandate as part of the Low Emission Vehicle Program [CARB 2008, ITS 2004]. Its main motivation has been to enable the large scale introduction of ZEVs. The ZEV-mandate initially required that 10 % of new cars sold in California to be zero-emissions vehicles by 2003. The time of introduction has been abandoned when it became apparent that the technology was not mature enough to compete in the market [MIT 2007]. However, the ZEV mandate approach has enjoyed some success in the past and finally led to the development and the low-scale deployment of several fully-electric vehicles [WWF 2008]. Today, the Californian Government requires car manufacturers to introduce zero-emission vehicles by 2014, independent of their fleet emission levels within the zero-emission mandate. However the number of required pure-ZEVs has been dramatically reduced compared to earlier regulations [UCS 2008]. It is assumed that further states of the U.S. will adopt corresponding regulations in the near term [BERG 2008].

Governmental efforts focus on the support of public-private partnerships between US OEMs, government agencies, national laboratories, and developers of low-carbon technologies. A first programme started in 1993 (Partnership for Next Generation Vehicles) which has been replaced by the Freedom CAR program in 2002 [MIT 2007].

The US Energy Act of 2006 offers federal tax credits for low-emission vehicles [MIT 2007, ABERN 2006]. Several state governments give further state tax credits. President Barack Obama recently unveiled a plan to give a 7,500 dollar tax credit to people who buy plug-in hybrid vehicles [WBCSD 2009]. Some state and local governments provide reduced parking, registration and toll fees or exempt low-carbon vehicles from emissions testing. The States of California and Virgina offer access to high-occupancy lanes regardless of the number of passengers [ABERN 2006]. Further state and local policies are encouraging the use and development of plug-in hybrid vehicles [EPA 2009].

US federal fleets are required to select the most fuel-efficient vehicles. Several states also mandate the purchase of hybrid vehicles [ABERN 2006].

The United States Department of Energy released a $ 2.5 billion programme for the development of electric-powered cars and the improvement of battery technology. As part of the economic stimulus programme enacted by the U.S. Congress, another $ 2 billion programme for battery development has recently been set-up [TNYT 2009, WBCSD 2009, FAST 2009].

The Rocky Mountain Institute (RMI) recently launched "Project Get Ready" (www.projectgetready.com) that is intended to help communities prepare for electric vehicles [GREEN 2009]. The "Project Get Ready" website offers a "menu" of suggested strategic actions for city and regional leaders based on input from technical advisers and cities already engaged in implementing plug-in and electric vehicles. This platform offers a database of all national activities and provides a benchmark for communities to prove that they are ready for mass adoption of electric vehicles. RMI plans to convene at least 20 cities to discuss lessons learned and best practices. A further goal is to document the progress of involved projects in order to help quantify the future potential of electric vehicles [GREEN 2009, RMI 2009]. At the moment, 6 cities in the US and Canada are member of "Project Get Ready".

Japan

Tax incentives for fuel efficient vehicles were introduced in 2001 and have led to an accelerated penetration of fuel efficient vehicles that fulfilled the 2010 fuel efficiency standards already in 2004 [GLOB 2009]. Tax credits of up to $ 3,500 have been available to hybrid buyers, but are now being phased out [ABERN 2006].

Japan remains the world leader with regard to the research and development of battery technologies showing the highest R&D budget for the development of lithium-ion batteries.

China

Individual Chinese municipalities ban gasoline two-wheelers from the city-centres. BERG [2008] assumes that conventional passenger cars could also be banned from the inner city as soon as electric vehicles become widely available.

Recently, the Chinese Government announced plans to turn the county into one of the leading producers of electric vehicles within three years. Government research subsidies for electric car designs have already increased significantly. An interagency panel is planning tax credits for the purchase of alternative energy vehicles. Today, subsidies of up to $8,800 are already offered to taxi fleets and local government agencies that purchase electric vehicles. Further, the state electricity grid started the set up of electric charging stations in Beijing, Shanghai and Tianjin [TNYT 2009].

Israel

Israel will start the large-scale introduction of electric vehicles in collaboration with Better Place in 2011/2012. As a fiscal measure to stimulate the purchase of EVs, the Israeli Government reduces the purchase tax for electrically driven vehicles from 79 % to 10 % until 2014, and to 30 % after 2019. Until 2012, about 500,000 charging and several battery exchange stations are planned to be established all over the country. At the long-term an annual purchase of 30,000 vehicles is expected [SYRO 2008].

Table 10: Selection of international initiatives and policies to stimulate the development and deployment of electric vehicles.

Country / Location	**Policy categories/ Fields of action**	**Examples for policies and initiatives**	**Status**	**Source**
Austria	Monetary incentives	Fuel consumption tax is CO2 based: alternative fuelled vehicles attract a € 500 bonus	In place	ACEA 2009
		Some pilot projects include access to "mobility card", car leasing and maintenance and free charging	Pilot projects	KLFO 2008
Belgium	Monetary incentives	15 % reduction of purchase price up to € 4,540	In place	ACEA 2009
		Wallonia: up to € 1,000 bonus (cars < 105 g/km), up to € 1,000 penalty (cars > 195 g/km)		ACEA 2009
	Public Procurement	Wallonia: 2 million € to buy electric vehicles like cars, cycles, vans	In place	-
Cyprus	Monetary incentives	30 % reduction in registration tax for cars less than 120 g/km	In place	ACEA 2009
		15 % reduction in annual circulation tax for cars less than 150 g/km	In place	ACEA 2009
		Premium of € 683 for purchase of new electric cars	In place	ACEA 2009
Denmark	Monetary incentives	Clean cars free of all taxes	Planned	AVER 2007
		Electric cars qualify for free parking	In place	BERR 2008a
	Infrastructure	Cooperation between Danish Energy Cooperation DONG and Better Place, investment of 100 million €	Planned	DEWE 2009
	Research	R&D project (5.6 mill. €) and fleet trial program (4.0 mill. €)	Planned	XU 2009
France	Monetary incentives	Tax exemption for electric vehicles (passenger cars and light commercial vehicles) of 5,000 € available	In place	ACEA 2009
		Company car tax: € 2 per gram emitted under 100 g/km or less	In place	ACEA 2009
		Free parking spaces for EVs	Planned	BERR 2008a
	Public Procurement	Mass order of 5,000 hybrid and fully electric cars	In place	AVER 2008
		Public-private procurement programme	Planned	CHAT 2009
	Standardisation	National charging network set-up	Start 2009	CARN 2009 CHAT 2009
	Research & Infrastructure	€ 400 million fund for R&D and demonstration projects	Committed	ENER 2008 CHAT 2009
		Including support (57+50 million €) of demonstration projects	Committed	CHAT 2009 MESR 2009

		Including € 90 million research fund (battery and vehicle technology)	Committed	CHAT 2009
Germany	Monetary incentives	€ 500 million programme to support pilot projects, research, development of battery technology and vehicles	Committed	WWF 2009
		€ 60 million (additional € 360 million by industry consortium) research and development for lithium-ion batteries	Committed	BMU 2008
		CO_2 based taxation system starts, EVs five years no tax	July 2009	COIN 2009
		Free inner circle parking, congestion	Planned	BERR 2008a
	Infrastructure	500 charging stations by end of 2009	Planned	TAGS 2009
	Standardisation	Common standard for plug, capacity of 400 voltage and 63 ampere	Developed	WELT 2009
Greece	Monetary incentives	No car registration or road tax	In place	HIEV 2009
	Non-monetary Incentives	Exclusion of circulation restriction	In place	HIEV 2009
Ireland	Monetary incentives	Exemption from vehicle registration tax for EVs	In place	BERR 2008a
		Tax remission of up to £2,500 for hybrid and flexible fuel vehicles	In place	BERR 2008a
	Public Procurement	10 % of national fleet to be electric cars by 2020	Planned	RTÉ 2009
Norway	Monetary incentives	No car registration tax, VAT and annual car tax	In place	MAYO 2009 OEN 2009
		Exemption from parking fees and combustion charge	In place	OEN 2009
		Free use of ferryboats on national raods in 2009	Planned	OEN 2009
Portugal	Monetary incentives	Electric cars are exempt from circulation and registration tax. Deduction of € 800 at purchase of EVs.	As of 2010	IMPO 2007 DOMB 2008
	Infrastructure	320 charging points by 2010 and 1,300 by 2011	Planned	GCC 2008
Spain	Monetary incentives	15 % rebate at purchase of an electric vehicle	Committed	BERR 2008a
		Registration tax is CO_2 based. Rates vary from 0 % (up to 120 g/km) to 14.75 % (200 g/km and more)	In place	ACEA 2009
Sweden	Monetary incentives	Green car rebate for buyers of electric and hybrid cars worth SEK 10,000	In place	SWE 2007
		Tax incentive as tax system is CO_2 based (SEK 10 – SEK 15 per gram of CO_2 emitted above 100 g/km)	In place	ACEA 2009
		Exemption from congestion charge in Stockholm	In place	ABERN 2006

	Infrastructure	1.5 million € investment in recharging infrastructure	In place	BERR 2008a
		500 charging points by end of 2010	Planned	IDAE 2009a
United Kingdom	Monetary incentives	£350 million for demonstration projects, research	Committed	BERR 2009
		Annual circulation tax is £ 0 below CO_2 emissions up to 100 g/km (compared to £ 400 at 225 g/km).	In place	ACEA 2009
		Exemption from parking fees in London	In place	KING 2008
		No congestion charge in London	In place	KING 2008
	Public Procurement	£20 million procurement programme	Planned	HMGOV 2009
	Infrastructure	25,000 charging points in London	Planned	EDIE 2009
		dedicated bays for car club EVs in London	Planned	MAYO 2009
	Standardisation	Support development of standards for charging infrastructure	Committed	DFT 2008
	International Collaboration	Develop international standards for charging infrastructure	Committed	DFT 2008
	Consumer behaviour	Incentive programme – rebate on purchase of cars	Planned to start 2011	BBC 2009
European Union	Monetary Incentives	Tax reductions for low-carbon vehicles	Planned	COM 2008 EUCO 2009b
	Public Procurement	Encourage public procurement of low-carbon vehicle	Planned	COM 2008 EUCO 2009b
	Research	€ 500 million funding for research & EIB loans for industry	Planned	COM 2008 EUCO 2009b
Unites States	Monetary Incentives	Tax credits for low-emission vehicles	In place	MIT 2007
		Reduced parking, registration and toll fees	In place	MIT 2007
		$ 2.5 billion programme for the development of electric-power cars	Committed	FAST 2009
	Non-monetary Incentives	Special lane access rights for low-carbon vehicles in California	In place	ABERN 2006
	Public Procurement	Some states mandate the purchase of hybrid cars.	In place	ABERN 2006
	Collaboration	Initiative to help communities prepare for deployment of EVs and to share best practices / lessons learned	In place	GREEN 2009 RMI 2009
Japan	Monetary Incentives	High tax incentives for fuel efficient vehicles	In place	GLOB 2009
		Tax credits of up to 3,500 for hybrid buyers	In place	ABERN 2006
	Research	Highest research budget for development of batteries worldwide	In place	ABERN 2006

China	Monetary Incentives	Subsidies of $ 8,800 on purchase of electric vehicles by taxi fleets or local government agencies	In place	TNYT
	Infrastructure	Charging stations in Bejing, Shanghai and Tianjin	In place	TNYT 2009
Israel	Monetary Incentives	Reduction of purchase tax for EVs from 79 % to 10 % until 2014	Planned	SYRO 2008
	Infrastructure	500,000 charging and several battery exchange stations until 2012	Planned	SYRO 2008

SUMMARY: BARRIERS AND POLICY ISSUES

Results from literature

- The electric propulsion system is confronted to a couple of persisting barriers for market penetration.
- Because of the early stage of technological development private investments are still rather limited due to high investment risks.
- The fact that information is a public good could further slows down innovation, as the innovator can not capture the entire economic benefit of its innovation due to spillovers.
- Alternative propulsion systems require high initial investments in technology development and infrastructure to be able to compete due to the technological "lock-in" of road transport – which is highly dominated by hydrocarbon fuels.
- A clear policy framework and the definition of a reliable time frame could reduce investment risks and foster the deployment of electrically driven vehicles.
- The following policies and fields of actions are discussed in the reviewed literature:
  - Monetary incentives,
  - Non-monetary incentives,
  - Regulation issues,
  - Infrastructure,
  - Standardisation,
  - International collaboration,
  - Consumer behaviour.
- A wide range of initiatives and governmental policies have already been implemented or are announced at the local, national and international level to foster the development and deployment of electric vehicles.
- Major activities that are already in place are:
  - Public procurement programmes (e.g. France, Belgium, UK, Ireland)
  - Reduced circulation taxes (e.g. UK, Austria, Cyprus, Portugal)
  - Reduced registration taxes (e.g. Cyprus, Denmark, France, Ireland, Portugal)

- Subsides / rebate for electric vehicle purchase (e.g. UK, Belgium, Sweden)
- Financial support of charging infrastructure (e.g. UK, Denmark, France)
- Financial support of demonstration projects (e.g. UK, Germany, France)
- Research funding (e.g. Germany, UK, US, European Union)
- Standardisation (e.g. UK, Germany)
- Exemption from congestion charge (e.g. UK (London), Sweden (Stockholm))
- Free parking (e.g. France, UK (London), UK (local))
- Special lane access (e.g. US (California))
- Collaboration at different levels to share best practices (e.g. US)

4 Environmental impacts

The determination of the environmental impacts from vehicles with an electric propulsion system has to consider the linkage to the electricity supply and becomes therefore more complex than for conventional technologies. While conventional internal combustion vehicles create the largest proportion of the fuel life-cycle emissions during driving, full electric vehicles do not produce any local air pollutants and green house gas emissions during vehicle operation. Conventional fuels cause only little emissions during production and distribution (about 15 % of total life-cycle emissions [BADI 2001]), whereas the electricity supply for electric vehicles may cause considerably higher emissions at the power plant level which varies depending on the source of energy production and is much more complex to characterise.

The environmental evaluation of electric vehicles has to consider several factors which are of major influence. On the vehicle side, energy consumption including potential losses during charging and of the battery at different driving conditions, the electric driving range and use pattern which determine the time of charging and the capability to substitute mileage by the electric driving mode are of particular relevance. The electricity generation and distribution losses determine finally the overall emissions of electric vehicles and corresponding energy consumption. In this context it has to be considered, that the electricity grid mix varies widely depending on geography, time of day, and season [MIT 2007].

Due to the large number of parameters which determine the final overall emissions of electric vehicles, the generated results are likely to vary within a large range depending on the assumed framework conditions.

In the following sections, the environmental impact of electrically driven vehicles with a major focus on greenhouse gas emissions is discussed based on the reviewed literature, referring to different energy scenarios and taking into account further interactions between the energy demand of electric vehicles and the electricity market.

4.1 Impact on CO_2 emissions considering average emission factors

A widely applied approach to estimate the greenhouse gas emissions of electric vehicles links the electric vehicle's energy demand with average emission factors of different power plant mix scenarios. This rough emission assessment neglects further implications on the electricity market of a rising electricity demand caused by the transport sector and neglects temporal and spatial variations of the energy supply, but gives a first estimate on potential benefits of electrically compared to conventionally fuelled vehicles under different grid mix scenarios (see also Table 11).

Note: The following considerations on the CO_2 impact of electric vehicles are derived from various sources that rely on varying framework assumptions. Assumptions on the energy consumption of the vehicle, the average annual vehicle distance travelled and the average CO_2 emissions of a comparable average conventional vehicle are crucial for the estimation of the overall CO_2 emission benefit of electric vehicles. However, in the reviewed literature these assumptions are only partly documented or vary greatly among the studies and lead correspondingly to varying overall results. Therefore, the overview given in this section and table Table 11 rather illustrates the potential range of vehicle-related emissions and the associated uncertainty, although a direct comparison of results from different sources is only partly applicable.

[BOST 2009] compares different national power-generation markets and their impact on well-to-wheel emissions of electric vehicles. As a result of the high carbon-intensity of power generation in China and India, BOST [2009] assumes that electric vehicles would hardly reduce CO_2 emissions compared to conventional internal combustion vehicles, neither today nor in 2020. With regard to the European power generation mix, characterised by a considerably higher share of low-carbon energy sources, such as renewable and nuclear energy, electric vehicles would generate 55 to 60 % less in CO_2 emissions than a conventional cars. The GHG benefit is expected to further increase in the future, when the carbon-intensity of power generation continues to decrease due to a larger amount of renewable energies and new technologies such as carbon capture and storage (CCS) [BOST 2009].

Eurelectric [EURE 2008] determines mean CO_2 emissions of a typical electric car of around 80 g/km assuming the current carbon intensity of the European electricity sector (410 g CO_2 per kWh), whereas an average conventional passenger car emits currently about 160 g CO_2 per kilometre. Assuming a carbon intensity of 130 g CO_2 per kWh of the EU grid mix in 2030, electric vehicles would emit less than 30 g of CO_2 according to the calculations of [EURE 2008].

A study of the European Association for Battery Electric Vehicles [EABEV 2009] comes to the conclusion that an electric vehicle on average, assuming the EU electricity mix, generates less than half of the CO_2 emissions of a fossil fuel vehicle of the same weight and performance on a well-to-wheel basis. In the case of electric vehicles that are mainly charged with electricity from coal power plants with emissions over 1000 g CO_2/kWh (such as in Poland of Luxemburg), well-to-wheel emissions are equal to or higher (~ 130 g/km) than those of a conventionally fuelled vehicle of the same size.

The Netherlands Environmental Assessment Agency states a reduction of CO_2 emissions by about 65 % and 50 % for future EVs and PHEVs, respectively, compared to an average current conventional vehicle and assuming the current EU-15 grid mix.

WWF [2008] compares the effect of different national grid mixes on the overall CO_2 benefit of EVs in relation to conventional gasoline and diesel vehicles. While the carbon-intensive, mainly coal-based power mix of Greece and Indiana (US) results in CO_2 emissions which are in the range of conventionally powered vehicles, the low-carbon energy supply of California and Austria leads to a emission reduction of more than 70 %. The average EU grid mix would still imply a reduction of CO_2 emissions by about 60 %, whereas the US average would reduce the emission benefit of EVs compared to conventional vehicles by about 40 % due to a higher share of coal fired power plants. With regard to the renewable energy targets of the EU, WWF [2008] points to the expected decreasing carbon-intensity of the European power sector which would further increase the benefits of an increasing electrification of automotive transport in the future. With regard to the illustrated calculations, WWF [2008] concludes that EVs offer already tremendous advantages over conventional vehicles where the electricity is derived from carbon-light generation sources.

Calculations for the United Kingdom [ETEC 2007, KING 2007] consider the impact on carbon emissions of total and partial replacement of passenger cars with vehicles using electricity under three illustrative grid mix scenarios. Grid mix A (450 gCO_2/kWh) represents the current UK status, grid mix B (351 gCO_2/kWh) equivalents to a new combined cycle gas turbine plant, whereas grid mix C (176 gCO_2/kWh) may be achieved by a strong use of renewables, nuclear and CCS. It is assumed that the electric driving mode consumes 16 kWh energy per 100 kilometres and that plug-in hybrid electric vehicles operate half of their total mileage in the electric mode. This assumptions result in CO_2 emissions for electric vehicles (77 to 30 g CO_2/km – grid mix A to C) and for plug-in hybrid vehicles (109 to 85 g CO_2/km) which are considerably lower than that of conventional vehicles, irrespective of the grid mix scenario considered. Compared to conventional vehicles, EVs would achieve an emission reduction of more than 50 % with the current grid mix and of more than 80 % under the assumption of a low carbon power mix (grid mix C). The emission reduction of PHEV would range between about 30 % under current conditions and up to 45 % under the most optimistic scenario.

A study of the Massachusetts Institute of Technology [MIT 2007] quantifies the green house gas benefits of plug-in hybrid vehicles in the US under the assumption of different electricity generation sources, ranging from a carbon-intensive coal power mix (942 gCO_2/kWh) to a clean grid mix with a 50 % share of non GHG-emitting sources (357 gCO_2/kWh). The current average and the possible 2030 US grid mix showing average grid emission rates of 640 gCO_2/kWh and 635 gCO_2/kWh, respectively. The calculation of potential EV/PHEV life-cycle emissions [MIT 2007] refers to the remaining uncertainties which are related to the energy supply in terms of the evolution of the electric grid, the future power demand of the electric vehicle market and the future marginal power plant. The calculation of GHG emissions for plug-in hybrid electric vehicles with varying electric range (10 to 60 kilometres) is characterised by a wide range of emissions depending on the applied grid mix. While the current average grid mix would result in emissions of about 90 gCO_2/km, a plug-in hybrid charged by coal would look considerably worse (up to 120 gCO_2/km, depending on the electric range). In contrast, the mentioned clean grid mix could result in overall GHG emissions of about 65 gCO_2/km for a PHEV with an electric range of 60 kilometres. However, MIT [2007] points out that plug-in hybrid electric vehicles show only marginal GHG emission benefits compared to conventional hybrid electric vehicles using the current average grid mix. With regard to electric vehicles, MIT [2007] refers to the less favourable energy and GHG emission balance compared to PHEV, due to the stronger impact of the battery weight on vehicle efficiency.

An analysis of the International Energy Agency [IEA 2007], which calculated the GHG emissions of PHEV, considering average grid mixes of different European countries showed that PHEVs operating in electric mode would be considerably cleaner than conventional vehicles, and probably cleaner than conventional hybrid vehicles. Due to the particularly low carbon-intensity of the French power supply (with a high share of nuclear energy) PHEVs in France would lead to the greatest reductions of GHG emissions. In contrast, the supply of PHEVs with coal-based electricity would lead to GHG emissions higher than those of conventional hybrids.

The environmental assessment of plug-in hybrid electric vehicles, carried out by the Electric Power Research Institute [EPRI 2007] evaluated the impact of three electric sector scenarios on GHG emissions of PHEVs. [EPRI 2007] showed a 28 % to 34 % GHG emission reduction of PHEV compared to conventional vehicles assuming current coal technology, but higher emissions (1 % to 11 %) compared to conventional hybrid vehicles. With decreasing carbon-intensity of the supplied electricity, GHG emission benefits of PHEV increase significantly and could achieve an emission level of about 90 gCO_2/km assuming an electric range of 20 kilometres. As it is assumed that vehicle efficiency will further increase over time and the carbon-intensity of the electric grid decreases, even lower GHG emissions could be achieved by 2050. EPRI [2007] states a GHG emission reduction of 40 % to 65 % of PHEV over the conventional vehicle depending on the applied electric sector scenario and the assumed electric driving range of the vehicle.

The American Council of an Energy-Efficient Economy states a 30 % GHG reduction potential of PHEV with an electric range of about 65 kilometres compared to conventional hybrid vehicles under the assumption of the Californian grid mix [ACEEE 2006]. When considering the US average grid mix, the GHG reduction would be limited to about 15 %, in regions with coal-heavy electricity generation, the plug-in hybrid would not reduce GHG emissions at all [ACEEE 2006].

[BRAD 2009] summarises CO_2 emission reduction results of plug-in hybrid vehicles from various studies. The results are divided into three categories based on the methods used to model the electrical grid. The first category considers electricity from single sources, as e.g. carried out by EPRI which assumes marginal, dispatchable sources such as natural gas. Under these assumptions, a PHEV with 30 kilometres electric range is estimated to reduce emissions by 44 % for an average driver, charging nightly. A PHEV with 50 kilometres electric range and the 2002 US electricity generation results in a 27 % reduction. Further studies which model the future US electricity generation, considering electricity dispatch and geographic variations, calculate a GHG emission reduction potential of more than 50 % (and in the range of 69 % to 37 %, depending on the US region) for a national average vehicle.

[IFEU 2007] points out that an average energy consumption of 20 kWh per 100 kilometres of an electric vehicle corresponds to the amount of fossil primary energy needed for a conventional vehicle which consumes about 5 to 6 litres of diesel or gasoline. For Germany, assuming electricity from hard coal-fired power stations with an emission level of about 770 to 840 gCO_2/kWh, the GHG emissions of electric vehicles would correspond to the amount that is emitted by an average conventional vehicle consuming between 5 to 6 litres of gasoline.

A recent study on the impact of electric vehicles on the German power sector and the national GHG emissions [WWF 2009], assumed an energy consumption of electric vehicles in the range of 15 to 20 kWh per 100 kilometres. In case of natural gas based electricity generation, GHG emissions of electric vehicles are in the range of conventional vehicles, whereas the assumption of coal-fired energy generation leads to considerably higher values which exceed the average emissions of conventional vehicles.

BERR [2008a] refers to average CO_2 emissions of electric vehicles of 69 g/km in 2010 assuming the Defra long term marginal factor (representing a new combined cycle gas turbine). Electric vehicle emissions are assumed to decrease further over time to 47 g/km by 2030. On the other hand, conventional vehicle emissions are expected to decrease from about 160 g/km by 2010 to about 110 g/km in average by 2030 as a result of a further improvement of conventional vehicle propulsion. The CO_2-benefit of electric vehicles remains therefore almost constant over time – at about 55 % compared to conventional vehicles.

With current grid mix carbon intensity (210 g CO_2/kWh in 2007), full battery EV in Austria could emit 40 g CO_2/km [PWC 2009]. The overall emission of light road vehicles could be reduced by 16 % (2 Mt CO_2) in 2020 assuming that the carbon intensity of the electricity mix goes down to 200 g CO_2/kWh in 2020 (due to penetration of renewable). The possible net economic effect is of the magnitude of 1.3 billion EUR mostly due to the reduced investments in power plants and oil imports [PWC 2009].

Table 11: Overview of well-to-wheel GHG emissions of electric (EV) and plug-in hybrid vehicles (PHEV) and their benefit compared to average conventional vehicles (CV)[1] considering different average grid mix assumptions (literature review).

Source	Region	Grid mix characteristics	Average carbon intensity [gCO_2/kWh]	Energy consumption of EV / PHEV [kWh/100km]	CO_2-emissions of EV / PHEV [g/100 km]	CO_2-emissions of CV [g/100 km]	CO_2-benefit compared to average CV
BOST 2009	Europe	-	-	-	-	-	55-60 %
EURE 2008	Europe	current European mix	410	18	80	160	50 %
EURE 2008	Europe	future European grid mix (2030)	130	18	30	160	81 %
EABEV 2009	Europe	current European mix	443	11-14	54[1]	~108	~50 %
PBL 2009	Europe	current EU-15 mix	389	14	60 (EV) / 85 (PHEV)	170	65 % / 50 %

1 the characteristics of the average conventional vehicle varies depending on the study (see also text for further details).

WWF 2008	Greece	mainly coal-based	781	-	-	-	11 %
WWF 2008	Indiana	mainly coal-based	973	-	-	-	-7 %
WWF 2008	Califor-nia	high share of renewables	273	-	-	-	>70 %
WWF 2008	Austria	high share of renewables	221	-	-	-	>70 %
WWF 2008	US	current US grid mix	620	-	-	-	40 %
KING 2007	UK	current grid mix	450	16	77 (EV) / 109 (PHEV)[2]	155	50 % / 30 %
KING 2007	UK	gas turbine plant equiv.	351	16	60 (EV) / 100 (PHEV)[2]	155	60 % / 35 %
KING 2007	UK	future low-carbon grid mix	176	16	30 (EV) / 85 (PHEV)[2]	155	80 % / 45 %
MIT 2007	US	current US mix	640	-	~90 (PHEV)[3]	160	43 % (PHEV)
MIT 2007	US	coal-based mix	942	-	120 (PHEV)[3]	160	25 %
MIT 2007	US	clean grid mix	357	-	65 (PHEV)[3]	160	60 %
EPRI 2007	US	current coal technology	-	-	-	-	28-34 % (PHEV)
EPRI 2007	US	future low-carbon mix	-	-	-	-	40-65 % (PHEV)
ACEEE 2006	Califor-nia	current Califor-nian mix	-	-	-	-	30 % (PHEV)[4]
ACEEE 2006	US	current US grid mix	-	-	-	-	15 % (PHEV)[4]
BRAD 2009	US	different re-gional grid mixes	-	-	-	-	37-69 % (PHEV)[5]
WWF 2009	Germany	old coal-fired power plant	900	12-20	220	160	- 38 %
WWF 2009	Germany	new coal-fired power plant	750	12-20	175	160	- 10 %
WWF 2009	Germany	natural gas power plant	-	12-20	90	160	44 %
BERR 2008a	UK	new combined cycle gas turbine	-	11-16	69	155	55 %
PWC 2009	Austria	Current grid mix	210	-	40	-	-

[1]: assuming that 60 to 70 % of kilometres are driven electrically.

[2]: PHEV drive 50 % of mileage in electric mode.

[3]: emissions of PHEV depend on electric range; here an average value is given.

[4]: PHEV with 65 km electric driving range.

[5]: variation of emissions results from geographically varying carbon-intensity of grid mix.

It has to be recognised that seasonal and daily variations of the grid mix are ignored in these first simplifying assumptions on the CO_2 emissions of electric vehicles based on average emission factors, despite of their relevance in practice. The carbon intensity of the current grid mix varies considerably over time. Thus the time of battery charging is of major importance for the carbon intensity of electrically driven mileage. Charging in the "off-peak" period would be more carbon efficient as there is more spare capacity at these times [KING 2008], but the future real-world charging of electric vehicles with regard to the time of charging is highly uncertain. A more detailed discussion of different charging modes and related impacts on emissions and electricity production is carried out in section 4.2.

Only few publications quantify the overall electricity demand and CO_2 emission reduction potentials under the assumption of different market penetration scenarios of electric vehicles. An overview of the generated results at different EV penetration rates is given in Table 12. Differences among the results of the reviewed studies in terms of energy demand and CO_2 emissions result from different assumptions concerning average energy demand and annual mileage of electric vehicles, the kind of substituted vehicles and varying grid mix characteristics. Therefore, again, this overview can only give a first impression of potential impacts of an increasing share of EVs, bearing in mind the rough estimations that are related to these calculations (see also **"**Note**"** on page 91).

Generally, the additional electricity demand generated by the introduction of EVs would have only little impact on the overall electricity supply, in particular assuming low EV penetration rates. In the case of Germany, a large-scale introduction of electric vehicles (50 to 100 % of the entire vehicle fleet) would increase the overall electricity demand by hardly more than 10 % [ENG 2007, WWF 2008]. HART [2009] estimates that 100 000 EVs need around 1750 GJ (~ 486 MWh) energy per day. On this basis 1 million EVs (German target for 2020, i.e. 2 % of today's fleet) would need 1.77 TWh per year whereas 5 million EVs (German target for 2030) would need 8.85 TWh per year. 1 million battery EVs could provide a 14 GW power capacity; that is already 2 times more than the total power available from pumped hydro storage capacities in Germany. BERR [2008a] examines different market penetration scenarios and their consequences on the electricity demand for the UK. In the following table only the results by 2030 for the lowest and highest scenarios are illustrated. The chairman of the EURELECTRIC task force on electric vehicles illustrated that a theoretical complete shift towards electric vehicles in the EU-27 would increase electricity consumption from today's 3,100 TWh to 3,570 TWh – an increase of only 15 % [EURE 2009a]. A recent study carried out by PwC and funded by the Austrian Climate and Energy Fund [PWC 2009] assessed the impacts of EVs on the energy system assuming a 20 % (1 million vehicles) penetration in Austrian car fleet by 2020-30. The study concludes that the overall electricity consumption would slightly increase (+3 %) whereas the overall energy consumption would be reduced by 8.4 TWh (37 % of the Austrian target set for 2016). No additional power plants and grid reinforcement would be needed to cover that extra demand. Adaption of distribution networks would just be limited to the connection of charging points (16,200 needed if EVs were to be introduced everywhere across the country, 2,800 only if they were to be mostly introduced in cities, investment needed between 111 and 650 million EUR).

ADEM [2009] argues that the French near-term target of 100,000 electric vehicles could be integrated into the French power grid without major problems. Even 1 million vehicles by 2020 or 4 million electric vehicles at the long term could be charged by the power grid, assuming that battery charging is accompanied by load management strategies avoiding additional peak load demand.

Table 12: Overview of potential impact of a large-scale introduction of EVs on energy demand and total CO_2 emission reduction (literature review).

Source	**Country**	**Market pentration**	**Energy consumption of EV / PHEV [kWh/100km]**	**Total amount of energy [TWh]**	**Increase of electricity demand**	**Average carbon intensity [gCO_2/kWh]**	**Reduction of total CO_2-emissions**	**Reduction of CO_2-emissions [mill. tons]**
ENG 2007	Germany	1 mill. PHEV/EVs	-	2	0.3 %	650	-	0.7
ENG 2007	Germany	40 mill. PHEV/EVs	-	61	10 %	650	-	29
ENG 2007	Germany	10 mill. EVs	-	30	5 %	650	-	-
ERTRA 2009	Germany	1 mill. EVs	-	1	< 1 %	-	-	-
HART 2009	Germany	1 mill. EVs (2 %)	14	1.77	-	-	-	-
HART 2009	Germany	5 mill. EVs (10 %)	14	8.85	-	-	-	-
WWF 2008	Germany	1 mill. PHEVs	16	1.5	0.25 %	-	-	-
WWF 2008	US	1 mill. PHEVs	16	1.5	0.04 %	-	-	-
EPRI 2007	US	20 % PHEVs	-	-	-	412-97	-	163-193
EPRI 2007	US	62 % PHEVs	-	-	7.6 %	412-97	-	394-478
EPRI 2007	US	80 % PHEVs	-	-	-	412-97	-	474-612
WWF 2009	Germany	1 mill. EVs	15-20	1.5-2	< 0.5 %	-	0-0.1 %	0-1.3
WWF 2009	Germany	10 mill. EVs	15-20	18-24	3-4 %	-	1 %	9.6-13
WWF 2009	Germany	20 mill. EVs	15-20	36-48	6-8 %	-	1.9-2.4 %	18.2-26
BERR 2008a	UK	0.5 mill EVs / 2.5 mill. PHEVs	11-16	4.2	1.1 %	-	-	2.3-2.5 [7]

BERR 2008a	UK	6 mill EVs / 15 mill. PHEVs	11-16	31	7.9 %	-	-	17.3-19.3 [7]
EURE 2009a	Europe	100 % EVs	18	470	15 %	-	-	-
PWC 2009	Austria	1 mill. EVs (20 %)	18	-	3 %	-	-	2.0

The potential GHG emission reduction is highly dependent on the penetration rate, the assumed vehicle characteristics, energy consumption as well as on the assumed future grid mix. In the reviewed literature an only rough estimation is provided that neglects the effects of different charging regimes and grid mixes. A more detailed analysis of these effects is carried out in section 4.2.

With regard to the future composition of the power sector, a further improvement and an increasing decarbonisation of electricity generation is expected [BERR 2008a, KING 2007]. With regard to conventional coal-fired power plants major improvements can be expected due to combined heat and power (CHP) electricity that increases the overall power plant efficiency. Therefore, when assessing the impact of EVs on CO_2 emissions from CHP power plants, only the fraction of emissions that is related to electricity generation should be attributed to the well-to-wheel emission calculation for EVs, leading to a considerably lower emission level compared to current coal-fired power plants. The EURELECTRIC commitment targets an increasing efficiency of power generation and investments to develop innovative low-emitting technologies to achieve a carbon-neutral power supply in Europe by 2050 [EURE 2008a]. As a consequence of an increasing decarbonisation of the power sector and a further improvement of current technology (e.g increasing efficiency of coal-fired power plants) much higher savings of greenhouse gas emissions from electric vehicles in the long-term could be achieved and would enable a significant decarbonisation of road transport in the long-term. Therefore, SCHM [2009] assumes that electric vehicles powered by renewable electricity would be a more sustainable long-term solution than conventional vehicles powered by biofuels because of the progressive increase of renewable electricity and the expected increased efficiency of electric drives.

SUMMARY: IMPACT ON CO_2 EMISSIONS TAKING INTO ACCOUNT AVERAGE EMISSION FACTORS

Results from literature

- The life-cycle greenhouse gas emissions of electric vehicles vary widely depending on the carbon-intensity of the assumed power grid mix.
- To assess the potential GHG benefit of electric vehicles compared to conventional vehicles the impact of different grid mixes is evaluated in the reviewed literature:

- Electricity from carbon-intensive coal-fired power plants leads to well-to-wheel GHG emissions corresponding or even exceeding the total emissions of average conventional vehicles.
- Current average European energy supply which shows considerably lower carbon-intensity would reduce GHG emissions by more than 50 %.
- Even higher reduction rates could be achieved in France, Austria or California showing very low carbon-intensive power generation.
- Further benefits are likely to be generated if the carbon-intensity of power generation continues to decrease.
- The GHG benefit of plug-in hybrid vehicles depends on the electric driving range and is assumed to be lower than that of pure electric vehicles as PHEV partly operate in conventional fuel-consuming driving mode.

- The impact of electric vehicles on the overall electricity demand is of rather modest amount in the short- and mid-term.
- The global GHG emission reduction potential depends on the assumed EV penetration rate, vehicle and grid mix characteristics and references.
- The determination of overall greenhouse gas emissions from electric vehicles has to consider the linkage to electricity supply.

Discussion and recommendations

The assessment of CO_2 benefits from electric vehicles based on average emission factors of different grid mixes represents a rather simplifying approach that provides a rough estimation but neglects further interactions between electric vehicles and the power grid (see section 4.2) that should be considered in this context.

It is self-evident that the overall reduction potential of electric vehicles is highly dependent on the assumed kind of electricity supply and the related carbon-intensity. Although, the current carbon-intensive grid mix in some regions leads to no or only little emission reduction of electric vehicles compared to conventionally fuelled vehicles, other regions with a low-carbon grid mix show much higher savings. The increasing decarbonisation of the power sector and a further improvement of current technology (e.g increasing efficiency of coal-fired power plants) would enable to generate much higher savings of greenhouse gas emissions from electric vehicles in the long-term and could lead to a significant decarbonisation of road transport.

On the other hand also conventional internal combustion technology is likely to further improve over the coming decades. Therefore, when evaluating the emission benefit of electric vehicles, those should be compared to the emission level of efficient conventional vehicles of the same size and on the basis of future conventional fuel-related emissions, rather than to the average emission factor of the existing vehicle fleet.

Further, the determination of the overall energy demand of electric vehicles and the potential to reduce greenhouse emissions requires more detailed information on energy consumption of electric vehicles and electrically driven mileage.

Under moderate market penetration rates, the additional power demand remains at a low level and the use of average emission factors for the power grid represents a useful approach to determine GHG benefits of EVs. Assuming a high market penetration of EVs and a related significant additional energy demand, the assessment on the impact of EVs on GHG emissions can not only be based on average emission factors but has to consider the interaction with the electricity market which is not yet analysed in detail in literature (see section 4.2).

4.2 Impact on CO_2 emissions taking into account interactions with the electricity market

4.2.1 Introduction

The discussion of greenhouse gas emissions induced by electric vehicles available in the literature comprises a range of different interactions between electric vehicles and the electricity market. The discussion in Section 4.1 focuses on the results obtained from literature regarding the impact considering average greenhouse gas emissions factors for the electricity mix. However, average emission factors only give a rough estimation of actual greenhouse gas emissions induced by electric vehicles. Interactions with the electricity market refer to short-term or marginal effects of power plant operation as well as to long-term effects regarding the development of the power sector. As can be seen in the literature, electric vehicles have implications for operation and greenhouse gas emissions in the power sector with regard to the following aspects:

1. Direct effects: The introduction of electric vehicles leads to an overall increase of electricity consumption and thus to an increase of greenhouse gas emissions.
2. Indirect short-term effects (related to power plant operation): Besides the additional electricity demand, electric vehicles lead to additional load demand during the time when the vehicles are connected to the grid and charged (e.g. [WWF 2009], [FFE 2007]). This means that additional CO_2 emissions depend on the type of power plant which is dispatched additionally due to the load increase during the charging time. If electric vehicles are charged during the night, base-load power plants (for instance, coal or nuclear) are predominantly affected, whereas during daytime medium- or peak load power plants (such as gas turbines, combined cycle power plants or pumped storage plants) are impacted. Correspondingly, greenhouse gas emissions vary according to the charging time. Similarly, the direct use of renewable energy sources for electric vehicles depends on the timing of the charging time. For instance, wind generation may or may not coincide with the load demand by electric vehicles.

3. Indirect long-term effects (related to the investment in new power plants): As mentioned above, the charging time of electric vehicles has direct implications for the type of power plants dispatched. In addition to short-term greenhouse gas emissions, an increased dispatch of certain power plant types leads to an increased competitiveness of these power plants in comparison to other investment options. In consequence, the long-term generation mix and thus long-term CO_2 emissions of the power sector may be affected by electric vehicles (e.g. [KINT 2007]).
4. Implications of an increased electricity and load demand by electric vehicles on other policy objectives in the power sector: Policy objectives in the power sector comprise a whole range of issues such as the promotion of renewable energies or cogeneration or of carbon capture and storage (CCS). The promotion of renewable energies for instance entails a higher share of fluctuating electricity production (e.g. from wind). Whether this policy goal is compatible with the promotion of electric vehicles based on renewable energies thus depends on whether power demand (electric vehicles) and power supply (renewable energies) can be matched, either by storage systems on the supply side or by flexible charging times on the demand side (e.g. [KEMP 2005a], [NREL 2006b]).

When electric vehicles are charged, they constitute an additional load in the power grid. The effect of this additional load on the grid, especially on power plant operation and greenhouse gas emissions depends on several factors:

- **The magnitude of additional load connected to the grid:** The additional load connected to the grid depends on the one hand on the amount of electric vehicles being charged at a certain point of time and the charging capacity. The charging capacity itself is dependent on the power electronics in the EV as well as on the maximum connected load of the socket. The number of electric vehicles connected depends on the penetration rate of electric vehicles and on the time of connection to the grid. The connected load is typically different for households, businesses and industry (e.g. [LET 2006]). Dedicated charging stations can be designed for different charging capacities[2].
- **Charging time:** The charging time is defined as the point in time when the electric vehicle is connected to the grid for charging. Charging may be carried out in the evening and during night time when commuters return home and connect their EVs to the grid (e.g. [WWF 2009]). Charging may also happen during the day when electric vehicles are charged while people pursue their daily businesses. Charging may also happen whenever the vehicle is parked and is connected to a charging point (e.g. [FFE 2007]). Correspondingly, base, intermediate or peak load generators are dispatched when EVs are charged.

[2] MAYO [2009] for instance highlights three types of charging points: slow charging points (3.1 kW), fast charging points (7.7 kW) and rapid charging points (100 kW).

- **Charging duration:** Charging duration is the amount of time needed to recharge the battery. The charging duration depends on the one hand on the energy required to recharge the battery, which in turns depends on the state of charge (SOC) of the battery and the general energy capacity of the battery. On the other hand, the charging duration is dependent on the charging characteristics of the battery (such as charging at constant electricity or I-U charging) as well as on the maximum connected load. Charging of a battery at a typical household socket may take longer than charging a battery with access to higher charging amperage and/or higher voltage (e.g. [FFE 2007]).
- **Load management:** The charging process can be modified by load management (e.g. [WWF 2009], [KINT 2007]). Charging time and charging duration can be modified thus changing the overall impact on the grid. For instance, by day time pricing or by automatically-controlled feedback mechanisms (smart metering, etc.), users could be incentivised to delay the start of battery charging by several hours, so that charging takes place during off-peak (night) rather than peak (day time) periods. Similarly, regular or speed charging could be chosen which affects the charging capacity and the charging time for a specified amount of electricity to be stored.
- **Structure of the power sector:** Many studies estimate greenhouse gas emissions of electric vehicles by assuming average grid emission factors considering the yearly generation mix of all sources in the grid (Section 4.1). However, additional emissions due to electric vehicles depend on the marginal power plant which is connected to the grid when electric vehicles are charged. During night time, typically base load power plants such as hydropower, nuclear or coal operate, whereas marginal power plants during day time in many systems correspond to gas-fired units (e.g. [HADL 2006]). Additional greenhouse gas emissions for electric vehicles therefore depend on the structure of the power sector and the charging time.
- **Availability of renewable energy sources:** The availability of renewable energy sources depends on the geographical region, the degree to which the potential has already been tapped and on time. Whereas hydropower is an important energy sources in northern countries (e.g. Sweden) and in mountainous areas (e.g. Austria), wind power is especially important in countries with a long coast line or in-country wind potential (e.g. Germany, Great Britain). The supply of solar energy is highest in southern countries (e.g. Spain). Correspondingly, the type (or the mix) of renewable energy available in each Member State may be different. The degree to which this potential has already been taped also differs between Member States. Furthermore, the availability of renewable energy is a function of time. Solar energy is only available during day time and highest irradiation occurs in the summer. Wind is also a fluctuating energy source both during the time of day and between seasons (e.g. [WWF 2009]). If renewable energy sources are to be used for fuelling electric vehicles, charging must be adapted to the (volatile) availability of these sources or storage systems must be

in place. Correspondingly, the load effect of electric vehicles does not only depend on the conventional power sector, but also on the magnitude and timing of availability of renewable energy sources. If charging of EVs can be adapted to the supply pattern of renewable energies, there may not be an additional load effect for conventional power plants. In contrast, if charging of EVs is not managed, fluctuating renewable energy sources may have load effects on the conventional power sector in addition to the effects induced by the charging of EVs.

The aforementioned aspects clearly demonstrate that the impact of electric vehicles on their integration in the power system and thus on greenhouse gas emissions is very much dependent on the energy-economic framework and on how flexible or rigid are both power supply (conventional power plants, renewable energy sources) and power demand (electric vehicles, other electricity consumers). In the following, three different "energy worlds" are described with which electric vehicles may interfere.

1. Incorporation of electric vehicles in the existing power structure (Section 4.2.2),
2. Use of electric vehicles to optimise the existing power sector (Section 4.2.3),
3. Integrate electric vehicles in an overall energy strategy (Section 4.2.4).

The discussion of these "energy worlds" related to the aspects above is drawn from different studies. However, further design options and combinations thereof are possible.

4.2.2 Incorporation of electric vehicles in the existing power sector

In this "energy world", the development of the power plant sector and the strategy for the deployment of electric vehicles are considered to be independent. In consequence, the power sector only responds to the additional power demand by electric vehicles; however, there is no integrated approach for matching power supply (power sector) and power demand (electric vehicles).

WWF [2009] analyses different scenarios for the interaction of electric vehicles with the German power sector. Especially, it is analysed what impact on the load demand would be induced by starting battery charging once drivers return home (6 p.m.) or if charging could be delayed by load management and be started only at 11 p.m. These analyses are carried out for different penetration scenarios and for different connected loads available (household connection vs. high amperage/voltage connection).

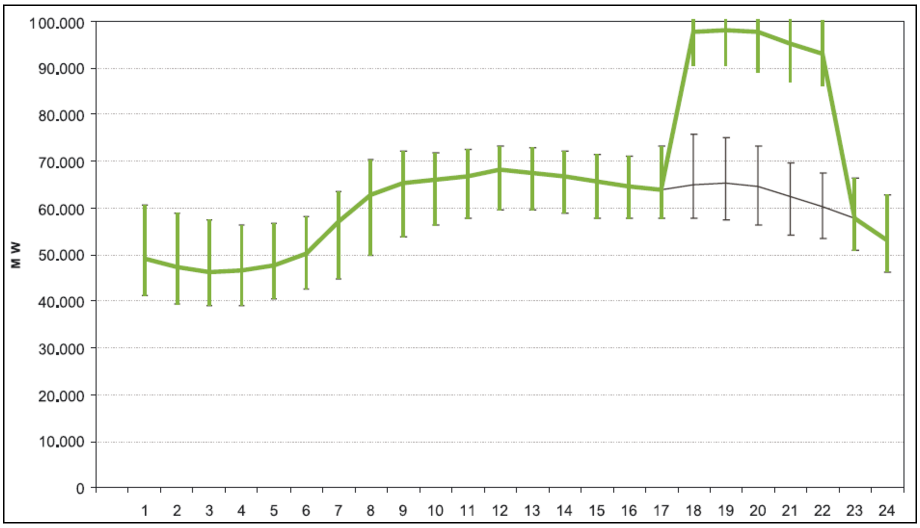

Figure 12: *Load profile on a Wednesday considering 20 million electric vehicles being charged starting from 6 p.m. during five hours (Source: [WWF 2009])*

Figure 12 shows the impact on the load demand if 20 million electric vehicles are charged starting from 6 p.m. during five hours in comparison to the original load demand without electric vehicles. According to the study, 20 million electric vehicles would correspond to an additional electricity demand of 60 TWh per year. The additional load would constitute 33,000 MW.

Considering the same penetration scenario, but a faster charging time (2 hours) would correspond to an additional load demand due to electric vehicles of up to 80,000 MW, which is more than twice as much as the original system load.

These examples illustrate that unmanaged charging of a large quantity of electric vehicles would engender significant problems in the power supply system (with regard to production and grid capacities).

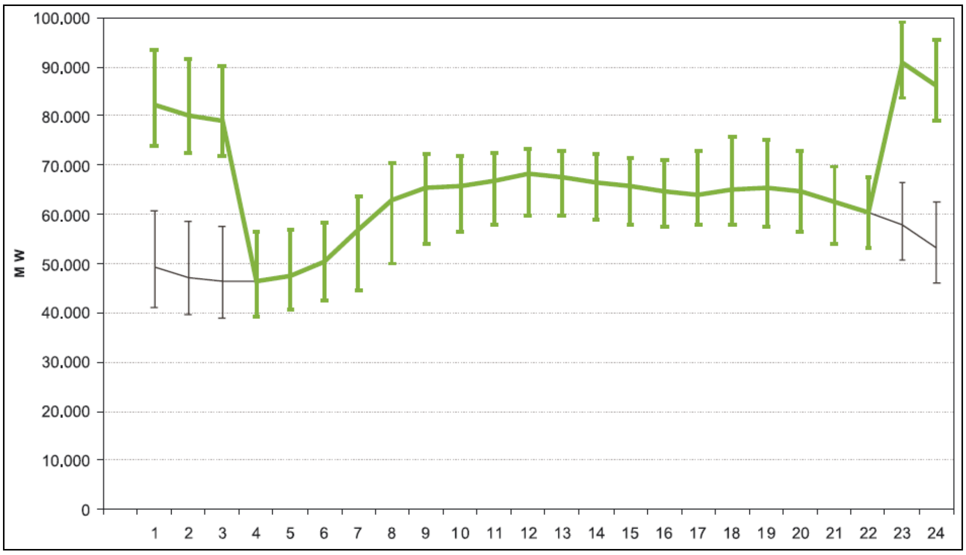

Figure 13: *Load profile on a Wednesday considering 20 million electric vehicles being charged starting from 11 p.m. (load management) during five hours (Source: [WWF 2009])*

If load management is implemented, that means the battery charging is only started at 11 p.m., then the additional load induced by electric vehicles is shifted towards night hours (Figure 13). The utilisation of medium and base load power plants is increased, i.e. the "night valley" is partially filled by the additional power demand of EVs. However, the additional load demand by electric vehicles also leads to an increased peak load demand with even higher loads than during day time. The peak load would reach up to 100,000 MW.

The integration of electric vehicles in the existing power sector as described in the aforementioned examples would lead to additional investments in flexible power plants covering the additional peak loads, such as natural gas-fired power plants. The increased utilisation of base load and medium load power plants by filling the night valley, leads to an increased competitiveness of capital-intensive power plants (hard coal, lignite, CCS, nuclear) with different implications on CO_2 emissions (high in the case of hard coal and lignite, low in the case of nuclear or CCS) ([WWF 2009], [IFEU 2007]).

FFE [2007] derive the load curve of EVs from an evaluation of all vehicle movements according to use classes (business, commuters, private) over the week assuming that electric vehicles are charged after every trip. This differs from WWF [2009] in which all drivers re-charge their electric vehicles at 6 p.m. and 11 p.m., respectively. In FFE [2007] the connected load is determined by defining use classes of vehicle trips. For business trips it is assumed that three-phase current is available (15 kW), whereas for commuting trips conventional household sockets are considered (3 kW).

The ensuing load is then a function of the penetration rate, vehicle movements during the week as well as charging capacity and duration. Since FFE [2007] assumes that no load management occurs, batteries are directly recharged after each trip even if the battery is only partially empty. In consequence, the additional load demand by electric vehicles follows the vehicle movement curve. The maximum additional load demand due to EVs in Germany is 7 GW in the optimistic scenario (assuming different degrees of substitution of conventional vehicles by electric vehicles depending on the use class), cf. Figure 14.

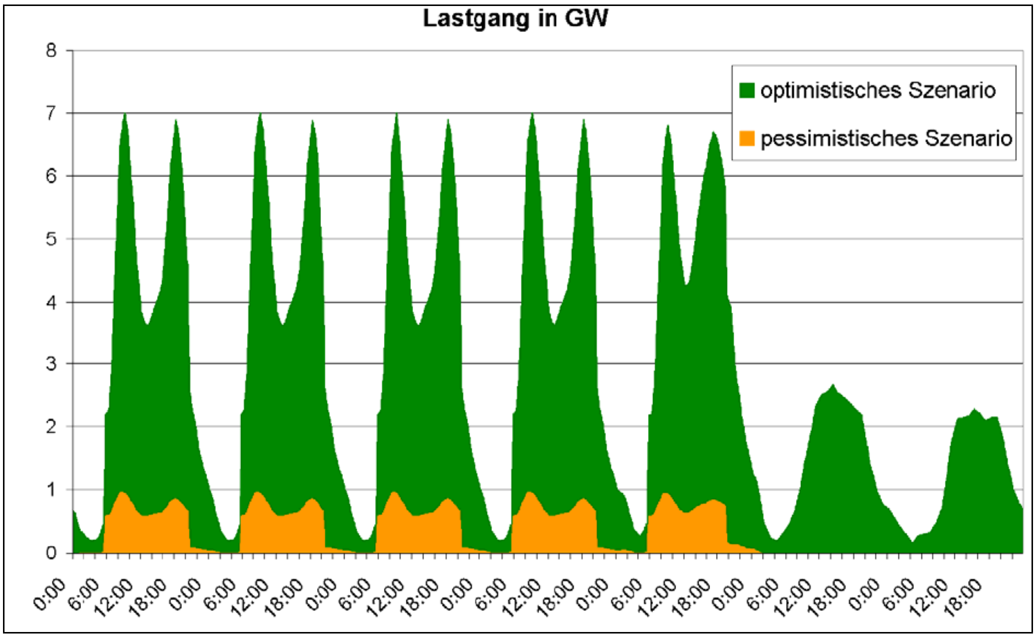

Figure 14: *Load curves for electric vehicles in the optimistic and pessimistic scenario (Source: [FFE 2007])*

Additional load peaks occur in the morning (when most commuters have reached their workplaces) and in the evening (when commuters return home). In consequence, the additional load demand increases the peak load in the power system (green areas in Figure 15). Electric vehicles increase the maximum load by about 10 %.

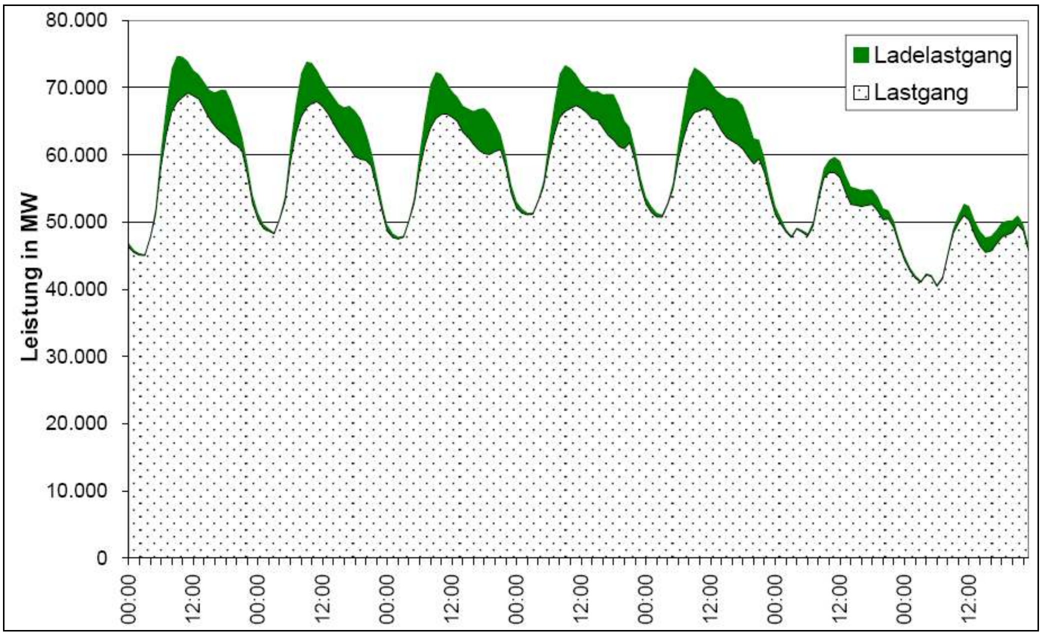

Figure 15: Load of the power sector including additional load by electric vehicles in the optimistic scenario (Source: [FFE 2007])

The load curve and the overall magnitude of the additional load differ between WWF [2009] and FFE [2007] due to different assumed penetration rates and to different charging characteristics (after each trip vs. in the evening/in the night). Nevertheless, the analyses coincide in the fact that peak load demand is increased by electric vehicles if no load management is considered.

In a case study for a U.S. region (VACAR region (Virginia, Carolina)) [HADL 2006], it is estimated that the "regional demand could increase by 1,400 to 6,000 MW [..] depending on the type of connection and timing". Two scenarios for the time of plug-in are discussed (evening, night). If EVs are loaded in the evening, they increase (in some cases significantly) the peak load, whereas late-night charging has little effect on peak capacity needs. Power plants actually dispatched also depend on the time of charging with the share of gas-fired power plants increasing with evening charging and the share of coal-fired power plants increasing with night charging. The authors further argue that sufficient generation capacity may be available, whereas regional transmission and distribution lines may not be designed to handle the additional load.

ETEC [2007] argues that the location where EVs are used is also of importance. It is expected that for EVs "load would be concentrated in urban areas associated with already significant grid capacity".

RIMO [2009] investigates four different fleet charging scenarios for a 10% market penetration of electric vehicles in the United Kingdom. The scenarios comprise "uncontrolled domestic charging, uncontrolled off-peak domestic charging, 'smart' domestic charging and uncontrolled public charging throughout the day". Uncontrolled domestic charging is considered to be the "worst case" scenario, i.e. with the highest impact on national grids. For this scenario, the mentioned market penetration of 10% would lead to an increase of daily peak load of only 2% or 1 GW. The impact of the other charging scenarios on peak load is even less pronounced. It is therefore considered that "grid capacity at a national scale should be adequate for this significant electrification of the vehicle fleet". However, local grid conditions have to be taken into account.

SUMMARY: INCORPORATION OF ELECTRIC VEHICLES IN THE EXISTING POWER SECTOR

Results from literature

- This energy world features an independent development of the strategy in the power sector and regarding the introduction of electric vehicles (except for some load management for electric vehicles). There is no integrated approach to match power supply (power sector) and demand (electric vehicles).
- Depending on the penetration of EVs and the charging characteristics, there may be significant effects regarding the load demand
    - Charging without load management increases peak load demand
        - Charging in the evening can significantly increase peak load demand above levels without EVs
        - Charging after each trip leads to increased peak loads in the grid.
    - Charging during night time (i.e. with some load management) can tap base load generation, but in case of high penetration rates with EVs also can lead to peak load situations in the night which are higher than daytime peaks.
    - Shorter charging times require higher charging capacities and thus increase load peaks in the grid
- Increased peak load demand may require investments in new peak generation capacity as well as grid capacity.
- If charging is shifted towards night time, the competitiveness of capital-intensive power plants (such as nuclear or lignite) is improved by increased load factors with corresponding implications on the future power mix and CO_2 emissions.
- Charging at peak situations implies high electricity generation costs, high grid load and often low-carbon electricity generation (natural gas, pumped storage).
- Charging at base load situations implies low electricity generation costs, more even grid loads and in some (lignite, hard coal), but not all (nuclear, hydro) cases high-carbon electricity generation.

Discussion and recommendations

The literature review shows that the effects of the integration of electric vehicles into the existing power sector depend significantly on the charging behaviour of the user. However, to date, only estimations of the use pattern, no "real-word" data is available which makes corresponding evaluations difficult.

Furthermore, impacts on the power sector depend significantly of the structure of the power sector in question. Generalised statements are therefore not valid, but national and regional circumstances have to be taken into account. However, a further integration of the European power network in the years to come may compensate regional differences by supplying power to one single market. Sufficient interconnection capacities are fundamental for this.

The literature results also demonstrate that for larger penetration rates of electric vehicles it can no longer be assumed that charging of electric vehicles and the development of the power sector can be considered separately. Significant increases of charging capacity may probably require an integrated view on electric vehicles and the power system:

- The assessment of CO_2 impacts assuming little or no load management should consider actual ("real-world") charging behaviour of vehicle users and the structure of the power sector in the respective area.
- For larger penetration rates, electric vehicles and the power sector should be considered in an integrated way.

4.2.3 Use of electric vehicles to optimise the existing power sector

The additional load demand by electric vehicles in combination with load management could lead to a better utilisation of the existing power sector. This would increase the efficiency of the affected power plants since there would be less load changes and less part load events. The competitiveness of base and medium load power plants would be increased over other options due to increasing load factors.

MIT [2007] state that "plug-in vehicles have the potential to interact in a synergistic fashion with the variable load profile typical of the electric grid by "valley-filling" – that is by taking advantage of excess capacity during off-peak periods and balancing daily variations in load" (Figure 16). Especially base load generators could thus increase their yearly operation time. According to KINT [2007], for the US as a hole, "about 84% of the energy needed to operate cars, pickup trucks, and SUVs [..] could be supported using generating, transmission, and distribution capacity currently available. This would require power providers to use the available electric generation, base-load and intermediate generation, at full capacity for most hours of the day". One condition for the valley-filling approach is that "the entire PHEV load is managed to fit perfectly into the valley without setting new peaks", which could be achieved for instance "via electricity pricing that discourages customers from charging the PHEVs during peak periods and encourages them to charge during off-peak periods" [KINT 2007].

KINT [2007] argues that the valley-filling approach "is likely to change the mix of future power plant types and technologies with important implications to base-load coal and nuclear technologies. This is potentially beneficial for these power generation technologies, as they typically have the lowest power production costs. [..] The development of a new transportation load may facilitate financing of low cost base load generation and renewables [..]". SCOT [2007] provides corresponding cost estimations for electric vehicles and utilities for the valley-filling approach for specific regional U.S. grids. It is argued that "the economics for both the prospective vehicle owner and the electric utility are promising". However, more detailed analyses are needed in this regard.

Furthermore it is argued that wind power could benefit also due to the generating profile "which [..] tends to peak at night" [MIT 2007].

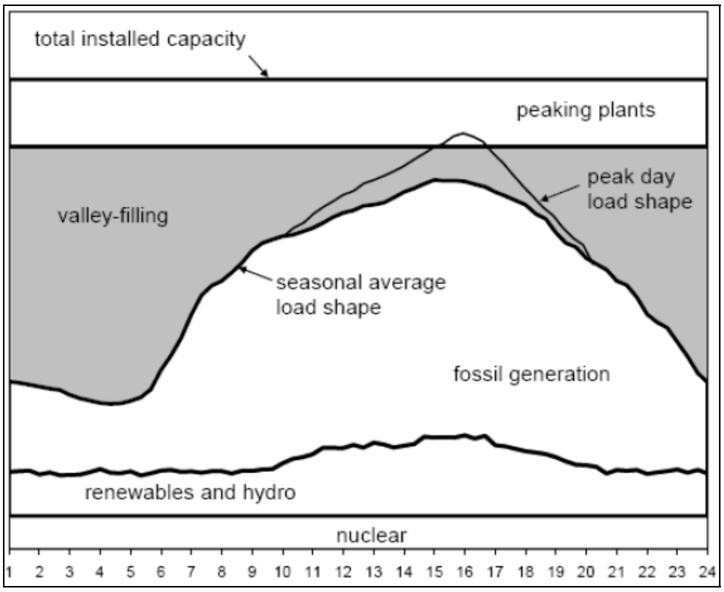

Figure 16: Valley-filling (Source: [KINT 2007],[MIT 2007])

Other sources argue that valley-filling by electric vehicles contradicts efforts so far achieved to reduce (emission-intensive) electricity generation, especially during night time. In Germany, for instance, there have been efforts to phase out electric storage heating which stores heat provided by base load electricity during the night and provide that heat during daytime. In Germany generators affected by this phase-out are (emission-intensive) lignite-fired power plants. Since electric vehicles could (partially) fill this night valley, ILGE [2009] refers to electric vehicles as "electric storage heating on wheels".

According to a study by ADEME [ADEM 2009], for an overall beneficial environmental performance of EVs it is indispensable that charging is done with low-carbon or zero-carbon electricity. In the case of France, this corresponds especially to nuclear, hydro and wind power. Today's low-carbon and zero-carbon electricity corresponds to a maximum of 4 GW during night time (midnight to 7 a.m.). This would allow incorporating one million of EVs. By 2020, additional 9 GW are expected to be available. Even considering additional electricity demand by rail, in 2020 four million EVs could be charged during night time.

BERR [2008a] also advocates charging of EVs during night time. For this purpose, "dynamic pricing smart metering will be required". In Britain, during night time mostly low-carbon sources (e.g. nuclear and hydro) operate which favours charging during the night from an environmental perspective. The paper argues that even if a combined-cycle gas turbine had to be dispatched for the additional demand by EVs, efficiency gains could be in the order of 5 % (from 52 % part load efficiency to 57 % full load efficiency). Charging during night time would also be beneficial since low-cost power plants are the marginal generators. Such a "grid-friendly" charging behaviour is suggested to be encouraged by dynamic electricity pricing via smart metering. Since it is expected that EVs will be used in city centres first, the impact on the local distribution grid has to be investigated. Quick charge capability could further impact generation and transmissions/distribution networks.

MAYO [2009] states for the London EV concept that charging at night, "using electricity from base-load generating capacity, will reduce the need for the more carbon intensive peak generating capacity"[3].

PBL [2009] also advocates night charging. In the case of the Netherlands, base load is provided by "relatively cheap coal and nuclear power stations". The authors argue that with a further expansion of wind capacity, wind electricity generation could also be tapped during the night. Furthermore, with some load management, "the dependence on [costly peak] gas-fired power stations could decrease".

Similarly, EABEV [2009] promotes night charging of electric vehicles. In the case of France, this would mean that the "less CO_2 emitting fraction of the electricity production" could be used. This would "provide electricity producers with a financial incentive to profitably replace low-capital peak power plants, which are less efficient and emit more CO_2, with capital-intensive power plants designed for continuous operation, which are more efficient and emit less CO_2 and air pollutants". It was estimated that, when charging during night time, "at least 23% of the cars in France can be electric cars without requiring significant increase in the electrical infrastructure".

<u>SUMMARY</u>: ELECTRIC VEHICLES TO OPTIMISE THE EXISTING POWER SECTOR

Results from literature

- This energy world features electric vehicles with load management designed to optimise the existing power sector by filling the "night valley" (low load during night time). Key aspects are an increase of the efficiency and load factors of power plants.
- Valley-filling could integrate a significant amount of electric vehicles with currently available generation and grid capacity.
- Significant efficiency gains could be tapped by valley-filling due to less part load situations and less load changes of power plants.

[3] The structure of the UK power mix includes a significant share of (base load) nuclear power capacity.

- Load factors of base and intermediate load generation (coal, nuclear) increase. Thus, the competitiveness of these power plants increases over other power plant options with corresponding implications on the future power mix and CO_2 emissions.
- Charging at base load situations implies low electricity generation costs, more even grid loads and in some (lignite, hard coal), but not all (nuclear, hydro) cases high-carbon electricity generation.
- Load management of electric vehicles is necessary, for instance by electricity pricing and smart metering.
- Valley-filling may contradict other efforts to reduce (emission-intensive) electricity generation.

Discussion and recommendations

The literature review shows that charging of electric vehicles during the night valley assumes that this is feasible from a technical point of view and considering consumer acceptance. However, real-world data whether this shift would actually take place and whether consumers would accept it is not available, which makes an evaluation of this approach difficult.

Furthermore, the argument of many studies that the valley filling approach could avoid additional peak loads may be questioned in case there is a large penetration of electric vehicles in the future (which could lead to peak during night time).

Base load power plants (such as nuclear or coal) would benefit from the valley filling approach, thus leading to incentives for further investments in these technologies. It remains an open question, though, whether an increased construction of (rather rigid) base load generators would be compatible with other policy goals, namely with the integration of renewable electricity generation into the power systems which would require flexible power plants to match supply and demand.

Furthermore, impacts on the power sector depend significantly of the structure of the power sector in question. Generalised statements are therefore not valid, but national and regional circumstances have to be taken into account. However, a further integration of the European power network in the years to come may compensate regional differences by supplying power to one single market. Sufficient interconnection capacities are fundamental for this.

Studying the impact on CO_2 emissions when EVs are used to optimise the existing power sector the following points should be taken into account:

- An assessment of CO_2 impacts assuming load management to optimise the current power sector should consider the type of base load generators (low-carbon, high carbon) in the respective area and base load investment options available.
- Real-world data on the technical feasibility of the shift to night times and consumer acceptance should be generated.

- Interactions with other policy goals (especially the promotion of renewable electricity generation) should be investigated.

4.2.4 Integration of electric vehicles in an overall energy strategy

This energy world comprises an integrated consideration of supply (conventional power plants, renewable energy sources) and demand (from electric vehicles) including its temporal variations. Key aspects are the integration of intermittent electricity generation from fluctuating sources of energy (such as solar or wind) or load management for electric vehicles.

According to MART [2009], the "co-evolution of power grids, energy storage and electric vehicles" provides the opportunity to interconnect the electric power and transport systems "for the first time in history". This would imply a shift of paradigm with regard to the concept of the power grid. "Load follows supply" would substitute "the conventional concept of "supply follows load", thus allowing incorporating the "variable output from even large installations of renewables".

<u>Vehicle-to-grid (V2G) concept</u>

A part from their function as load demand, electric vehicles could also be used to supply electricity to the grid when this is needed (vehicle-to-grid concept (V2G)) [IFEU 2007]. Comparatively few electric vehicles connected to the grid can improve the local quality of the grid and the voltage since they can be used as source or sink of power, according to the specific situation. This could also help to reduce the amount of regulation reserve needed. Large quantities of electric vehicles coupled to the grid could be used as virtual power plant for regulation reserve. Electric vehicles could provide spinning and regulation reserve capacity or functions as energy storage. However, the amount of electricity (work) stored is comparatively low. 1 million electric vehicles could only store 10 GWh assuming a battery capacity of 10 kWh per vehicle. However, regulation reserve that could be provided is significant. The same amount of vehicles could provide 3 GW of positive/negative regulation reserve (assuming a connected load of 3 kW). In the case of Germany, this corresponds to about half of the installed capacity of pumped-storage power plants (6.7 GW_{el}).

WIET [2008] argues that a bi-directional connection of electric vehicles to the grid could provide additional revenues from V2G grid services such as frequency-response and spinning reserve or from arbitrage deals. It is estimated that under the assumption that electric mobility will become the dominating propulsion technology V2G services and arbitrage deals could provide revenues of several 100 € per year.

According to CARB [2003], "energy congestion" could also be reduced by V2G since "transmission and distribution assets will be freed up and transmission and distribution construction will be reduced". The authors argue that "had vehicle-based generation been commercialised at the end of 2000", the California electricity crisis in 2000 and 2001, with energy shortage and rolling blackouts, could have been prevented if 200,000 vehicles capable of generating 10 kW each (2 GW in total) had been available to the California System Operator as "fast response, dispatchable, distributed power resource".

According to NREL [2006b], "to maximise the economic value of the PHEV to the consumer, it is almost certain that the charging and discharging [of the] vehicle will be controlled directly or indirectly by the utility system. External control allows the vehicle to be charged with the lowest-cost electricity, and also allows the vehicle to provide high-value ancillary services".

ENG [2005] assumes that the battery capacity in EVs is greater than the usual day-to-day electricity need, thus allowing providing regulation reserve to the grid. Estimates for the case of Germany indicate that 4 million EVs (corresponding to about 10% of the German car fleet) could provide 100 GWh of reserve capacity at the low voltage grid level. The paper further argues that EVs could be used as emergency generators for households in case there is a blackout of the overall grid. The V2G use of EVs is restricted to the number of charging cycles of the batteries. The authors discuss the need for batteries to cope with 1,000 charging cycles per year.

BERR [2008a] mentions the challenge of V2G that "energy providers will need to be fully confident of the availability and consistent reliability of the V2G energy, and the vehicles users will want to be confident of having a fully charged battery when they need it". Dynamic pricing could "make export of electricity to the grid more attractive during periods when wholesale prices are high". The increased cycling may pose problems to the lifetime of batteries. Correspondingly, V2G is only interesting from economic perspective if battery costs are low, wholesale market prices are high and lifetime of batteries (due to cycling) does not pose to tight restrictions.

LET [2006] argue that PHEVs should be "considered as both new load and, new distributed resources". PHEVs "could generate revenue for the vehicle owner by providing grid-support services". According to their estimations, even a penetration of EVs of 50% would hardly contribute to the system peak load, but would increase load factors and reduce cycling of generation facilities.

KEMP [2005b] and LET [2006] discuss several grid services which could be provided by EVs. V2G does not appear to be suitable for base load power, but peak power could be provided by V2G vehicles. However, corresponding operating hours per year would be low, so only limited revenues could be expected. More promising markets for V2G are expected to be ancillary services such as regulation reserve (frequency response) and spinning reserve (reserve capacity that can be provided in a matter of minutes). Limiting factors for the amount of grid services V2G could provide are onboard vehicle electronics, capacity of the plug circuit, energy storage capacity, and state of charge (SOC). According to an assessment carried out by LET [2006], the capacity restriction lies on the side of the plug circuit (e.g. 2 kW for households, 10 kW for commercial buildings). However, according to KEMP [2005b], the capacity restriction is dependent on the type of grid service to be provided and on the specific restrictions of EVs and connected load. The amount of reserve capacity that can be provided to the grid depends on the required duration of dispatch and on the SOC [LET 2006] [NREL 2006b]. Depending on the assumption regarding the duration of dispatch and the ensuing reserve capacity, revenues of up to more than $ 3,000 per year and electric vehicle are estimated. Further revenue estimations are available in KEMP [2005b]. Involved costs include "additional cost to provide V2G functionality to a PHEV and the communication and control equipment to allow remote dispatching" [LET 2006]. However, battery degradation due to discharging and re-charging remains an open issue.

BERR [2008a] discusses the possibility of linking electric vehicles to the house (vehicle-to-house, V2H) instead of connecting it to the grid. This would obviate "exporting energy back to the grid", could reduce grid demand since it constitutes an additional supply to the house, "and could also provide emergency backup in the event of power outages". V2H could be "useful in remote locations where supply can be threatened by adverse weather conditions and has high risk of power failure".

ZHON [2009] evaluates the economic value of the V2G concept with regard to two system balancing services (BS): frequency response and immediate reserve. Net profit calculations are performed for three charging scenarios (grid connected EVs at home, grid connected EVs at work, and a combination of these) taking into account revenue from providing grid services as well as "effective storage cost and any additional electricity buying costs over and above that used in normal EV operation".

DALL [2009] discusses several "possible control strategies for electric vehicles" and the corresponding "load shifting potential and automatically controlled load management" for EVs and its impact on the need for controllable power plants to integrate intermittent supply. The analysis shows that "energy required per year from controllable power plants [..] in electricity systems with a high share [..] of intermittent supply" could be reduced by up to 33% considering a simulation including demand-side management in households and PHEVs.

LASS [2009] discusses the impact of different electric car charging profiles on power demand and on corresponding load losses in the medium voltage network. The paper shows that "the charging mode has a significant impact on the peak load level". Without any load management peak power could be up to three times higher than the current level, whereas with an intelligent charging system "overlapping of the existing peak load and the additional charging load" could be avoided.

HART [2009] estimate "availability and storage capacity potential of passenger cars in Germany" which could be used for the compensation of the fluctuating character of renewable energy production. "The conclusion shows that the overall plug-in availability [..] is high (> about 90 %) and therefore the potential of the mobile storage to support the grid is able to compete with existing stationary storage technologies".

<u>Integration of renewable electricity generation</u>

IFEU [2007] analyses the different interactions between the use of renewable energy sources and electric vehicles. Electric vehicles could be used as additional load during periods with excess electricity from renewable sources which under normal conditions could not be consumed in the grid (e.g. during periods of strong wind). Corresponding incentives could be set for example by flexible tariffs for charging electric vehicles (price response). Price response may also consider the overall load situation in the grid (such as if there is a power shortage due to a failure of a conventional power plant).

WIET [2008] discusses the possibility of using electric vehicles in order to tap excess electricity by wind power in Germany. It is estimated that excess electricity would be 9 TWh for an installed wind capacity of 38 GW and 28 TWh for an installed capacity of 48 GW. In the former case, 4.5 million BEVs and 2 million fuel cell vehicles (FCVs) would be needed to use this excess electricity, in the latter case 14 million BEVs and 6 million FCVs. For the case of Northern Germany it is argued, however, that even an optimistic market penetration of EVs would not be sufficient to large high amounts of excess electricity from wind power if grid constraints remain.

KEMP [2005a] and KEMP [2006] analyse the use of V2G for a large-scale integration of wind energy into the grid. They argue that back-up capacity as well as storage capacity could be provided by innovative technology. Whereas BEVs and PHEVs are especially suitable for storage (due to the storage of electricity), PHEVs and fuel-cell vehicles could also provide back-up capacity. Similarly, BEVs and PHEVs are suitable to be used for regulation and spinning reserve, whereas PHEVs and fuel-cell vehicles are suitable for non-spinning reserves. Overall estimations indicate that "V2G could provide storage to level out the fluctuations of wind power, even when wind becomes half (or more) of total electrical generation" since most power scarcity (high demand, low supply) only last for few hours according to the analysis.

According to a scenario in NREL [2006b], if an aggressive introduction of EVs (substituting 40 % of U.S. LDV gasoline use) takes places and V2G is introduced, wind capacity and electricity generation could be more than doubled in comparison to the case without electric vehicles. According to that study, the additional electricity generation by wind "can meet the entire additional PHEV demand", and provide further wind electricity for other purposes. It is argued, though, that this benefit is dependent on the size of the PHEV fleet, the PHEV plug-in rate, the battery size or the extent to which the IC engine is allowed to run to provide greater capacity.

A German utility representative [WWF 2009] argues that load management of electric vehicles could be an interesting option for managing offshore wind power or an increasing number of solar roofs.

EPOSS [2009] furthermore states that "on-board smart solar cells" could be used which would "drive the vehicle 15 km in central Europe and 25 km in southern Europe".

OSTE [2009] discusses the Danish case for a large-scale integration of wind power (50%) and its interactions with an increased penetration of electric vehicles. According to a cost-benefit analysis assuming a share of EVs on overall road transport of 10% and V2G equipment, 150 million € could be saved per year using V2G functionality compared to additional costs of 190 million € if simple charging is assumed. Cost effects are estimated by considering load frequency control (LFC) as well as manual activated reserve.

RAUT [2009] explores the possibility of using "frequency dependent charging (FDC) of plug-in vehicles". This would be "an effective way to improve a power system's frequency stability with low costs".

SUMMARY: INTEGRATION OF ELECTRIC VEHICLES IN AN OVERALL ENERGY STRATEGY

Results from literature

- This energy world features an integrated consideration of supply (conventional and renewable power generation) and demand (electric vehicles). Key aspects are the provision of ancillary grid services, the integration of renewable electricity generation, and load management.
- Vehicle-to-grid (V2G) concept: Electric vehicles function bi-directionally – as load demand and as load supply to the grid whenever this is needed. V2G could
    - allow for the integration of significant numbers of EVs,
    - improve the local grid quality and thus reduce the amount of regulation reserve needed,
    - provide spinning and regulation reserve capacity, the use as peak load source is of lesser importance,
    - increase load factors and reduce cycling of power plants,
    - provide significant revenues for electric vehicles.
- Vehicle-to-house (V2H) concept: Electric vehicles are connected to houses, could reduce grid demand and could be used as emergency generators.
- Electric vehicles could be used to integrate significant amounts of (excess) electricity from renewable sources (such as from periods with strong wind).
- Comprehensive load management and consumer acceptance are crucial.
- Battery costs and the number of charging cycles (battery degradation) may pose restrictions to the implementation of this concept.

Discussion and recommendations

The literature review shows that a flexible charging (and discharging) of electric vehicles as part of an overall energy strategy assumes that this is feasible from a technical point of view and considering consumer acceptance. However, technical matters such as battery degradation and behavioural aspects such as the acceptance of load management and related business models by the customers remain open issues.

Furthermore, objectives of such an integrated strategy can be diverse: they can be cost-oriented, i.e. the objective could be to reduce peak load, to increase efficiency and load factors of existing power plants or to reduce reserve capacity. They could also be emission-oriented, i.e. the objective could be to maximise the integration of renewable electricity generation. Objectives of the energy systems as a whole and guiding principle (such as cost or emissions) are thus crucial for the evaluation of this concept. However, to date such a comprehensive evaluation has not been performed.

Furthermore, impacts on the power sector depend significantly of the structure of the power sector in question. Generalised statements are therefore not valid, but national and regional circumstances have to be taken into account. However, a further integration of the European power network in the years to come may compensate regional differences by supplying power to one single market. Sufficient interconnection capacities are fundamental for this.

Studying the impact on CO_2 of EVs in an integrated energy strategy the following points should be taken into account:

- An assessment of CO_2 impacts assuming an integrated approach of load demand and load supply should consider the technical feasibility (smart grid, battery) of the concept as well as consumer acceptance.
- An evaluation of this concept should consider the overall guiding principles (such as costs or emissions) governing the development of the overall energy strategy.
- The characteristics of conventional and renewable power generation in a specific region should be taken into account.

4.3 Impact on CO_2 emissions taking into account interactions with current EU legislation

As discussed in the previous section, the environmental benefits of electric vehicles depend on the electricity generation source used for charging the batteries. While using renewable energy sources for charging the batteries may be free of greenhouse gas emissions, charging batteries with fossil fuel-fired power plants may lead to significant additional greenhouse gas emissions. The overall magnitude of the impact of electric vehicles on the power sector depends on the penetration rate, yearly mileage, and the efficiency of batteries.[4]

However, besides the technical characteristics of the power generation sources and its implications on greenhouse gas emissions, the legal framework is of decisive importance for judging whether mobility with electric vehicles can be considered emission-free or whether it leads to additional greenhouse gas emissions. However, information in the literature regarding this topic is very limited. The following considerations are therefore largely based on WWF [2009][5] and own considerations.

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4 ADEM [2009] especially highlights the option of capping the specific energy consumption of electric vehicles in order to limit the impacts on the power sector.

5 [KING 2008] also includes several consideration regarding different policy measures in place. However, the impact on CO_2 emissions due to the interaction of EVs with EU regulations is not directly addressed.

The following European legislation is relevant in this respect:

- The Renewable Energy Directive
- The European Emissions Trading Scheme (EU ETS)
- The CO_2 Passenger Car Regulation
- The Fuel Quality Directice (which is not yet discussed in literature)

Regarding the use of renewable electricity for charging the batteries of the electric vehicles, emission reductions could only be obtained if the renewable electricity used for EVs is additional to existing renewable electricity policy.

According to the **Renewable Energy Directive** by the European Union, the community-wide share of renewable energies in the community energy consumption should reach a target of 20 % in 2020. With regard to electricity consumption by electric vehicles, there are two interactions with the directive: related to renewable *electricity* production and related to the overall target related to renewable energy (including other forms than electricity).

<u>Renewable electricity production:</u>

Since the EU renewables target is an overall community-wide target, any surplus of renewable electricity production in one member state may be compensated by a lower renewable electricity production in another member state [EUCON 2008, EUPA 2008] by a statistical transfer between these member states. This means, that if additional renewable electricity is produced in one member state in order to charge electric vehicles this could not lead to an overall increase of renewable electricity generation beyond the EU targets since due to the statistical transfer this additional renewable electricity is offset by a smaller production of renewable electricity in another member state. In sum, electric vehicles would either be charged with conventional (fossil and nuclear) electricity or, if charged with renewable electricity, the corresponding amount of renewable electricity would no longer be available for other consumers (households, etc.) which would lead to increasing emissions from electricity generation for other consumers. In consequence, the current legal framework does not establish additionality of renewable electricity generation for electric vehicles beyond established EU targets. Until 2020, electric vehicles charged by renewable electricity will therefore probably not lead to an overall increase of renewable electricity production. For the current legal framework, it is therefore not conclusive that electric vehicles are charged with “green” electricity.

This phenomenon is depicted in Figure 17. According to the EU Renewables Directive, there is an overall target for renewable electricity generation (circle at the bottom of the graph). Each member state has to contribute to this overall target. In the first case on the left side, a member state (member state 1) has national legislation for the promotion of renewable electricity in place (green block on the top left) which allows the member state to comply with its national target (“Compliance MS 1”). In the second case on the right side of the graph, the same member state increases the promotion of renewable electricity generation in order to charge its electric vehicles (“REN electricity for EVs”). However, in the current legal framework this additional electricity generation for electric vehicles is “soaked up” by member state 2 which, due to the statistical transfer included in the directive, can reduce its national efforts for the promotion of renewable energies and still complies with the directive. The overall sum of renewable electricity generation in the EU is thus the same in both cases which means that the renewable electricity used by electric vehicles is not additional.

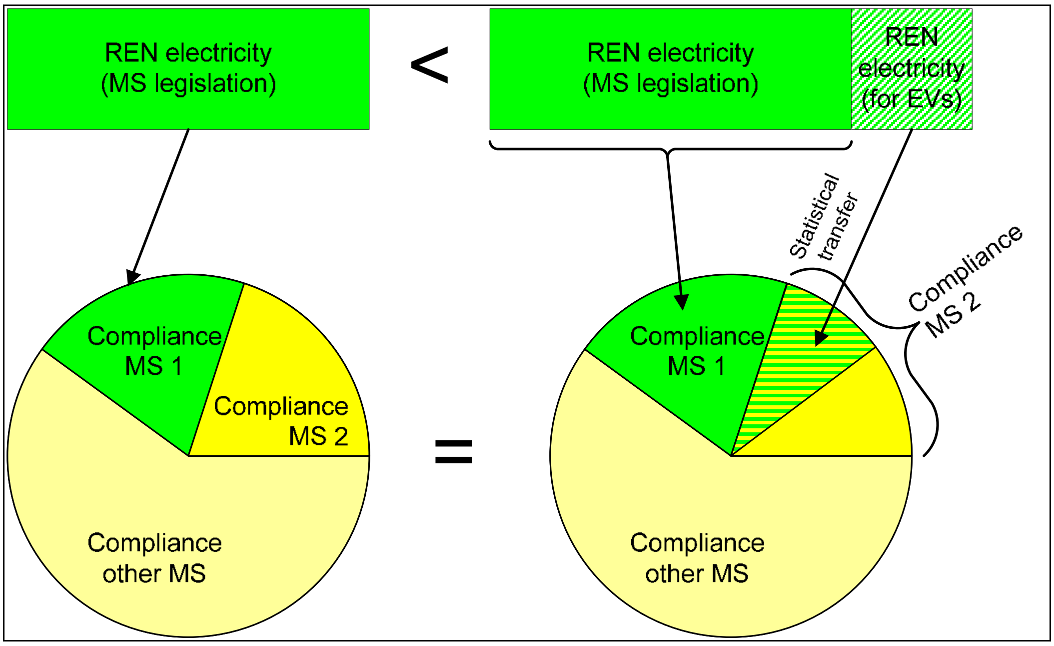

Figure 17: Accounting of renewable electricity generation according to the EU Renewables Directive (Source: Öko-Institut)

If renewable electricity consumption by electric vehicles is looked at from a national perspective, similar phenomena occur. In Germany renewable electricity for electric vehicles would not increase the overall electricity generation from renewables since all such generation is covered by the existing German feed-in law [WWF 2009]. This means charging with renewable electricity in Germany under the current framework would be offset by a lower renewable electricity consumption in other sectors (households, etc.).

Renewable energy consumption

Since the EU target refers of renewable energy consumption in general (electricity and other energy forms), even if overall renewable electricity generation in the EU was increased due to electric vehicles, the overall renewable energy balance (and thus greenhouse gas reduction effects) would remain the same since efforts to promote other forms of renewable energy, such as for heating and cooling, could be decreased and the overall target would still be met. In that case electric vehicles would not be emission-free, but would have to be assigned the greenhouse gas emissions generated by fossil energies necessary to compensate for the decrease of use of renewable energies for heating and cooling.

Figure 18 displays this phenomenon. A member state has a renewable energy target according to the EU Renewables Directive (circle) which is made up of renewable electricity generation and renewable energy for other purposes such as heating and cooling. In the first case (left side), the member state produces a certain amount of renewable electricity (box on top left, upper part of left circle) and complements with a certain amount of renewable energy other than electricity (lower part of left circle). In the event that the member state increases its renewable electricity generation in order to charge its electric vehicles (box on top right), the share of electricity of the member states' renewables target would increase (upper part of right circle). In consequence, the member state could reduce its efforts to promote renewable energy use other than electricity (lower part of right circle). In consequence, renewable electricity for electric vehicles would not lead to additional renewable energy production for the member state as a whole.

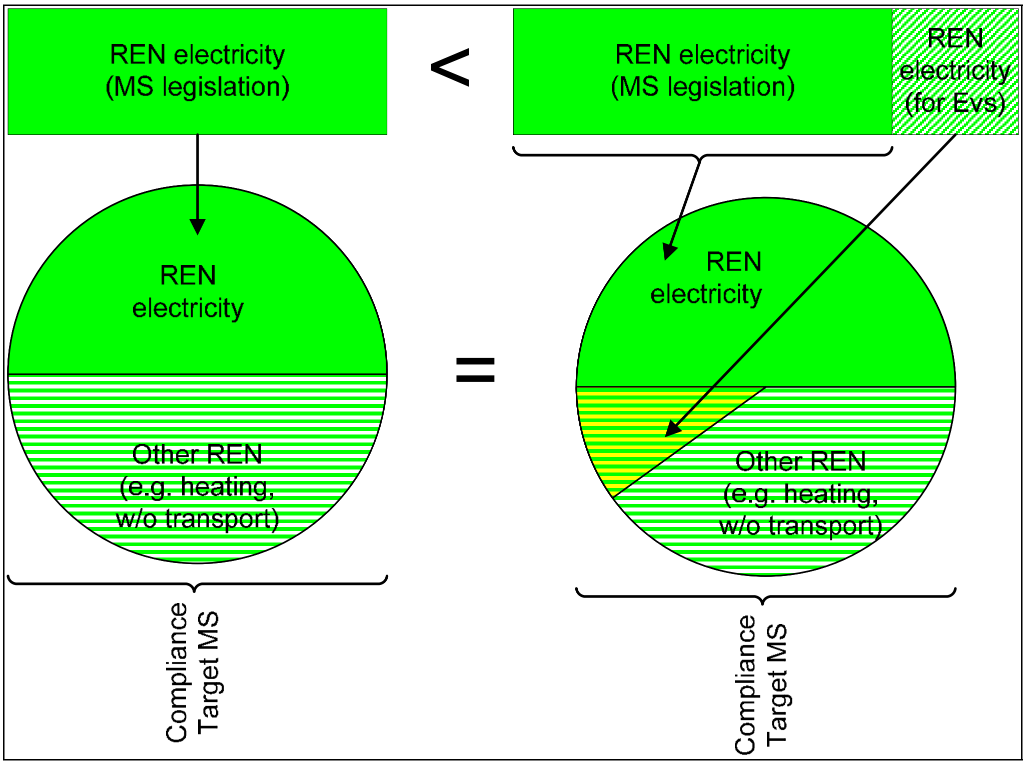

Figure 18: Accounting for renewable energy production according to the EU Renewables Directive (Source: Öko-Institut)

As a consequence of this legal framework for the promotion of renewable energies on national and EU level, additional renewable electricity generation for electric vehicles cannot be considered as emission-free until 2020. An emission-free charging of electric vehicles could only be assumed if the promotion of renewable electricity generation in member states is increased beyond what is already established by the European Union (renewables directive) and national legislation without any possibility of offsetting or statistical transfer.

A different perspective on the use of renewable energy sources by electric vehicles is obtained when considering the interactions with the **European Emissions Trading Scheme (EU ETS)** [WWF 2009]. Under the EU ETS, absolute emission levels of electricity generators and other large emitters are capped. Any additional electricity consumption (as by electric vehicles) thus does not lead to any additional greenhouse gas emissions in the EU ETS. The cap is fixed until 2020.

Any shift of emissions from the use of fossil fuels in the transport sector, which is not covered by the EU ETS, to electricity generation, which is covered by the EU ETS, leads to decreasing emissions in the transport, but to equal emissions under the EU ETS. In consequence, additional electricity consumption used by electric vehicles can be considered emission-free [WWF 2009].

In order to evaluate the impacts of additional electricity consumption by electric vehicles on CO_2 emissions after 2020, for which the cap under the EU ETS is not yet fixed, it is necessary to assess whether the additional electricity demand by electric vehicles will be reflected in a future cap setting. If it is not considered when the cap is set (i.e. the cap is not increased due to additional electricity demand by electric vehicles), the additional electricity used by electric vehicles could still be considered emission-free. However, if the cap is adjusted due to electric vehicles, electricity consumption by EVs cannot be considered emission-free anymore [WWF 2009].

A third dimension of assessing the systemic impact of electric vehicles on greenhouse gas emission is the interaction with the **CO_2 Passenger Car Regulation**. For the year 2015, an average emission of 130 g CO_2/km is defined for the whole fleet of new cars which have to be achieved by technical energy efficiency measures. For 2020, emission standards of 95 g CO_2/km are planned. Currently, electric vehicles are accounted for with 0 g CO_2/km under this Regulation. In consequence, other vehicles are allowed to emit more thus reducing the incentive for innovation regarding conventional internal combustion engines [WWF 2009]. Additioanlly, car manufacturers would be allowed to count EVs 3.5 times for their overall car fleet in 2012 (down to 1 in 2016). This would effectively reduce the level of the CO_2/km target for the entire fleet of one manufacturer and therefore the level of ambition of this legislation.

From the above considerations it can be concluded that until 2020 the introduction of electric vehicles probably does not lead to a significant reduction of CO_2 emission in the overall system [WWF 2009]. The design of the legal framework regarding additionality of renewable electricity generation, emissions trading and the CO_2 standards for passenger cars is thus decisive for the issue of whether electric vehicles will achieve additional emission reductions [WWF 2009].

<u>SUMMARY</u>: IMPACT ON CO_2 EMISSIONS TAKING INTO ACCOUNT INTERACTIONS WITH CURRENT EU LEGISLATION

Results from literature

- The legal framework is decisive for the question whether electricity consumption by electric vehicles can be considered emission-free or lead to additional greenhouse gas emissions.
- Renewable Energy Directive
  - Overall EU target for renewable energy consumption (electricity and other energy forms) is 20 % by 2020
  - Additional renewable electricity generation in one member state may be offset by a lower generation in another member state
  - Additional renewable electricity generation may be offset by a lower use of other renewable energy sources
- European Emissions Trading Scheme (EU ETS)
  - Absolute emission levels are capped (until 2020); additional electricity generation does not lead to additional greenhouse gas emissions. Shift from emissions in transport sector (fossil fuels) to EU ETS, leads to decreasing emissions in transport sector.
  - Cap setting after 2020 is crucial: if electric vehicles are considered when setting the cap (i.e. cap is increased), electricity consumption by EVs can no longer be considered emission-free.
- CO_2 Passenger Car Regulation: Electric vehicles are accounted for with 0 gCO_2/km for the overall fleet target in 2012/2015 (130 g CO_2/km). Incentives for innovation in IC engines could thus be reduced, according to literature.
- Until 2020 the introduction of electric vehicles probably does not lead to a significant reduction of CO_2 emissions in the overall system, according to literature.

Discussion and recommendations

The literature results clearly demonstrate that the definition of the legal framework plays a pivotal role in the question of whether electric vehicles could provide a real and significant contribution to overall greenhouse gas reductions.

Generally, the issue can be broken down to three levels of interaction between the legal framework and electric vehicles:

1. **Interactions within legislation:** The promotion of electric vehicles directly interacts within different types of legislation. The framework regarding renewables legislation, emissions trading and emissions standards for internal combustion engines were designed without explicitly considering an increased penetration of electric vehicles. Consequently, the level of ambition of legislation depends fundamentally on whether and how electric vehicles are considered:

a. Regarding the promotion of renewable electricity, additional benefits of electric vehicles regarding greenhouse gas reduction can only be accrued, if renewable electricity consumed by electric vehicles goes beyond renewable electricity production already defined by national and community targets and corresponding legislation. If this additionality is not ensured, emissions reduced in the transport sector are offset by increasing emissions in other sectors (which formerly used renewable electricity now used by EVs).

b. Regarding emissions trading, additional benefits of electric vehicles only arise if the level of ambition regarding cap setting is defined regardless of electric mobility. In the event that the cap is inflated due to an expected increase of charging of electric vehicles, additional emissions due to electric vehicles occur in the emissions trading sector.

c. Regarding emission standards for internal combustion engines, additional benefits of electric vehicles are only accrued if the level of ambition for other vehicles remains the same regardless of penetration of electric vehicles. If electric vehicles lead to an inflation of emission standards for conventional vehicles, emission reduction effects of electric vehicles are offset by conventional vehicles.

2. **Interactions between different types of legislation:** Besides the interaction within legislation, different types of legislation also interact between each other in the context of electric mobility. For instance, an (additional) increase of renewable electricity production due to electric vehicles leads to a lower electricity production from conventional power plants covered under the EU ETS. Consequently, emission certificates formerly used by fossil-fired power plants are freed up and used elsewhere in the emission trading sector. Therefore, if additional renewable electricity for electric vehicles is available, the cap in the EU ETS has to be adjusted downwards in order to maintain the level of ambition in the trading sector. There may be other pertinent types of interaction.

3. **Interactions with overall national and EU greenhouse gas targets:** besides avoiding carbon leakage inside of legislation (1.) and between legislation (2.) due to the introduction of electric vehicles, interactions with overall national and EU greenhouse gas targets have to be taken into account. In the event that transport emissions (from fossil fuels) decrease due to the introduction of electric vehicles and offsets regarding renewable electricity generation and emissions trading can be avoided (see above), emission reductions generated by the transport sector due to electric vehicles could be offset by reduced greenhouse gas reduction efforts in other (non-trading) sectors (such as in households) if the overall national and EU target remains the same as without the introduction of electric vehicles. Overall national and EU greenhouse reduction targets should therefore reflect the introduction of electric vehicles by downward adjusting of the overall target.

Due to the limited information available in literature, further analyses should be carried to investigate interaction between national and EU legislation and electric vehicles regarding environmental effects. These analyses should assess

- how additionality of renewable electricity generation for EVs could be established beyond the EU target taking into account the 10 % target for transport and existing national support schemes,
- how cap setting under the EU Emissions Trading Scheme could reflect additional electricity demand by EVs in order to ensure that reductions of emissions in the transport sector are not compensated by increasing emissions in the EU ETS,
- how the development of further emission standards for passenger cars could be designed in a way that incentives to improve the efficiency of IC engines are maintained, even assuming a significant introduction of EVs,
- how the Fuel Quality Directive can be used to ensure the use of additional renewable energies for EVs,
- how "carbon leakage" between different types of legislation can be avoided, and
- how overall national or community commitments regarding an international climate commitment could reflect emission reductions achievable by electric vehicles in a way to avoid an increase of emissions (or lower efforts) in other sectors.

These aspects should be considered in the design and negotiation of the future legal framework already during the next years including the climate negotiations in Copenhagen at the end of 2009.

4.4 Impact on air quality and noise

The impact on local air quality and on vehicle noise emissions is of particular relevance when analysing vehicles with electric driving mode. In contrast to GHG emissions which are relevant on a global scale, air pollutants and noise emissions are of particular concern on the local level from a public health perspective.

4.4.1 Air quality

While emissions of regulated air pollutants from vehicles continue to fall across the EU in average, traffic-related emissions of air pollutants continue to cause major air quality problems and associated health effects in urban areas [EUCO 2007, EEA 2009]. Despite the progressive tightening of air emissions limits applied to road vehicles, particulate matter and NO_x did not improve significantly and still exceeded the targeted limits during the last years, especially in urban areas [EEA 2008, EEA 2008a, EEA 2009]. The exposure to particulate matter, particularly $PM_{2.5}$, was estimated to reduce statistical life expectancy by approximately nine months in the EU in the year 2000 [EUCO 2007]

As already discussed, vehicles in electric driving mode do not have any tailpipe emissions – including air pollutants, but may show a varying amount of upstream emissions related to the fuel mix and efficiency of power generation, as well as emissions from transmission and distribution of the power to the end users [ACEEE 2008].

It can be expected that all urban emissions would significantly improve, since grid electricity is mostly generated outside urban areas where air pollutants are presently concentrated [BRAD 2009, EABEV 2009, PBL 2009]. Due to the 'displacement' of air pollutants from vehicle tailpipes near streets in mostly urban and densely populated areas to remote power plant sites considerable population exposure benefits are generated [IEA 2007]. It is assumed that rural emissions of non-reactive primary $PM_{2.5}$ and CO cause only one fourth of the damage compared to urban emissions. The damage costs per kg of reactive pollutants' rural emissions (VOC, NO_x, SO_x) are also estimated to be lower than for urban emissions, although on a smaller scale [IEA 2007]. With regard to plug-in hybrid electric vehicles a further displacement of air pollutant emissions is likely to occur on the local level due to a modified operation of the internal combustion engine. At current conditions with a dominating share of conventional vehicles, higher concentrations of non-reactive tailpipe pollutants occur at intersections than at mid-block locations. In contrast, plug-in hybrid electric vehicles would reduce air pollutant concentration at intersections due to the electric acceleration assistance. As sidewalk and vehicle queues' build up at intersections, zero emissions at intersections should provide the highest value in terms of human exposure reduction [IEA 2007].

The time of emissions is of considerable relevance and could be shifted from day to night-time in the case of electrically driven vehicles. Assuming a night charging of electric vehicles, ozone concentrations are likely to be reduced compared to emissions of conventional vehicles during daytime, as chemical reactions in the presence of sunlight favour the formation of ozone.

The amount of total air pollutant emissions per kilometre is largely determined by the energy supply and may vary widely depending on the source of energy production. An evaluation of PHEVs [IEA 2007] indicates a long-term ability to provide at least small improvement in air quality in the U.S. and small to significant improvements in Europe due to the cleaner grid mix and a higher share of diesel vehicles with higher tailpipe air pollutant emissions. But the effect is considered to remain smaller than the benefits associated with the displacement of air pollutants to non-urban areas.

An ACEEE-analysis of air pollutant emissions from electric vehicles indicates a general improvement of NO_x emissions compared to conventional vehicles, whereas the relative SO_x emissions performance depends upon the electric power fuel mix [ACEEE 2008]. Assuming a further improvement of power plant emissions due to national regulations (e.g. the Clean Air Interstate Rule in the US), further benefits of the electric driving mode could be acquired with regard to SO_x, NO_x and mercury pollutants [ACEEE 2008, BRAD 2009].

BRAD [2009] states for PHEV with an electric range of 30 kilometres a 44 % reduction potential for NO_x and non-methane organic gasses assuming a marginal US powerplant capacity during night charging. Organic compounds (VOCs) and CO could decrease by more than 90 % because of the reduction in internal combustion engine operation, whereas particulate emissions (PM_{10}) would increase slightly and SO_x even drastically because of the emissions due to coal-fired power plants.

With regard to the current UK grid mix, in contrast to zero tailpipe emissions that would improve air quality in urban areas, BERR [2008] assumes higher overall emissions of NO_x and SO_x and some potential negative consequences for air acidification with EVs. With an increasing proportion of renewable power and reductions of the use of coal power generation these impacts would reduce over time.

A study of the Electric Power Research Institute [EPRI 2007a] finds that in many US regions deployment of PHEVs would reduce exposures to ozone and particulate matter, and reduce deposition rates for acids, nutrients, and mercury because of the significant reduction in emissions from gasoline and diesel fuel use and because caps are in place for some conventional pollutants for the electric power sector.

A further aspect which is not yet dicussed in detail are the climate effects of O_3 and fine aerosol particles related to the introduction of EVs. First modelling results are presented in [ATEN 2009]. Sensitivity studies were undertaken to assess the radiative forcing impacts of a potential major technology shift that would reduce on-road transportation emissions by 50 % (by PHEVs) with the replacement energy supplied either by a clean zero-emissions source or by the power generation sector, which results in an estimated 20 % penalty increase in emissions from this sector. Their model results for two different scenarios indicate that "full assessment of the environmental impacts of technology and policy changes designed to counter global climate change must consider the climate effects of O_3 and aerosol air pollution that may outweigh CO_2 effects depending on the replacement energy source".

<u>SUMMARY</u>: IMPACT ON AIR QUALITY

Results from literature

- Traffic-related emissions of air pollutants continue to cause major air quality problems and associated health effects in urban areas. Particulate matter and NO_x are of particular concern.
- The major benefit which can be drawn form electric vehicle operation with regard to air quality is the "displacement" of harmful air pollutants from urban to rural areas, where population exposure is lower.
- With regard to the total amount of generated air pollutants, benefits depend on the grid mix properties and on the type of substituted conventional vehicles.
- A further effect results from the temporal shifting of energy demand and emission production as certain chemical reactions mainly occur at the presence of sunlight (e.g. ozone formation).

- The displacement of local air pollutants generates higher environmental benefits than the slight reduction of the total amount of air pollutants.
- Assuming more stringent power plant emission regulations in the future, the benefit of electric vehicle operation with regard to air quality improvement could further increase.

Discussion and recommendations

Despite major improvements of air quality in urban areas, traffic-related air pollution remains an issue of concern in high traffic areas. While major improvement can be expected from the displacement of air pollutants from urban to rural areas through the increased use of electric vehicles, the overall emission benefit compared to conventional vehicles depends on a further improvement of emissions from conventional propulsion technology and the development of power plant emission regulation:

- Further research would be helpful to asses the impact on air quality in the context of further emission reduction that is expected for conventional cars due to tightened emission standards (see EURO 5, 6). The effectiveness of improved emission standards have to be critically assessed for real-world urban driving conditions.
- Highly polluted urban areas should be of main interest. Further, more detailed analysis should be carried out for certain urban hotspots such as intersections and inner-urban high traffic roads where air quality standards are often exceeded.

4.4.2 Noise

Urban traffic noise levels usually exceed the guidelines set by the World Health Organisation for the protection of health. Latest assessments suggest that around 20 % of the European Union's population suffer from noise levels that scientists and health experts consider to be unacceptable [EUCO 2007]. Surveys show that road traffic is the most important source of serious noise nuisance [PBL 2009, EEA 2009].

EU Member States reported standardised noise data in a structured way for the first time in 2007, following the adoption of the Environmental Noise Directive in 2002 [EEA 2009]. According to the Directive, strategic noise maps have been drawn up using common noise indicators that allow the assessment of the exposure to ambient noise in major agglomerations. However, the current EU legislation does not set neither ambient noise limits nor target values that are mandatory [EEA 2009].

Noise from traffic is determined by the vehicle powertrain, the tyre-road interaction and wind resistance [EEA 2009]. Noise measurements show highest values at 50 km/h zones; at speeds below 40 km/h vehicle noise is dominated by the engine, at higher speeds tyres and wind resistance start to cause the major noise nuisance [PBL 2009].

The electric propulsion system is characterised by considerably lower noise emissions than the conventional internal combustion engine powertrain. As major noise annoyance in urban areas is caused by mopeds, scooters and motorcycles (around 20 % from scooters, 11 % by motorcycles), the electrification of these means of transport could generate even greater benefits. Passenger cars score with only 6 % below nuisance from neighbours or neighbourhood activities [PBL 2009].

A test documented in the UK Department for Transport's 'An examination of vehicle noise test procedures' paper states that a diesel van produces noise levels of 75.6 and 71.4 dB(A) on two tests, while an equivalent electric van was quieter, producing levels of 68.8 and 68.2 dB(A) respectively [BERR 2008a]. As a result of a large-scale introduction of EVs, noise emissions from road transport could be significantly reduced, in particular at low speed driving situations and during vehicle acceleration. Noise nuisance from motorways would diminish only partly [PBL 2009].

As a consequence, drivers as well as pedestrians and other road users will need to become accustomed to vehicles driving whose speed cannot be detected by increased engine noise [BERR 2008a]. PBL [2009] states that without specific built-in modifications, electric driving would create diminished road safety for other road users that rely partly on sound as a warning system for approaching traffic. A study cited in [PBL 2009] comes to the conclusion that "when road-traffic changes occur, the risk of accidents goes down, at least temporarily". Nevertheless, research has shown that quieter means of transport (e.g. tramways) lead to a slight increase in road accidents [PBL 2009]. EABEV [2009] refers to statistics that do not show that electric vehicles cause more accidents.

Therefore, whether electric vehicles with low noise emissions could cause traffic safety problems due to a reduced perceptibility for other traffic participants remains a question that needs to be further evaluated and should be addressed in the scope of the announced pilot projects.

SUMMARY: IMPACT ON NOISE

Results from literature

- Urban noise levels are mainly caused by road traffic and usually exceed the WHO-guidelines.
- According to the EU Directive on noise, major European agglomerations started to report standardised noise data (noise maps).
- Noise emissions from electric vehicles are significantly reduced at low-speed driving and during acceleration. Therefore, the noise level would be particularly lowered in urban driving situations, whereas interurban driving is mainly dominated by rolling noise and noise from wind resistance.

Discussion and recommendations

Urban noise is of particular concern and mainly caused by road traffic. The electric propulsion is likely to reduce propulsion-related noise nuisance significantly, but in particular noise at higher speeds will be only reduced to a small extent as it is mainly dominated by rolling noise and wind resistance. Simulation approaches are required to determine the overall impact on urban noise of a large-scale introduction of electric vehicles:

- The impact of a large-scale introduction of electric vehicles on noise mainly in urban areas is only poorly studied and should be further investigated.
- Noise reduction potentials that are related to other means of transports (e.g. motorcycles and scooters) should also be considered.

Effects on road safety are only poorly studied for electric vehicles and need to be further investigated. Experiences from early markets and fleet tests could represent valuable sources of empirical data.

5 Summary

The development of electric vehicles and related research is currently characterised by considerable dynamics. Therefore, at present, projections of technological development and deployment of electric vehicles and the associated environmental impacts remain uncertain. This report provides an insight into the current status of electric propulsion technology, an overview of related public and private activities, an illustration of potential pathways towards a large-scale introduction of electric vehicles and a discussion of the most relevant environmental impacts.

What is needed to get a global picture on the environmental impact of a large-scale introduction of EVs?

The literature review clearly demonstrates that four spheres have to be considered in an integrated way in order to evaluate the environmental effects of a large-scale introduction of electric vehicles:

1. **The technical sphere:** Fundamental technical questions relate to the reliability of battery systems, the energy demand per vehicle, but also to issues like the technical feasibility to integrate EVs in the energy sector in a flexible way (regarding degradation of batteries, bi-directional connection to the grid etc.).
2. **The mobility sphere**: EVs could generate a positive impact on the environment only if they substitute significantly mileage from conventional cars. So questions with regard to acceptance and mobility behaviour are crucial. Furthermore, embedding electric mobility in an overall mobility concept including aspects such as modal shift and new linkages between different means of transport should be considered.
3. **The energy sphere:** The environmental benefits of EVs also depend fundamentally on what type of electricity (fossil, renewable, nuclear) is used for charging and what consequences charging has on the operation of existing power plants and construction of new power plants.
4. **The legal sphere:** Finally, potential environmental benefits arising from a well-designed technical concept and sound integration into the energy system can only be accrued, if overall legislation regarding all aspects of energy production and consumption as well as greenhouse gas reduction is designed in a way that emission reduction in the transport sector are not offset by increases of emission in other sectors.

Figure 19 illustrates a potential approach which allows getting a global picture of the potential of electric vehicles regarding their contribution to greenhouse gas reductions considering all influencing factors and their interactions in an integrated way.

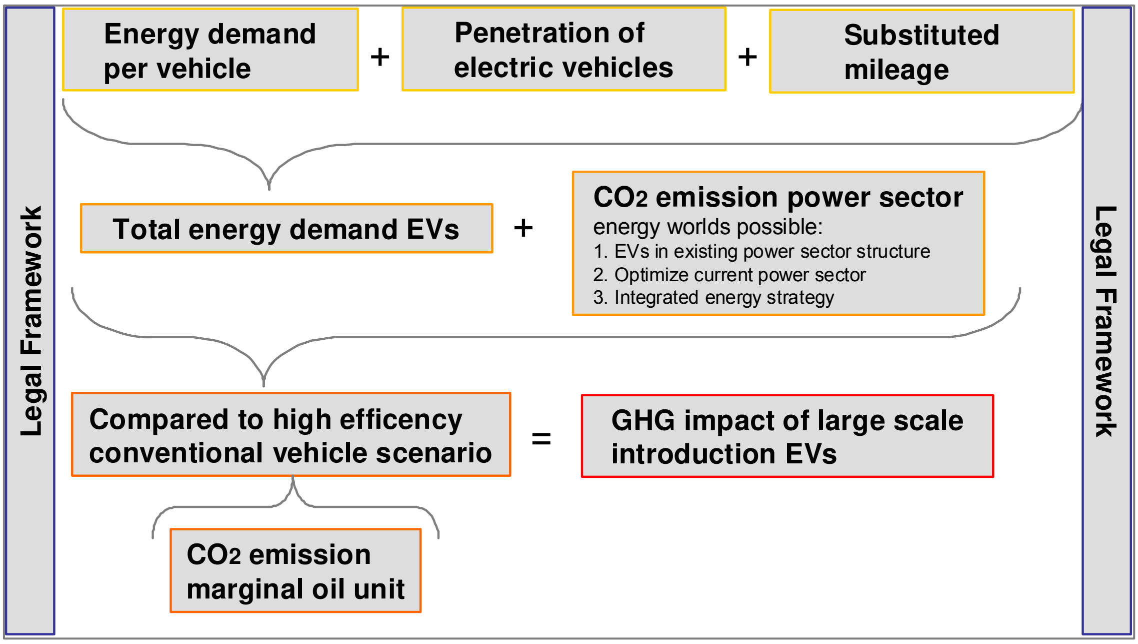

Figure 19: Interaction of factors influencing the overall GHG emission impact of a large-scale introduction of EVs.

The total energy demand of electric vehicles is determined by the average energy demand of state-of-the-art EVs (technical sphere), the assumed market penetration and the electrically substitutable mileage (mobility sphere). In this context, detailed information on travel lengths, motives and charging profiles as a function of time, day and season are of particular interest for an overall assessment. In addition, economic aspects are also important and should be taken into account when regarding future potentials of electric vehicles. While the higher investment costs of electric vehicles are apparent for purchasers, running costs of different vehicle types are less transparent and not fully factored in at the moment of vehicle purchase. These economic considerations finally determine the penetration rate of electric vehicles and are therefore of main importance with regard to the overall potential of electrically substitutable mileage (mobility sphere).

The overall GHG emissions of electric vehicles are finally derived by the coupling of the energy demand of all EVs with the GHG emission for power generation taking into account interactions between load demand from electric vehicles, fluctuating renewable energy sources and conventional power plants (energy sphere). Furthermore, interactions of electric vehicles with other legal frameworks (renewables, emissions trading, non-trading sectors,…) have to be analysed (legal sphere). Finally, by comparing the resulting emissions to a scenario of high efficiency conventional vehicles and the related emissions of the marginal oil unit, the impact of a large-scale introduction of electric vehicles on climate protection can be assessed.

At the moment, none of the reviewed studies follows this research approach to determine the environmental impact of EVs. This is probably among other reasons on the one hand because the transport and the energy sector are regarded – historically grown – separately and on the other hand due to a lack of data. As soon as such "real world" data are available it is highly recommended to initiate a study following the approach depicted above. That would enable a reliable assessment of the impact of EVs on greenhouse gas emissions which is urgently required to build up an adequate political framework to meet the required emission reduction targets for climate protection.

In more detail: As a result of this literature review, with regard to the main aspects which have been discussed in this paper, the following summaries and conclusions can be drawn and remaining fields for further research have been identified:

Battery technology

The battery system remains the key technology – and main bottleneck – of electric vehicle propulsion. However, due to the important progress of battery technology in recent times, it is assumed that automotive battery technology will be available for large-scale EV use in the near future. The high costs of large battery systems are still considered a major drawback, but considerable cost degression is expected to occur in the future. Battery cost reduction is assumed to be crucial for the economic attractiveness and the large-scale deployment of EVs. Today, only few studies consider the impact on global raw material demand and supply and potential environmental impacts of a large-scale battery production, recycling and disposal. A large-scale introduction of electric vehicles would result in a considerable demand for new materials for battery production. Currently, there is a controversial debate about the global lithium supply and production in the context of a large-scale introduction of electric vehicles.

The literature review illustrates the need for further investigation with regard to further cost reduction potentials, the reliability of large automotive battery systems, the long-term lithium supply, the recycling potential and lithium recovery as well as more profound life-cycle analysis of large automotive batteries.

Electric vehicles

In the scope of this study, only vehicles with electric driving capability and grid charging (EV and PHEV) have been considered, as mild and full hybrids are rather seen as improved conventional vehicles. Major strengths of electric propulsion are the efficiency of the powertrain, zero tailpipe emissions and the diversification of energy supply. Major shortcomings are related to the remaining high price premium and driving range limitations. Due to the early stage of technological development only little data on real-world energy consumption is currently available; most of the data are based on simulations, assumptions and estimates. A growing activity in development and commercialisation of electrically driven vehicles can be observed as a result of recent major progress of battery technologies. In addition, a considerable number of fleet tests of electric vehicles, including the installation of the required charging infrastructure, are carried out or have been announced in different European countries.

The EVs that are discussed in the reviewed literature are mainly foreseen to be produced at small scale; the time of market introduction of some vehicles is still uncertain and will be mainly determined by further improvement of battery technology. To achieve a relevant market share, EVs have to prove their suitability for daily use and have to achieve customer acceptance. Furthermore, the availability of adequate charging infrastructure will be an essential prerequisite.

In the scope of announced fleet tests of state-of-the-art EVs, particular interest should be directed towards the collection of data on in-use energy consumption and vehicle acceptance. A reliable assessment of the overall energy efficiency and of the related greenhouse gas emissions has to be carried out on a well-to-wheel basis and should rely on real-world energy consumption.

Market introduction of electric vehicles

In the context of electric vehicle properties differing from those of conventional vehicles, new business models are discussed in the literature to overcome some of the main barriers such as the additional costs, energy supply, charging infrastructure and time and the limited driving range. Today, estimations of potential driving and charging behaviour as well as the identification of early target groups and areas rely mainly on the analysis of available average transport data. In the literature, it is stated that despite an average driving pattern in Europe with a high share of short trips that is perfectly suited for EVs, vehicle purchase has rather been determined by maximum range requirements that can not be fulfilled by EVs. Urban and suburban areas are assumed to be the most promising early target markets and additional EVs seem especially interesting for repeated driving patterns such as commuting and for vehicle fleets with low daily driving ranges and charging stations at their depot. Because of the limited driving range, it is further assumed that EVs may mainly be used as second cars for short distances, whereas a supplementary conventional vehicle would assure to cope with longer distances. However, plug-in hybrid vehicles can also cope with long-distance travelling which could extend the early market to other target groups. In the context of the deployment of electric vehicles, a large number of governmental policies and initiatives have been announced or have already been established on an international, national and regional level. The reviewed literature highlights the urgent need for corresponding measures to overcome the remaining market barriers.

Due to the early stage of electric vehicle deployment, the economic attractiveness of the mentioned business models remains uncertain as they are related to high economic investments and risks and only little information on their acceptance is available – mainly from niche applications. The identification of main target markets for electric vehicles and the share of electrically substitutable mileage are typically based on statistical analysis. The current approaches seem to be not sufficient to identify future potentials of electric vehicles as mobility behaviour and vehicle purchase are determined by further influencing factors.

As soon as new business models are established, further information on their acceptance should be derived to allow a more profound projection of the potential future market penetration rates of EVs. Valuable data can be derived from the recently announced fleet tests. As the data on real-world energy consumption, driving and charging behaviour, vehicle use pattern and substituted mileage are fundamental for reliable market penetration scenarios and an assessment of the environmental impact of EVs, data compilation of all demonstration projects should be facilitated, e.g. by the establishment of a European data centre.

Market penetration scenarios

In the reviewed literature it is generally assumed that electric vehicles could achieve a considerable market penetration in the future. Due to a multitude of influencing factors and remaining barriers, penetration scenarios in the reviewed literature vary greatly. The most optimistic scenarios would be related to technological penetration rates that exceed typical technological diffusion in the automotive sector. More moderate penetration scenarios could be in better accordance to historical diffusion of innovative technologies.

As a consequence of the remaining uncertainty on technological development and consumer behaviour, reliable predictions of electric vehicle deployment are difficult to outline. As the electric propulsion technology represents a radical new technology within the transport sector, historic data is of limited usefulness in order to draw conclusions on the future deployment. A sceptical view on the future potentials of EVs could be derived from the history of electric vehicle development as its market introduction failed already several times within the last decades.

On the basis of additional real-world data – likely to be generated in the course of the upcoming fleet tests – the wide range of existing market penetration scenarios should be critically re-assessed so that more substantiated projections could be established. Further, alternative mobility concepts that could be linked to the use of EVs should be considered when discussing future potentials of electric vehicle application..

Air quality and noise emissions

Traffic-related emissions of air pollutants continue to cause major air quality problems and associated health effects in urban areas. Zero tailpipe emissions of electric vehicles lead to reduced local air pollution. While the overall emissions depend on the associated power generation, major benefits are likely to occur due to the displacement of air pollution to locations of power generation where lower human exposure is found.

A further reduction of air pollutants depends on the development of power plant emission regulation. Further research is needed to quantify the future benefit of electric vehicle use in the context of tightened emission standards (EURO 5 & 6) for conventional vehicles. Highly polluted urban areas should be of main interest. Further, more detailed analysis should be carried out for certain urban hotspots such as intersections and inner-urban high traffic roads where air quality standards are often exceeded.

Urban traffic noise levels usually exceed the WHO-guidelines and cause major health problems. Corresponding surveys show that road traffic is the most important contributor to urban noise.

Noise emissions from vehicles are significantly reduced at low-speed electric driving and during acceleration. Therefore, the noise level would be particularly lowered in urban driving situations, whereas interurban driving is mainly dominated by rolling noise and noise from wind resistance. However, currently only little data is available dealing with corresponding effects in the case of a large-scale introduction of EVs.

Further research should investigate the effect of the introduction of electric vehicles on urban noise levels in greater detail. With regard to the impact of electric vehicles on road safety, clarification is needed – corresponding valuable data is likely to be derived from the announced fleet tests.

Impact on CO_2 emissions considering average emission factors

The determination of life-cycle GHG emissions depends on the carbon intensity of the related power grid mix. The available literature states a wide range of GHG emission benefits compared to conventional vehicles due to the consideration of different national grid mixes. Under moderate market penetration rates, the additional power demand remains at a low level and the use of average emission factors for the power grid represents a useful approach to determine GHG benefits of EVs. With regard to the determination of the overall GHG emission reduction potential of a large-scale introduction of electric vehicles, only a few approximate estimates are available from the reviewed literature.

While electric vehicles yield small or no reduction of emissions when electricity is provided by conventional carbon-intensive coal-fired power plants; a low carbon intensity energy mix results in much greater savings. Under the assumption of an increasing decarbonisation of the future electricity generation, electric vehicles could contribute to a considerable decarbonisation of the transport sector.

A more elaborated assessment of the overall greenhouse gas reduction potential has to consider detailed information on the real-world energy consumption. The comparison between EVs and conventional vehicles should be done on the well-to-wheel basis for the same time horizon; it should take account of the changes in carbon intensity of the electricity supply and of the progress in energy efficiency of electric and conventional vehicles through that time. In the case of a larger market penetration and correspondingly larger energy demand, further interactions with the electricity market have to be considered (see below).

Impact on CO_2 emissions taking into account interactions with the electricity market

Actual CO_2 emissions due to electricity consumption by electric vehicles depend on the type of generation source used for the additional electricity demand which in turn depends on the structure of the power sector and the charging characteristics of EVs. Electric vehicles also influence the competitiveness of power plants and the integration of renewable energy sources, and thus the future power mix and CO_2 emissions.

The literature reviewed considers interactions with the power sector in different ways. The deployment of EVs and the development of the power sector are not directly linked in several studies. Other studies consider the use of EVs to optimally utilise existing power plants. In other literature available, EVs are integrated in an overall energy strategy.

The perspective chosen on the integration in the energy sector plays a pivotal role in assessing the environmental impact of electric vehicles.

In the scenario where there is no integration between the management strategies of the power sector and the introduction of electric vehicles, an increase in peak load demand can be expected. This may require new investments in generation and grid capacity. Charging during the night time also increases base load generation. Charging at peak situations implies high electricity generation costs, high grid load and often low-carbon electricity generation (e.g. gas turbines, pumped storage hydro), whereas charging at base load situations implies low electricity generation costs, more even grid loads and in many, but not all, cases high-carbon (lignite, hard coal) or nuclear electricity generation. This scenario is therefore not suitable for a large-scale introduction of EVs due to capacity restrictions in the grid in the case peak load is increased. In case base load electricity is predominantly used, grid capacity restrictions do not constitute a prominent problem. However in these cases, charging of electric vehicles in many cases occurs with CO_2-intensive (hard coal, lignite) or nuclear electricity.

If the event load management is used to optimise the existing power sector by charging during the (low load) night valley, a significant number of EVs could be incorporated in the existing energy system. Efficiency and load factors of base and intermediate load generators (especially nuclear and coal) could increase. Charging at base load situations implies low electricity generation costs, more even grid loads and in some, but not all cases, high-carbon electricity generation. CO_2 impacts thus depend on the type of base load generators in the respective area and base load investment options. From the point of view of grid capacity, this scenario therefore does not pose major challenges. However, charging of electric vehicles in these cases mostly occurs with CO_2-intensive (hard coal, lignite) or nuclear electricity. In addition, this strategy may hamper the incorporation of renewable electricity generation, since less flexible base load generators have competitive advantages which contrast with the need of flexible power supply in order to integrate intermittent renewable electricity generation.

For an integration of EVs in an overall energy strategy, power supply (conventional, renewable) and demand (EVs) are considered jointly. Electric vehicles function both as load sinks and load sources when needed by the grid. Significant numbers of EVs could be integrated, ancillary grid services could be provided by EVs and significant amounts for fluctuating renewable electricity could be integrated in the system. Load management is crucial. CO_2 impacts depend on the technical feasibility (smart grid, battery), consumer acceptance and the characteristics of conventional and renewable power generation. If designed in a smart way, this energy world could allow for an increased integration of renewable energy sources and limit the impact on the grid. Flexible electricity supply (renewables) could be matched in an intelligent way with flexible electricity demand (electric vehicles, other consumers). An integration of electric vehicles could thus provide additional CO_2 benefits.

The literature results demonstrate that many issues regarding technical feasibility, consumer behaviour and regional characteristics of the energy sector are still open, thus making an evaluation of the proposed EV scenarios difficult. For larger penetration rates of electric vehicles, it can no longer be assumed that EVs and the development of the power sector can be considered separately. Furthermore, guiding principles (such as costs, or emissions) chosen have significant impact on the environmental integrity of electric vehicles. Depending on the integration of EVs in the power sector, other policy goals (such as the promotion of renewable electricity production) may be hampered or supported.

The literature review illustrates the need for an integrated consideration of technical feasibility, the use pattern of electric vehicles and the electricity sector. Further research should therefore address actual use patterns, especially regarding charging characteristics, as well as short-term and long-term interactions between the charging of EVs and the electricity sector in a specific region. Guiding principles (such as costs, or emissions) for the integrated approach need to be reflected, too. Other strategic priorities in the power sector (such as the promotion of renewable electricity) should also be considered.

Impact on CO_2 emissions taking into account interactions with current EU legislation

The literature results clearly demonstrate that the definition of the legal framework plays a pivotal role in the question of whether electric vehicles could provide a real and significant contribution to overall greenhouse gas reductions. Electric vehicles lead to three types of interactions with legislation:

1. Interaction within legislation, e.g. charging of electric vehicles directly infers with provisions contained in the EU Renewables Directive, EU Emissions Trading, the EU Fuel Quality Directive or the EU Passenger Car Regulation.
2. Interaction between different types of legislation: charging of electric vehicles influences interaction between different policy fields, for instance an increase of renewable electricity generation (for charging EVs) interferes with conventional power plants under the EU Emissions Trading Scheme.
3. Interaction with overall national and EU greenhouse gas targets: whether electric mobility could lead to overall emission reductions on a national and EU level depends on whether and how emission reductions in the transport sector are taken into account when overall emission targets are negotiated (in order to avoid that emission reductions are offset by emission increases in other sectors).

The design of future legal framework is crucial for evaluating the environmental benefits of electric vehicles. Due to the limited information available in the literature – e.g. the interaction with the Fuel Quality Directive or the link to the specific 10% target for renewables in transport within the the RES-Directive is not yet discussed in literature but are very important aspects, it is recommended to further analyse the interactions between EU legislation and the introduction of electric vehicles regarding environmental effects.

Further analysis should evaluate:

→ How additionality of renewable electricity generation for EVs could be established beyond the EU target taking into account the 10 % target for transport and existing national support schemes,

→ How cap setting under the EU Emissions Trading Scheme could reflect additional electricity demand by EVs in order to ensure that reductions of emissions in the transport sector are not compensated by increasing emissions in the EU ETS,

→ How the Fuel Quality Directive can be used to ensure the use of additional renwable energies for EVs.

→ How the development of further CO_2 emission standards for passenger cars could be designed to ensure that incentives to improve the efficiency of IC engines are maintained, even assuming a significant introduction of EVs,

→ How “carbon leakage” between different types of legislation can be avoided, and

→ How overall national or community commitments regarding an international climate commitment could reflect emission reductions achievable by electric vehicles in a way to avoid an increase of emissions (or lower efforts) in other sectors.

The EU policy framework for renewable energy production and emissions trading is already fixed until 2020 and should therefore be next updated for the period after 2020. Under these fixed framework conditions and above all considering the rather modest market penetration assumptions of EVs until 2020, it can be expected that the overall environmental impact of EVs shall remain low up to 2020. However, potential trends of electric vehicle deployment should be considered during the design and negotiation of all relevant future policy frameworks for the energy and transport sector, including the climate negotiations taking place in Copenhagen at the end of 2009. If this takes place in an appropriate way, the environmental benefits of electric vehicle use could be increased.

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7 Glossary

Ancillary grid services	Grid services beyond the production of electricity (such as regulation or spinning reserve).
BEV	Battery electric vehicle
CV	Conventional (internal combustion engine) vehicle
Controllable power plant	Power plant whose load can be increased and decreased according to the requirements of the plant operator
Distribution	Final stage in delivery of electricity
EV	Electric vehicle
Fast charging	Charging of electric vehicles with high electric power in order to reduce the charging time
Frequency response	Measure taken to stabilize the frequency of the grid
IC	Internal combustion
ICE	Internal combustion engine
Marginal power plant	The last power plant dispatched to supply electricity to the grid for a given grid load.
PHEV	Plug-in hybrid electric vehicle
Regulation reserve	Reserve capacity for frequency response.
Smart grid	Grid to deliver electricity from suppliers to consumers using digital technology to save energy, reduce cost and increase reliability and transparency.
Spinning reserve	Power capacity provided by spinning generators in order to deliver power to the grid in a matter of minutes.
Structure of the power sector	Mix of power plants available to supply power to the grid.
Transmission	Bulk transfer of electricity over longer distances
V2G	Vehicle-to-grid
V2H	Vehicle-to-house

8 Appendix

8.1 Market overview of further EV/PHEVs

Table 13: Overview of available and announced plug-in hybrid and battery-electric vehicles – prototypes, concept cars, test fleet and small-scale produced vehicles (literature review).

	Manufacturer / Model	**Type**	**Electric range [km]**	**Purchase price**	**Market in-troduction**	**Source**
	Chrysler / Jeep EV	PHEV	64	n/a	test fleet 2009, market launch 2010	GEWA 2009
	Chrysler / Town & Country EV	PHEV	64	n/a	n/a	AUBI 2009c
	Daimler / BlueZero E-Cell	EV	200	n/a	concept car, small scale production by 2010	ABG 2009c
	Diedre / Redigo Softcar	EV	120	€ 6,000 + leasing for batteries	2010	GRAU 2009b BIOM 2009
	Dodge / Dodge Ciruit (sportscar)	EV	240-320	n/a	2011	HYCA 2009b
	ECC / Citroen C1 ev'ie	EV	95-120	£ 16,850	available (small scale production)	ECCP 2009
	Eco & Mobility / Next-ère	EV	80-150	€ 5,000	n/a	ABG 2009f
	Eco & Mobilité / Simply-city	EV	80-150	€ 5,000	prototype	ECO 2009 ABG 2009a
	EcoCraft / ES / EL	EV (van)	50-80	n/a	available (small scale production)	ECAU 2009
	EFFEDI Auto-motive Group / Maranello SCE	EV	50-70	€ 14,800	available (small scale production)	MARA 2009 SOFT 2009

	ElBil Norge / Buddy	EV	150	$ 43,000	available (small scale production)	UNSA 2009 NORG 2009
	FAM / F-City	EV	80-100	n/a	concept car	FAM 2008
	Fisker / The Karma	PHEV	80	$ 79,000	(small scale production) 2010	FIKA2009 AUBI 2009c
	Ford / Ford Focus EV	EV	160	n/a	late 2011	HYCA2009a
	Heuliez / Friendly	EV	100 -250	< € 14,000	prototype	HEUL 2009
	MINDSET / Mindset	PHEV	100-200	n/a	2009 (small scale production)	MIND 2009
	Newteon / My Car	EV	80	€ 11,990	available (small scale production)	NEWT 2009e
	Opel / Opel Ampera	PHEV	60	n/a	2011	OPEL 2009a OPEL 2009b
	Opel Trixx / Opel	EV	55	n/a	2010	FOCUS 2007a GECA 2009 FOCUS 2007b
	Optimal Energy / Joule	EV	200	n/a	2010 (small scale production)	OPTI 2009
	Renault / Kangoo Be Bop Z.E.	EV	100-160	n/a	2011	AUBI 2009a REN 2009a
	Toyota / Toyota FT-EV	EV	80	n/a	concept car (launch 2012)	CAMA 2009

	Toyota / Prius	PHEV	10	n/a	test fleet	CNET 2009
	Venturi, PSA/ Berlingo	EV	100	€ 25,000 – 35,000	autumn 2009	WGA 2009d ABG 2009e
	Venturi, Michge-lin / Volage	EV	320	n/a	prototype, 2012	AMS 2009c
	Venturi / Fetish	EV (sports-car)	290	€ 297,000 + VAT	limited to 25 buyers, Sep. 2009	VENT 2009
	Voyager ev / Chrysler	EV	64	n/a	n/a	AUBI 2009
	VW up! / Volkswagen	EV	n/a	n/a	Concept car Small scale production starting in 2010/2011	AMS 2008

Table 14: Overview of converted plug-in hybrid and battery-electric vehicles (literature review).

	Manufacturer / Model	**Type**	**Electric range [km]**	**Purchase price**	**Market introduction**	**Source**
	Micro-Vett / DAILY ELECTRIC	EV	70-100	n/a	n/a	MIVE 2009b
	Micro-Vett / Daily Hybrid	HEV (van)	50-100	n/a	n/a	NEWT 2009g
	Micro-Vett / Electric Porter	EV	90-120	n/a	n/a	NEWT 2009b
	Micro-Vett / Fiat Fiorino	EV	70-100	From € 29,000 excl. VAT	n/a	NEWT 2009c

	Micro-Vett / Fiat DOBLO ELECTRIC	EV	150	n/a	n/a	MIVE 2009a NEWT 2009a
	Micro-Vett / Ydea electric	EV	200	€ 24,000	available	SOFT 2009
	NEWTEON / Fiat 500	EV	100	38,000 €	preserie of 50 units / launch late 2009	NEWT 2009f

Table 15: Further electric four-wheel concept vehicles (literature review).

	Manufacturer / Model	**Type**	**Electric range [km]**	**Purchase price**	**Market introduction**	**Source**
	Venturi / Eclectic	EV	50	n/a	concept car	VENT 2009b
	Venturi / Astrolab	Elec-tric-solar hybrid	110	n/a	concept car	VENT 2009c
	Estrima / Birò	EV	45-60	n/a	n/a	NEWT 2009d EST 2009