Assessing the status of electrification of the road transport passenger vehicles and potential future implications for the environment and European energy system

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Öko-Institut e.V.
Institut für angewandte Ökologie
Institute for Applied Ecology

Transport & Mobility Leuven

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Electric mobility in Europe – Future impact on the emissions and the energy systems

Final report of task 2 - Assessing the status of electrification of road transport passenger vehicles and potential future implications for the environment and European energy system

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Table of Contents

List of Figures

List of Tables

Summary

Electric vehicles charged with low-emission electricity are one of the key options to reduce emissions in passenger road transport. However, the introduction of electric vehicles will inevitably lead to greater interaction between the mobility and the electricity sector. When electric car penetration reaches higher levels, the electricity demand from electric cars will become a relevant factor within the energy system and impacts the operation of power plants and grid infrastructure.

The analysis of the impact of increasing electric vehicle car fleets in Europe therefore forms the core of the study. A literature review summarizes the general impact of electric vehicles on the power system and provides an overview of different smart charging strategies for electric vehicle integration. Two electric car scenarios of medium (50% electric car fleet in 2050) and high (80 % electric car fleet in 2050) electric vehicle penetration are used to show the impact of electric vehicles on CO_2 and air pollutant emissions for the EU-28. These scenarios are compared to the EU Reference Scenario from 2013 (8% fleet penetration of electric cars by 2050) in order to provide an overview of how much electric vehicles influence the power production and how much they can contribute to emission reduction. Other sectors and their impact on future emission reduction are not part of the study as the focus is on electric vehicle integration into the power system only. Therefore, the basis for the development of other sectors is the Reference Scenario of 2013.

Electric vehicles may become important consumers in power systems

Assuming a fast development of electric cars, the demand share of electric cars to total electricity demand will reach levels of 4-5% in several European countries by 2030. According to the EV-high scenario, the electric vehicle demand share of total electricity demand varies between 3% and 25% among the EU-28 countries by 2050. It will increase to more than 10% in many countries. On EU average, it will make up 9.5% by 2050 with an electric car stock penetration of 80%. As a transport fuel, electricity would become a relevant energy option with roughly 50% (around 450 TWh/a) of the passenger car fuel mix by 2050. The electricity demand from electric cars is obviously smaller in the EV-mid scenario (around 280 TWh/a - for EU-28) and electricity constitutes less than 25% of the final energy demand of passenger road transport.

High electric vehicle penetration strongly reduces emissions of CO_2 and most air pollutants

The increase in the number of electric cars leads to reductions in CO_2 and local air pollutant emissions in the transport sector. Depending on the set-up of the power sector (assumption of same generation mix as in the Reference Scenario 2013 for emission balance), these positive effects will be (partially) offset by additional emissions in the energy sector caused by the additional electric demand of passenger cars. By contrast, less liquid fuel use reduces the WTT emissions of fuel production. However, with a net reduction of 255 Mt CO_2/a in total (avoided emissions in transport sector and WTT emissions from power and fuel production) for the year 2050, high electric car penetration share (EV-high scenario) does have a strong positive CO_2 impact in comparison to the EU Reference Scenario 2013 (effect of electric vehicle integration).

For 2050, the total emission reduction (including WTT emissions) implies a CO_2 abatement in passenger road transport of 84% compared to 2010 (-395 Mt CO_2/a). This covers the integration of electric vehicles and energy efficiency improvements which are also part of the Reference Scenario 2013.

The impact of local air pollutant emissions from electric vehicles and emissions from power generation cannot directly be compared as the human and animal exposure to the air pollutants is different for both sectors. Nonetheless, the net balance of passenger road transport (TTW) and power generation emissions provides an overall picture of the emission effects. Electric vehicle penetration of 80% results in local air pollutant emissions reduction (PM, NO_x and SO_2) in passenger transport (TTW) of more than 80% for all pollutants in comparison to 2010 levels. The offset of additional emission in the power sector for NO_x and PM is small compared to the reductions in the transport sector. By 2050, it is 3% for PM and around 15% for NO_x. A different effect can be observed regarding SO_2 emissions. The increased use of coal in power generation results in additional SO_2 emissions which surpass the emission reduction in passenger road transport by the factor 5.

The positive impact on CO_2 and most air pollutant emissions is obviously smaller with less penetration of electric cars (EV-mid). By 2050, the total CO_2 emission reduction including the WTT emissions from power and fuel production is 157 Mt CO_2/a when compared to the Reference Scenario 2013 (impact of higher electric vehicle integration). The CO_2 emissions drop in relation to 2010 is 297 Mt CO_2/a (63% reduction), which also includes the energy efficiency gains from the Reference Scenario 2013. The air pollutant TTW emission drop of passenger road transport reduces to 55-67% for SO_2 and PM in comparison to 2010. Thus, other measures would be needed to achieve the same emission levels in passenger road transport as in the EV-high scenario.

The interactions of sectors due to a functioning ETS are not considered in this analysis. Emission reductions of less liquid fuel production and additional emissions in the power sector are in the same order of magnitude under the taken assumptions and they shall not crucially influence the carbon price of the ETS system.

Additional generation capacities are required to satisfy electric vehicle power demand

In order to satisfy the additional electricity demand of 80% car stock penetration significant additional generation capacity could be required. Up to 150 GW of generation capacities are added to the energy system due to electric cars (130 GW more than in the Reference Scenario 2013). Assuming constant generation mixes to the Reference Scenario 2013, this includes up to 47 GW wind, 25 GW solar, 41 GW fossil and 11 GW nuclear capacities with the applied first-order estimate. These capacities require significant additional investments in particular for wind and solar power and increase land use for electricity generation. As nuclear and coal power plants have significant negative environmental effects and they do not fit into a future energy sector that needs to complement fluctuating renewable energy supply, additional nuclear and coal capacities should be avoided. Instead, additional renewable capacities should be installed to replace the required additional coal and nuclear capacities. This would include 87 GW wind, 45 GW solar, 24 GW hydro and 13 GW biomass capacities.

Literature review indicates that smart charging will become crucial

The intensity of electric vehicle charging could also potentially put local grid infrastructures under substantial stress and lead to severe technical problems in network operations. A literature review reveals that the critical number of electric vehicles for grid operation depends on the local context and no general threshold can be set. Case studies show that severe operation problems can occur with electric vehicle car stock penetration of approx. 10%.

However, due to the possibility of altering electric vehicle charging profiles through smart charging approaches negative effects of electric vehicle charging can be partially counteracted. Different smart charging strategies may be applied, depending on the chosen goal of electric vehicle demand management: reducing grid constraints by smoothing load profiles (network-oriented charging), maximizing utilization of renewable energy production to reduce CO_2 emissions (renewable energy-oriented charging) or minimizing charging cost by shifting charging to low-costs periods of electricity generation (cost-oriented charging). These strategies might run contrary or be complementary to each other depending on the local and national context of the energy system.

The potential to use electric cars as an aggregated large scale storage option appears very limited due to low overall storage capacity and the competition with other more cost-efficient storage options. Additional tear and wear of the battery might also be a reason for the limited electricity storage potential. However, electric cars could potentially provide important system services to contribute to grid stability. Most importantly, as smart charging approaches imply reduced freedom compared to user-driven charging, it depends strongly on the user acceptance of smart charging concepts. Concepts on incentivizing smart-charging might become a key challenge with increasing penetration of electric vehicles.

Electric vehicle integration challenges are different for each regional power system

As generation mixes and grid infrastructure are very diverse across countries and across regions, electric vehicle penetration leads to diverse integration issues. Even between countries with similar renewable energy shares, the appropriate strategies for charging can be very different depending on the renewable technologies and the remaining types of generation capacities. In countries with high fluctuating renewable energy supply the coordination of the electric vehicle demand with fluctuating supply will become a major challenge. Electric vehicles also provide a valuable source of flexible demand that can foster the integration of renewable energy (e.g. Portugal, Denmark and Germany). Nonetheless, countries with a focus on solar energy (preferred charging peak during the day) will apply different charging strategies than countries with a focus on only wind or solar and wind electricity production (more volatile preferred charging peak due to wind power).

In countries with high shares of fossil power plants as part of their electricity production strategy (e.g. Poland, Czech Republic), electric vehicle demand could lead to substantial higher CO_2 emissions (e.g. through additional coal power plant generation) in the electricity sector. Smart charging could increase renewable electricity integration in such countries as well. Furthermore, in regions with a weak network infrastructure, additional grid reinforcement or implementation of specific smart charging approaches might be required to ensure stable functioning of the infrastructure.

However, with the implementation of smart charging approaches, the required new capacities for specific technologies can be reduced. For example, by renewable energy-oriented charging patterns the additional capacity for dispatchable plants such as coal and nuclear generation plants could potentially be reduced by harvesting renewable surplus-production and by increasing production of existing plants.

Broader transformation of transport system is needed to address all negative effects of the transport sector

Overall, the analysis reveals that an increasing electric vehicle penetration heavily impacts the operation of the energy sector and integration of electric vehicle demand poses very diverse challenges on the management of power systems at local, national and European level. Thus the transport and energy sector development will be more closely coupled and policy making and operation of both sectors has to become integrated in the future.

In terms of total emission balances in the long run, electric mobility can lead to significant reductions in CO_2 and most air pollutant emissions. It will be a relevant part of a future sustainable transport system. Nonetheless, integration of electric vehicles does not address all negative effects of the transport system. Improvements in road safety and reduction of congestion, land use and noise levels require a more systematic transformation of the transport system to achieve modal shift and traffic avoidance.

1. Introduction

Fossil fuels are the main energy option in the transport sector. As a result, the emissions of the transport sector are high and transport is one of the main polluting sectors. Greenhouse gas (GHG) emissions have grown over recent decades, as technical progress has not been enough to offset rising traffic volumes. The application of low-carbon fuels such as sustainable biofuels and synthetic fuels based on renewable electricity as well as a shift to alternative drive technologies are options and can help reduce the burden placed on the environment. However, it will not solve other problems such as congestion, noise, road safety and land use. Fundamental changes in the transport system, including technological solutions and behavioral change are needed. Measures to reduce these effects from the transport sector are modal shift to more efficient and non-motorized means of transport and traffic avoidance.

One major alternative drive technology option is electric vehicles (EV), which can use renewable electricity directly as their source of energy. Thus, electric vehicles are a promising option for achieving the long-term EU GHG goal (2050) of a cross-sectoral emission reduction by 80-95% compared to 1990. Electric vehicles also reduce the dependency on crude oil. The energy supply of the transport sector is diversified. In addition, the zero tailpipe emissions (GHG and air pollutants) of electric driving reduce air pollution in urban areas.

Up to now, the transport and the electricity sector are only weakly connected due to the dominance of fossil fuels based on crude oil. But the interdependence of both sectors will become stronger. On the one hand, the rising number of electric vehicles will lead to higher electricity demands. On the other hand, the increasing share of renewable power will make it more important to coordinate battery charging with the availability of wind and solar power generation. As a result, the layout of the energy sector has to be adapted to the new electricity consumer to achieve the goal of overall GHG emission reduction.

This report addresses the following questions:

- What are the interactions of electric vehicles and the power sector, and which challenges will arise through these interactions?
- How can the European power system cover the additional electricity consumption by electric cars?
- How are net emission balances of transport and power sector affected by an increasing number of electric cars?

For the EU-28 these questions are covered in most parts of the report. Country-specific information and examples are given throughout the study to highlight some specific challenges.

The first part of the report (section 2) summarizes potential interactions of electric driven vehicles and the energy system. A literature review of existing studies which address the impact of electric vehicles on the energy system is provided in this summary. Challenges of electric vehicle integration into the electricity grids are addressed and potential smart charging strategies are introduced. Additionally, relevant parameters and factors for renewable energy integration in case of electric vehicle charging are described.

The second part of the report (section 3) addresses more specifically how the European energy system can cover the additional electricity demand from electric vehicles in passenger road transport, and which electricity generation will be used for electric vehicle charging if high electric vehicle shares in the total car stock are applied. A net balance of GHG and air pollutant emissions of the transport and the electricity sector is also shown to understand if and how the goal of emission reduction will be achieved.

The basis of these analyses in the second part of the report is the EU Reference Scenario 2013 (Capros et al., 2013) which includes a rather slow market penetration of electric cars (8% of total car fleet by 2050). Consequently, two more electric vehicle scenarios (EV-mid and EV-high) are set to conduct the analyses with higher shares of electric vehicles. Overall energy system modelling has been out of scope of this study and other sectors' development has been set constant to the Reference Scenario 2013 data. The analyses therefore include only changes in the passenger road transport and their direct impact on power generation.

The final part (section 4) concludes the reports with the summary of the findings and the challenges of the integration of an electric vehicle fleet into the European energy system.

2. Interplay of electric vehicles with the energy sector

With the growing expansion of electric vehicles the required power demand for vehicle charging becomes an increasingly important factor within the European energy system. When electric vehicles reach significant market shares, the associated electricity demand will influence the operation of energy markets and the grid infrastructure.

The following section describes the general impact that electric vehicles have on energy systems and presents related recent research results and some country-specific findings. Particular emphasis is given to smart charging approaches and their potential benefits for the environment and energy systems.

2.1. General impact of electric vehicle charging

Charging electric vehicles requires electricity. This additional electricity demand needs to be met by additional power generation, and it needs to be integrated into the grid infrastructure. Up to 2030 additional overall demand by electric vehicles is estimated to be limited in Europe and therefore will not significantly influence the electricity system (see section 3, and Kampman et al., 2011). But in the long term, when electric vehicles reach greater market shares, the required electricity will significantly impact power systems in Europe.

How will the electricity demand of electric vehicles be met?

The new demand will need to be met by additional electricity production, thereby influencing the operation of generation plants. Crucially, the additional demand can influence the electricity generation of fossil fuel power plants and thus lead to an increase of greenhouse gas emissions of the energy sector. The decarbonizing of the transport sector is one of the primary motivations for introducing electric vehicles to the market. Therefore the critical question is what type of generation is used to cover this additional electricity demand. Electric vehicles only have a better environmental performance than conventional vehicles if the additional demand is met by a low-carbon intensive energy mix (Hacker et al., 2009). This is relevant not only for the use phase of the electric vehicles, but also for their production and their end-of-life phase. Electric vehicles can have significant higher emissions than conventional cars within a pure coal based electricity system (Verbeek et al., 2015).

Electricity systems and the mix of conventional and renewable generation plants differ greatly within Europe. Therefore the emission impact of electric vehicles depends strongly on the national energy context. Furthermore, the time at which charging takes place also affects which generation plants satisfy the additional electricity demand of electric vehicles. Depending on total system load and marginal costs of available generation plants, different types of power plants increase their production (see box “The merit order principle”).

For example, if electric vehicle charging occurs in times of low renewable energy generation and when conventional power plants can increase their production, the additional demand will lead to higher carbon-intensive conventional generation. On the other hand, electric vehicle demand could also be mainly satisfied by renewable energy production when electric vehicle charging occurs in times of high wind or solar production.

The assessment of the effects of electric vehicles on the operation of power plants and the associated environmental impact requires a more detailed analysis of the energy sector. Section 3 presents such an environmental assessment of electric vehicle integration into the European energy system.

Local distribution grids will be put under stress

Besides the influence of electric vehicles on the operation of generation plants, electric vehicles also have an impact on the grid infrastructure. So far, no relevant impact on the transmission grid level are foreseen (Grünig et al., 2011), but the power requirements of electric vehicles can put local distribution grids under critical stress.

It is expected that electric vehicle charging will first occur on a concentrated basis in urban-suburban environments, among a homogenous owner group (Hacker et al., 2009). Therefore the charging of electric vehicles will likely be highly geographically concentrated and will occur most likely after work with a high simultaneousness during evening, when demand is already high (Nobis et al., 2011; Figure 2).

As local grids are not designed for this type and intensity of load, electric vehicles can bring local grids to their technical limits. The impact of EV charging on local grids is influenced by the power levels EV charging takes place. Charging with common household sockets with a charging power of 2.3 kW requires relatively long charging times of 8-9 hours for a full battery re-charge. This slow charging puts less stress on local grids as the load is more evenly distributed over a longer period. Increasing the charging power to 22 kW or higher voltages reduces charging times significantly (down to 30 minutes) but also significantly increases the risk of negative impacts to the grid infrastructure.

Distribution grids and network capacities vary greatly within Europe. While countries with highly developed grids (e.g. Netherlands, Germany, Denmark) will be better capable of handling the additional consumption of electric vehicles, countries with lower developed grids (e.g. Poland, Hungary, Estonia, Lithuania) are more prone to negative effects, such as technical failures within the distribution grid (Haupt and Bärwaldt, 2009; Kampman et al., 2011). However, based on current EV development trends the countries with a less developed grid infrastructure will probably not be the forerunners in electric vehicle uptake. The relevant questions therefore is, how countries with intermediate energy systems (e.g. UK, Spain, Italy) and expected earlier update of electric vehicles will cope with the network challenges (Grünig et al., 2011).

Functioning of electricity markets: The merit order principle

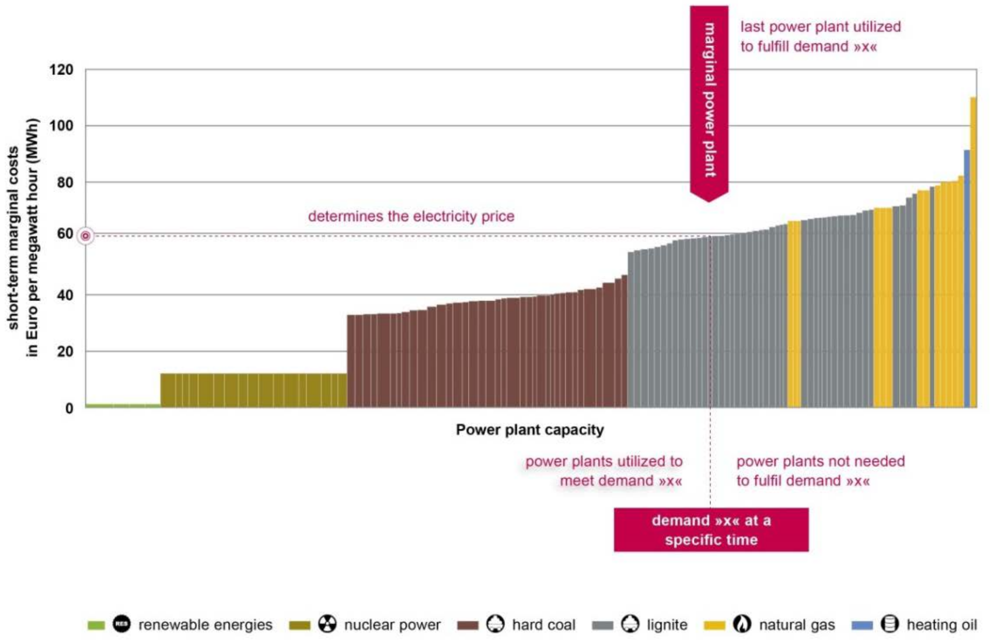
In most energy markets, prices are determined on the basis of the merit order principle, at the intersection between supply and demand. Specifically this means that the energy suppliers offer electricity from their available power plants on the power exchange at a particular price which is usually mainly on the basis of short-term operating costs. These offers are then sorted by price. In the above example taken from Germany the cheapest price offers come from nuclear and lignite power plants while gas- and oil-fired power plants produce expensive electricity (based on operating costs) – which is shown by the increasing price in the graph.

If power consumption increases – for example, during the morning or evening – electricity is needed from additional power plants to fulfil demand. In the graph the (vertical) line showing electricity demand moves to the right. The higher demand is met first of all by hard coal power plants, the electricity of which is more expensive than the already fully utilized technologies (e.g. nuclear power plants). During peaks in power consumption, gas-fired and pumped storage power plants are utilized.

Beginning with the lowest operating costs (shown in the graph as short-term marginal costs on the y-axis) power plants with higher costs are utilized until power demand is fulfilled. The most expensive power plant needed in each case to meet demand determines the electricity price on the spot market. This power plant is the so-called marginal power plant.

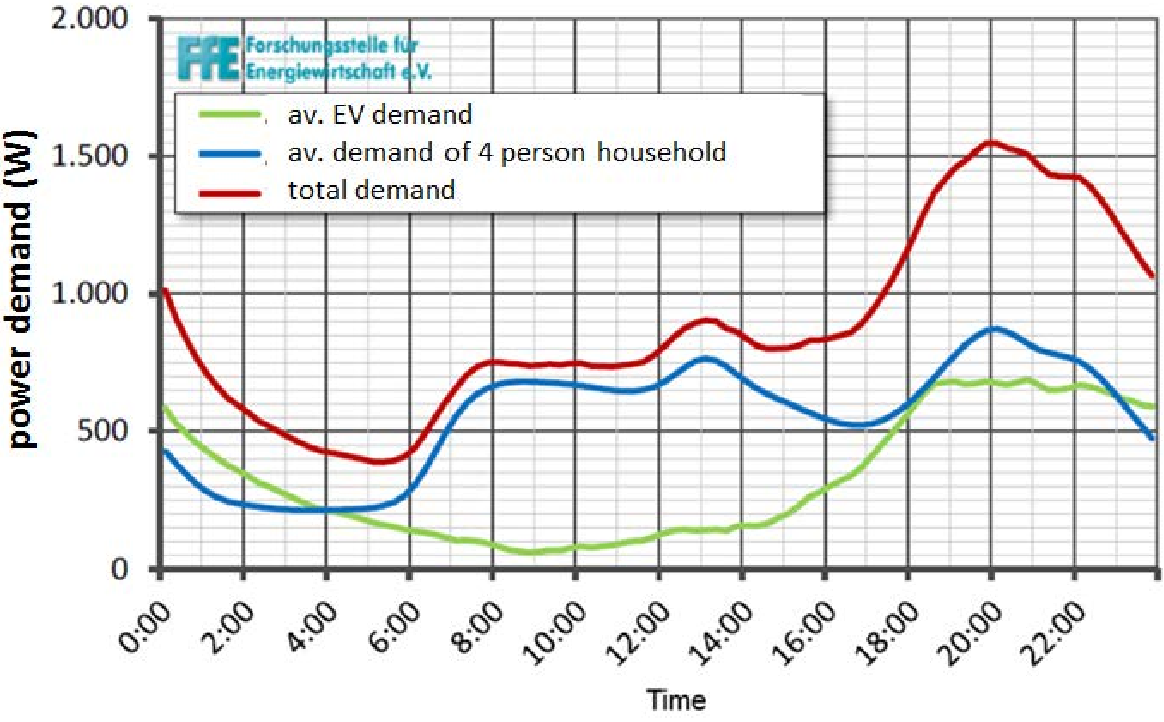
Renewable energies are included in the power mix, which suppress the conventional power plants from the supply curve (right side of graphic). Based on the logic of the merit order principle, renewable power plants are positioned in front of nuclear power and coal-fired power plants because they cause almost no (fuel) costs and profit currently from feed-in priority in Germany. The feed-in of renewable power thus leads to a cheaper marginal power plant – e.g. a lignite instead of a hard coal power plant – being utilized as the last one needed to meet demand. The most expensive forms of power generation are then no longer used and during such hours the electricity is particularly low-priced.

Figure 1: The merit order principle



Source: Illustration by Oeko-Institut

Figure 2: **Load curves (user-driven charging) of electric vehicle charging, private household and both aggregated (Germany)**



Source: Nobis et al., 2011.

Smart charging strategies are crucial

In principle, charging times of electric vehicles are flexible: Most electric vehicles are likely to be connected to the grid for much longer time periods than would be necessary to perform the actual charging process. "Smart charging" approaches make use of this flexibility by optimizing charging times in various ways. The overall impact of electric vehicles on electricity systems strongly depends on how charging times are managed.

Various studies have analysed the impact of electric vehicles on national grids in Europe and predict severe technical limitations if charging is not controlled in any way (user-driven charging). Research in Germany indicates that even with the relatively well-developed national infrastructure, the management of charging might be necessary in the medium-term due to technical restrictions of the grid infrastructure (Schill and Gerbaulet, 2015). Multiple studies on the UK energy system also show how uncontrolled charging in residential areas is detrimental to operations of local grids and that rising electric vehicle penetration can, in fact, cause considerable technical challenges like voltage droppings and thermal limit violations (Hoog et al., 2015; Lopes, J. A. P. et al., 2011; Masoum, M. A. S. et al., 2012; Mu et al., 2014; Papadopoulos et al., 2012; Richardson et al., 2012; Sharma et al., 2014). Other studies estimate that technical problems in distribution grids could already emerge at electric vehicle penetration rates of 12% (Richardson et al., 2012; Salah et al., 2015).

An Italian case study concerning the Province of Milan finds that with penetration levels of only 5% electric vehicles would increase peak load significantly and that with penetration levels of 20-25% electric vehicle charging would heavily impact total daily power requests, making the implementation of controlled charging necessary to ensure safe functioning of the technical infrastructure (Perujo and Ciuffo, 2010).

In conclusion, the analysis shows that the additional electricity demand could increase the generation of fossil-fuel power plants and uncontrolled electric vehicle charging could negatively affect electricity grids. The impact of EV charging on local grids heavily depends on the local context (quality of grid infrastructure, generation mix, characteristics of EV charging) and in certain cases a negative impact can already be expected at low penetration rates of around 10%. In order to reduce the expected negative effects on local grids and GHG emissions, smart charging approaches will become crucial to reducing the intensity of electric vehicle charging and the additional generation by conventional power plants.

2.2. Smart charging of electric vehicles

Smart charging is the management of electric vehicle charging in contrast to uncontrolled, fully user-driven charging. This comprehensive management of electric vehicle charging requires a communication infrastructure that enables charging stations to be controlled centrally and that provides necessary system information (e.g. wind production, grid capacity). Also, the respective regulatory framework must allow strategic control of electricity consumption. The owners also have to accept smart charging strategies to allow the energy suppliers shifting the battery charging to more favourable hours.

User acceptance is key for the success of smart charging

The potential flexibility of electric vehicles that allow for different charging strategies depends on the number of electric vehicles connected to the grid, the mobility patterns of electric vehicle owners and the functionality of charging stations. If electric vehicles are connected for charging not only at home but also during the day (e.g. at the workplace), the potential for altering charging times through controlled charging increases significantly (Babrowski et al., 2014).

Most importantly, the willingness of car owners to participate in smart charging schemes is the prerequisite for application of smart charging approaches. Under current EU legislation, electric vehicle owners have the right to charge at any time and be delivered power accordingly (Kampman et al., 2011). Therefore, smart charging requires that electric vehicle owners give up a certain degree of their freedom to charge their vehicle at any desired time and also accept that the battery will not be fully charged at certain times. If electric vehicles are also used for feeding back electricity into the grid for auxiliary services or storage concepts (vehicle to grid; see section 2.3), owners also need to be compensated for the wear and tear of the battery. Therefore, financial incentives and flexible tariffs will play an important role in incentivising and enabling smart charging (Schill and Gerbaulet, 2015; Schuller and Hoeffer, 2014). To be able to benefit financially from smart charging, clear price incentives through flexible and tariffs smart metering[1] must be available to electric vehicle owners.

Smart charging strategies are currently not applied as the required infrastructure is often not in place and the small electric vehicle fleets do not require smart charging strategies. Car users connect their vehicle to the charging infrastructure and battery charging starts immediately. The controlling of electric vehicle charging can be useful and can in principle follow different goals. Car

[1] In contrast to standard electricity meters that only measure total consumed electricity for annual billing purposes, smart metering systems are capable of more precise tracking of consumption and instant communication with the electricity supplier. Smart meters therefore allow for different billing and charging options (e.g. time-depending flexible tariffs).

owners, for instance, have an interest in charging as fast as possible to maximize the flexibility of the availability of the car. Economically charging at minimum costs will be the main rationale of charging for electricity suppliers and most users. In contrast, network operators are interested in ensuring the well-functioning of the grid by avoiding strong demand peaks. They prefer stretching electric vehicle charging over long time periods. From an environmental perspective, increasing the use of renewable energy production is necessary to minimize GHG emissions. So far, no common understanding of the specific goals of smart charging has emerged, but the following three charging strategies are most prominent in research and pilot projects (see also Schierhorn and Martensen, 2015):

- Network-oriented charging
- Renewable energy-oriented charging
- Cost-oriented charging.

2.2.1. Network-oriented charging

In order to reduce the stress put on local grids by electric vehicle charging, the simultaneousness of charging periods needs to be reduced through the shifting of charging times. Smart charging approaches therefore often aim to reduce the intensity of electricity demand of electric vehicle by smoothing load patterns of electric vehicles and shifting charging times to low demand periods.

Research from the UK illustrates that staggering charging start time and delaying electric vehicle charging until after the high demand in evening times results in significantly more network-friendly charging profiles (Lacey G. et al., 2013). Projections for the year 2030 in Germany also show that power demand of electric vehicles does not hamper system stability if charged strategically (Loisel et al., 2014). It has also been found that smoothing load profiles by coordinated charging (e.g. scattering beginning of charging cycles and shifting charging to night times) can be achieved without limiting the mobility of electric car owners. (Metz and Doetsch, 2012).

However, network-oriented charging can entail adverse environmental effects. In systems in which conventional generation plants with high GHG emissions (e.g. coal power plants) dominate production in off-peak periods, shifting charging to these periods will increase the generation of these plants and the emissions in total (Babrowski et al., 2014).

Nevertheless, the negative impact of electric vehicle charging on local grids will become a severe problem when market penetration levels reach high shares. Furthermore, the increasing volatile renewable electricity production from solar and wind power in many European countries will lead to quick changes of generation that needs to be integrated by local grids. Therefore, local grids will already be increasingly under stress even without electric vehicles charging. Smart charging of EV can contribute to match volatile generation of solar and wind power with consumer demand. Network-oriented smart charging can also reduce the expected high simultaneousness EV charging, which can become critical for the grid infrastructure due to high peak load.

Smart charging aiming at reducing stress on local grids can therefore become a valuable strategy to avoid infrastructural investments. It can also help to avoid power outages due to grid instabilities and thereby contribute to reliable system operation.

2.2.2. Renewable energy-oriented smart charging

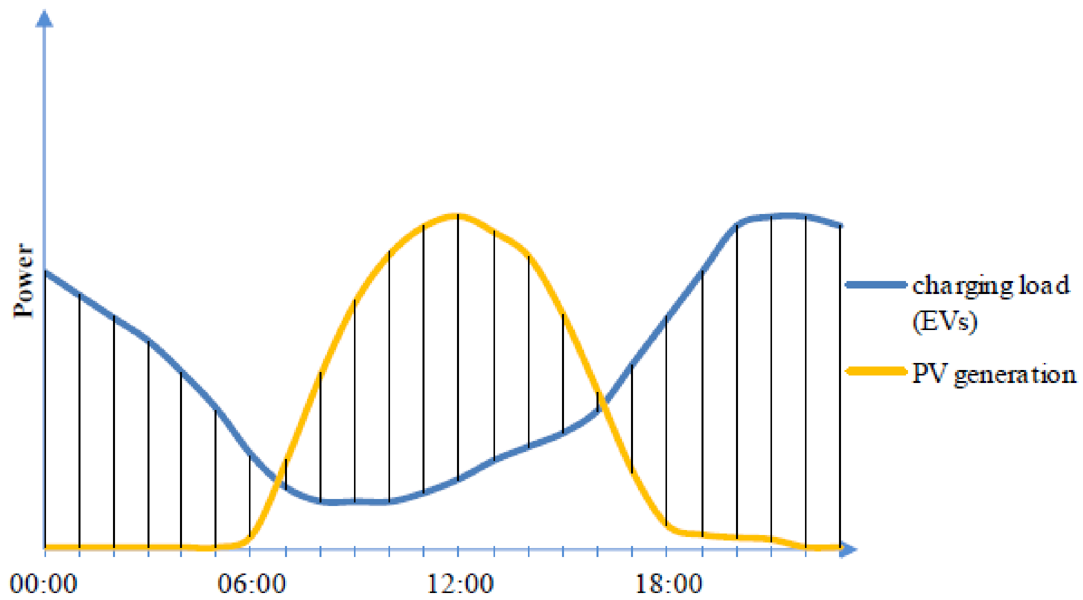
As described above, the environmental performance of electric vehicles evidently depends on the effects of the additional electric vehicle demand on electricity generation. In most power systems, the type of power plants dispatched varies throughout day and night (e.g. larger share of solar during the day and larger share of fossil-fuel generation during night).

From an environmental perspective, electric vehicle should be charged in periods of high RES-E[2] production and minimized in times of high fossil-fuel generation. Furthermore, in networks with an excess of RES-E production that would otherwise not be integrated into the system, RES-E oriented charging potentially allows for the additional integration of RES-E production.

The potential to increase RES-E consumption by electric vehicles is relatively high, but depends on the national generation profiles and technologies. Research on the German power sector shows that by utilizing wind and solar oriented charging approaches, the share of renewable energy used for electric vehicle demand can be more than doubled (Schuller et al., 2015).

For increasing the use of photovoltaic (PV) production for electric vehicle charging, creating opportunities to charge electric vehicle during the day (e.g. at workplaces) and of strategically shifting charging times from night to day is crucial (Babrowski et al., 2014; Fattori et al., 2014; Schuller et al., 2015). Figure 3 shows that typical electric vehicle load patterns and PV generation profiles are diametrically opposed.

Figure 3: Comparison of a characteristic PV generation and cumulative electric vehicle charging load (user-driven charging)



Source: Uhlig et al., 2014

Research on Portugal shows that in order to reach climate protection targets, a significant electric vehicle market share could consume the large production of solar plants during daytimes (Nunes et al., 2015a, 2015b). Linking electric vehicle charging to wind production is more complex due to the more unpredictable nature of wind generation.

Linking EV charging times to one specific RES-E technology is difficult to achieve as charging times will always vary to a certain degree even if high levels of RES-E-oriented smart charging is implemented. The analysis of different RES-E portfolios shows that the highest utilization of

2 RES-E: Renewable Energy Sources – Electricity.

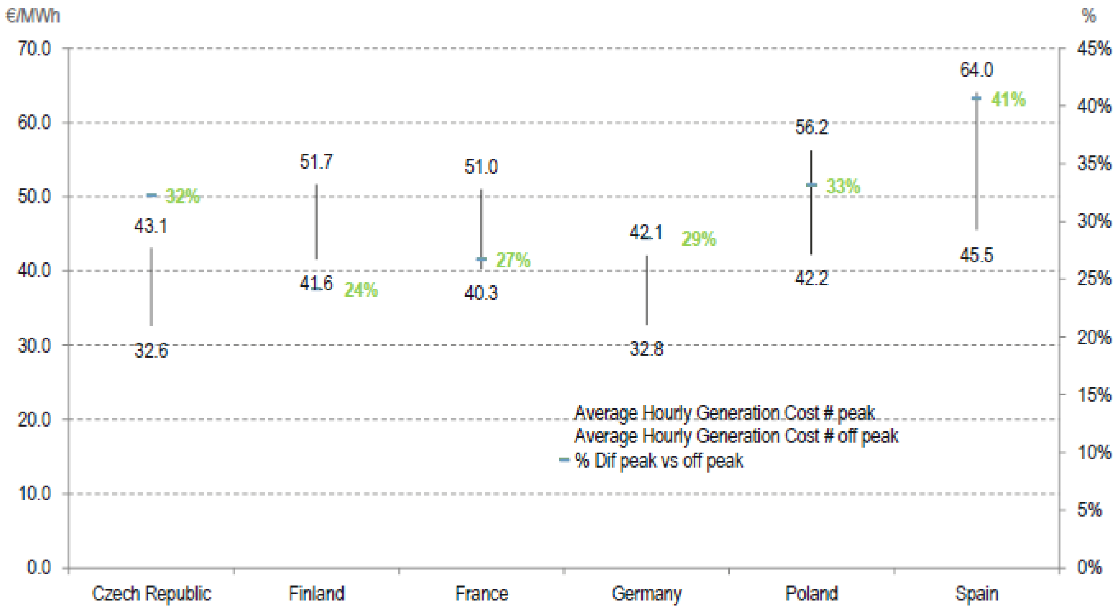
renewable energy can be achieved with a mix of solar and wind generation as charging can be shifted potentially throughout the whole day to low-emission generation hours (Schuller et al., 2015). However, there is no single RES-E generation mix optimal for EV charging as RES-E generation profiles are country-specific and EV charging profiles depend on the local context (e.g. between urban and rural areas). Nobis et al. (2011) shows simulation results of the differences in load profiles for electric vehicle charging between uncontrolled charging (Figure 2) and smart charging based on renewable energy generation profiles in Germany. While uncontrolled electric vehicle charging shows low load levels during the day and high levels in the evening, RES-E-oriented charged leads to a shift of electric vehicle load from evening and night to day hours when renewable production from solar is high.

Overall, RES-E oriented charging can be an important strategy to minimize additional GHG emissions caused by electric vehicle power demand. However, the impact varies greatly between power systems and the specifics of the regional generation portfolio determine the design and need of such charging approaches.

2.2.3. Cost-oriented charging

From an economic perspective of the individual electric vehicle owner and utilities, smart charging can be used to minimize charging costs by shifting charging to low-price periods. Therefore, cost-oriented charging is another smart charging strategy that is often discussed.

Figure 4: Spread between on-peak and off-peak wholesale prices (€/MWh) in six EU countries



Source: Eurelectric, 2015

Wholesale prices for electricity are determined by the marginal generation costs and the level of demand (see box "Functioning of electricity markets: The merit order principle"). The economic benefits gained through cost-oriented charging depend on the price difference between low and high price periods. Figure 4 illustrates the current differences between low and high price periods on the wholesale market in 6 European countries. Wholesale prices vary from 24% (Finland) and

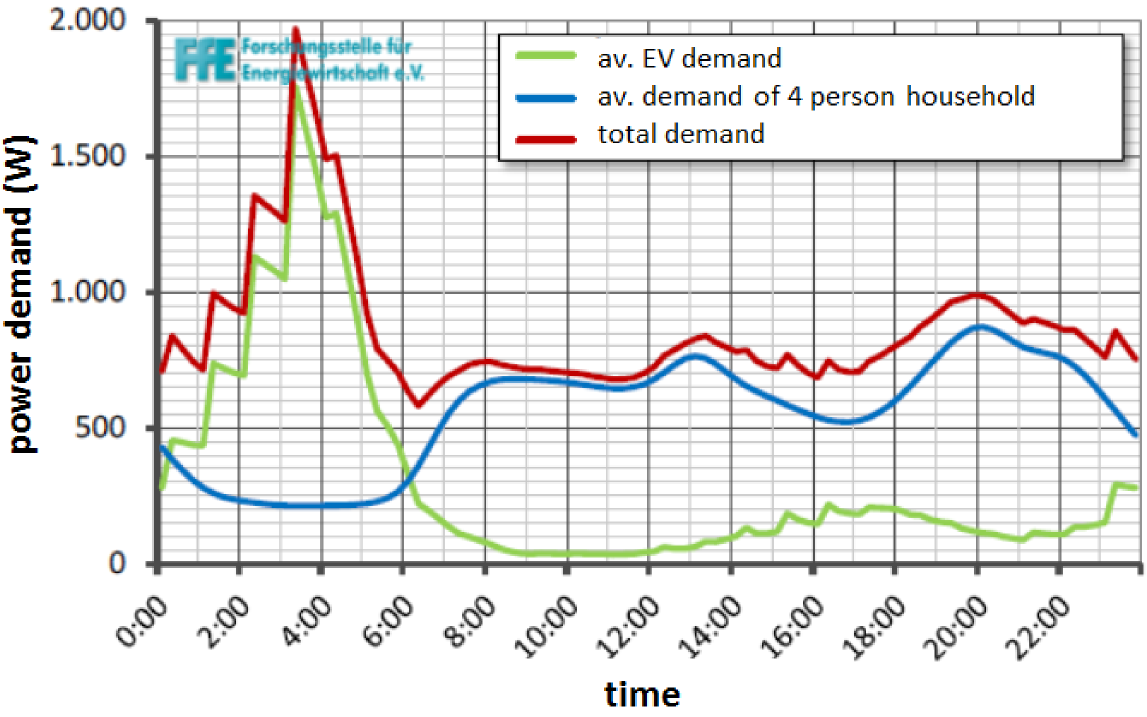
41% (Spain). However, electricity prices for end consumers are strongly determined by additional taxes and other charges (e.g. for network use). Varying wholesale prices are also often not passed through to end consumers. Therefore, the price differences and financial saving potentials for end consumers are lower. With an increasing production of fluctuating renewable energy the spread between high and low prices is expected to increase, thereby the potential benefits for cost-oriented charging will also increase.

Low-price periods often coincide with low demand periods as only generation plants with low marginal cost are dispatched to meet demand. From an overall system perspective, cost-driven charging is therefore likely to lead to a smoothing of system load profiles.

Figure 5 illustrates how cost-oriented charging according to prices of the European Energy Exchange leads to a significant shift of electric vehicle demand to night times. Peak demand at evening times is thereby shifted (see user-driven charging in Figure 2 for comparison) and stress on local grids can potentially be reduced.

The environmental implications of cost-driven charging approaches depend on the respective types of plants in operation in low-price periods and therefore differ among European energy systems. Depending on the national generation technology mix, cost-driven charging can influence the electric vehicle specific supply mix. In systems in which low-price periods coincide with fossil coal power generation, cost-driven charging can lead to higher utilization of these plants and higher GHG emissions. This is, for example, the case for the German power sector (Hacker et al., 2014; Schill and Gerbaulet, 2015).

Figure 5: Load curves (cost-orientated charging) of electric vehicle charging, private household and both aggregated (Germany)



Source: Nobis et al., 2011

On the other hand, the example of Belgium illustrates that cost-oriented charging can also reduce GHG emissions when off-peak periods are dominated by nuclear power generation (Rangaraju et al., 2015).

With increasing shares of fluctuating RES E generation in the European energy system, the influence of low carbon technologies such as wind and solar on electricity prices becomes more dominant. In the long run, cost-driven charging will therefore foster higher utilization of RES-E production and become more and more attractive from an environmental perspective.

2.3. Provision of storage power by electric vehicles

Besides the importance of the management of charging times for successful integration of electric vehicles into European energy systems, electric vehicle batteries could be used to store electricity and feed it back into the grid when necessary. This concept of bidirectional integration of electric vehicles into energy systems is called “vehicle-to-grid” (V2G).

One goal of V2G approaches is the uptake RES-E generation in times of low demand (e.g. high wind production during night) and power provision when needed. With increasing fluctuating RES-E generation in the future these short-term flexible storage options become more valuable. Furthermore, electric vehicles could also provide so-called “system services”. These services, which are necessary to ensure proper grid functioning, are managed by grid operators and comprise the provision of very short-term flexibility in order to stabilize the grid (e.g. voltage and frequency control). So far, V2G concepts have only been applied in research contexts and have not yet been implemented on a larger scale.

While electric vehicles with V2G abilities could theoretically provide valuable services, various studies based on pilot projects and market simulations conclude that the potential benefits of V2G concepts are rather limited (Grünig et al., 2011; Juul and Meibom, 2011, 2012; Kristoffersen et al., 2011; Loisel et al., 2014; Tomić and Kempton, 2007). One of the major constraints is the increase in charging cycles caused by V2G applications that lead to a higher degradation of batteries. With batteries being one of the main cost factors of electric mobility, the use of electric vehicles as storage capacity is not likely to be economically viable (Loisel et al., 2014). In addition, the actual storage capacity of electric vehicles is relatively limited compared to other storage technologies, which may also be more competitive (Grünig et al., 2011).

Research on the Danish power system shows that V2G options will have very limited effects on the overall energy management and are more likely to be used only for system services (Ekman, 2011).[3] A comparison of the potential financial benefits of providing system services shows that no profits can be gained in the Swedish market.

Overall, electric vehicles will most likely not become a viable medium-term storage option due to high battery costs and limited storage capacity. However, the V2G approach can enable electric vehicles to play an important future role in the provision of system services.

2.4. Conclusions

As long as penetration levels of electric vehicles remain low, the required electricity for electric vehicle charging has no greater effect on the operation of energy systems. With electric vehicles

[3] An example of a system service is the offer to reduce/increase consumption on a very short notice (seconds to minutes). These balancing services are required to ensure the stability of the electricity grid and are managed by network operators.

reaching significant market shares, as expected for 2030 onwards, the new additional demand of electric vehicles will influence energy markets and can cause technical problems to the functioning of the grid infrastructure. Case studies show that negative impact on grid stability can occur with electric vehicle fleet penetration of around 10% in certain cases. However, the effect of electric vehicle integration depends on the local context of grid technology as well as of supply and demand curves of electricity.

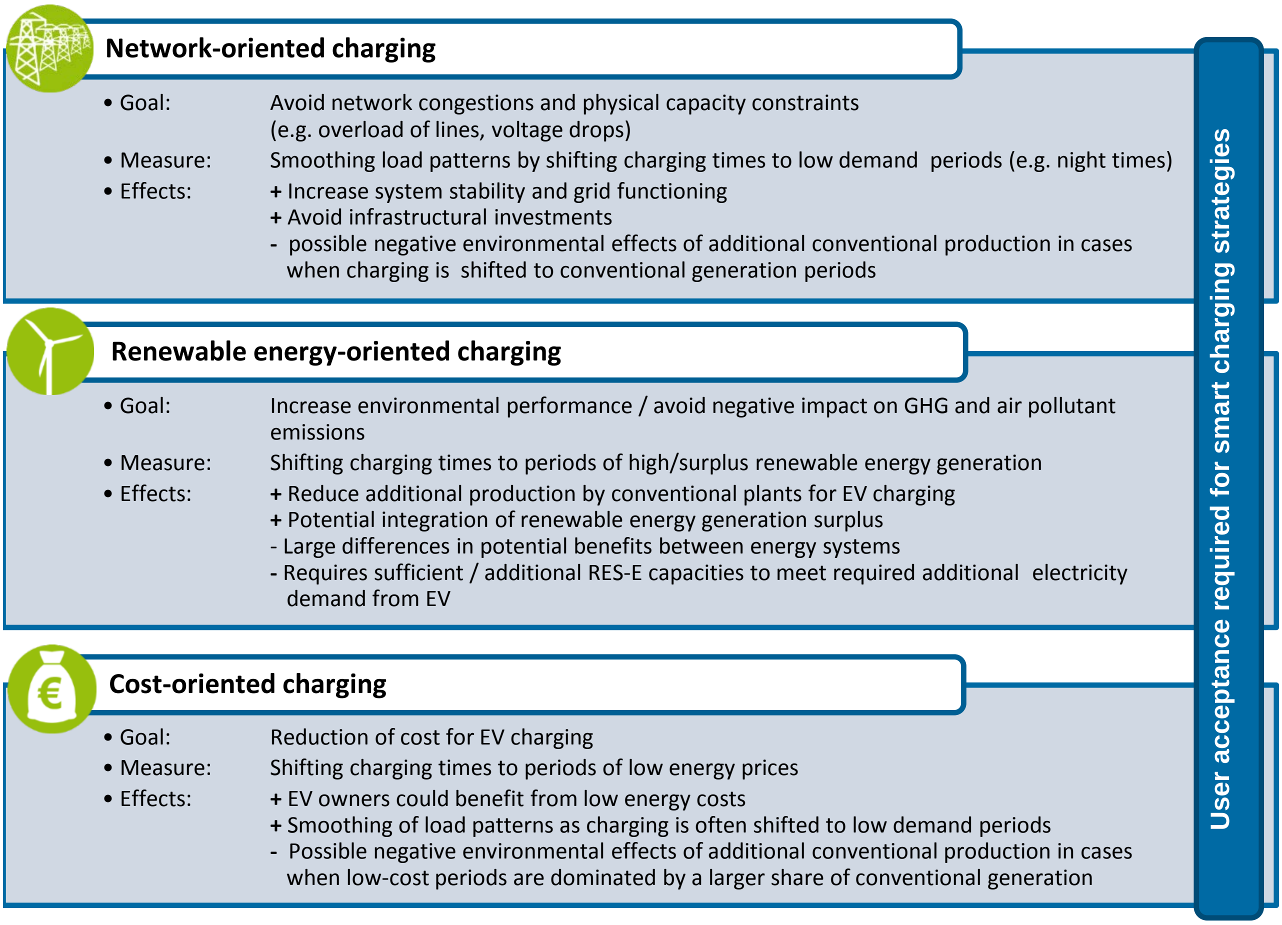
In cases in which the demand from electric vehicles is satisfied by additional production of conventional power plants, electric vehicles lead to an increase in GHG emissions in the power sector. However, with the smart charging of electric vehicles these potential negative effects can be significantly reduced and electric vehicles could partially be charged by RES-E surplus production that could otherwise not be integrated.

Smart charging approaches aimed at smoothing load patterns of electric vehicles can significantly reduce the stress on local grids and will therefore become indispensable under certain conditions. Smart charging can also improve the utilisation of RES-E production for electric vehicles charging and consequently reduce additional GHG emissions by additional production from fossil fuel power plants. Different strategies for smart charging can be contradictory to each other: For example, cost-oriented charging can lead to higher utilisation of fossil-fuel plants as these plants often dominate production in low-cost periods. The potential to use electric vehicles as an aggregated large-scale storage option appears very limited due to low overall storage capacity and the competition with other more cost-efficient storage options. However, electric vehicles could potentially provide important system services to contribute to grid stability.

As long as the number of electric vehicles is low, smart charging will not play an essential role in electricity system management. However, this will change drastically over time with larger electric vehicle penetration levels. Broad application of smart charging approaches requires a certain regulatory framework and technical infrastructure. The appropriate timeframe for implementing these framework conditions and the optimal strategy for charging of electric vehicles differ within European countries and depends on the regional and local context. Both depend on the electric vehicle development, the grid and charging infrastructure as well as the composition of different generation technologies.

Additionally, the car users have to participate in smart charging and have to accept that the battery charging is shifted from immediate charging to system-driven charging. Research has shown that shifting battery charging is possible with current car usage; but the acceptance and the required amount of financial incentive to make car users take part in smart charging has not yet been analyzed in depth. Thus, smart charging will be required and will also be possible technology-wise; the user acceptance for smart charging will also be relevant and concepts oriented at the user needs have to be developed.

Figure 6: Overview of different smart charging strategies



Source: Authors' own illustration

3. The impact of different electric car penetration levels on the European energy system

The previous section highlighted general aspects of the interplay of electric vehicles and their integration into the electricity system. Section 3 addresses more specifically how the European energy system can cover the additional electricity demand from electric vehicles in passenger road transport, and which electricity generation will be used for electric vehicle charging. A net balance of GHG and air pollutant emissions of the transport and the electricity sector is also shown to understand if and how the goal of emission reduction can be achieved.

The basis of these analyses is the EU Reference Scenario 2013 (Capros et al., 2013) and its assumptions regarding the transport and the electricity sector. They are presented in section 3.1. The EU Reference Scenario 2013 exhibits a slow market penetration of electric vehicles because this scenario considers only existing and binding legislation until spring 2012. Consequently, the long-term GHG emission target in 2050 will not be reached in the EU Reference Scenario 2013.

Section 3.2 highlights assumptions and outcomes of other European long-term scenarios. Most are target-driven and the CO_2 reduction of at least 80% in 2050 (compared to 1990) is reached. High market penetration of electric vehicles is one possible pathway for the decarbonisation of the transport sector. Higher shares of electric vehicles are therefore taken into account in the EV-mid and EV-high scenario (section 3.3). These scenarios demonstrate challenges of electric vehicle integration into the European electricity system; examples of country-specific challenges are also provided (section 3.4).

3.1. The EU Reference Scenario 2013

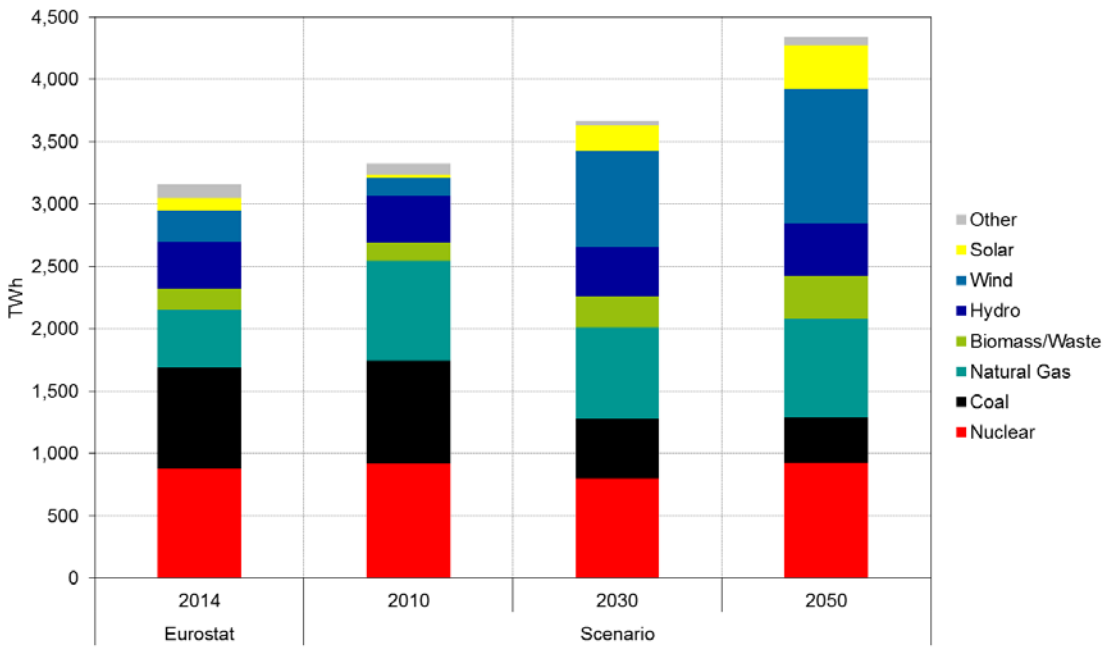
The EU Reference Scenario 2013 (Capros et al., 2013), also referred to as "reference scenario/case" below, serves as a baseline for the development of the energy consuming sectors in the EU up to 2050. In this study, it is also the reference for the transport baseline scenario. All EU legislation, binding targets and Member State initiatives until spring 2012 are considered in the market driven approach for the period up to 2050. The scenario is a projection of developments in the absence of any further policies.

Most binding EU legislation aims at the year 2020, and therefore rather strong efficiency gains are assumed until 2020. Efficiency improvements are achieved slower after 2020 without binding EU legislation. The E3M-Lab of the National Technical University Athens authored the reference scenario in collaboration with IIASA and EuroCARE applying economic modelling on behalf of the EU Commission.

3.1.1. Electricity sector

Figure 7 shows how electricity demand and generation mix change over time. The increase in electricity demand is projected to be lower than the assumed GDP growth due to the implementation of energy efficiency policies. Until 2020 electricity demand increases by 0.5 % annually and 1% thereafter.

Figure 7: Electricity demand and generation mix (EU-28)



Source: Authors' own representation of Capros et al., 2013; Eurostat 2016

The importance of renewable power generation is increasing. Generation shares of RES-E increase to 43% in 2030 and 50% in 2050. While electricity production from biomass increases slightly, wind and solar power primarily drive the renewable expansion. The increase of RES-E generation is accompanied by a steady decrease of conventional fossil generation, mainly from coal and lignite power plants.[4] Generation from nuclear power decreases up 2025 due to national phase-out policies and remains at about 22% until 2050. In terms of added capacity, solar and wind power comprise over 50% of the new generation capacity between 2030 and 2050.

Table 1: Fact Sheet of EU Reference Scenario 2013

General framework	
Overall GHG emissions	Reduction of 44% in 2050 (compared to 1990)
GDP development	Steady increase in GDP up to 2050 (1.4-1.6% p.a.)
Population development	Increases of 0.7% up to 2040 and a slow decline thereafter
Transport sector	
GHG emissions	-8% compared to 2010 level (slight increase after 2035 due to freight transport and aviation)
Main GHG abatement strategies	Energy efficiency gains
Final energy demand	-1% in 2050 compared to 2010 Fossil fuel share in passenger road transport in 2050: 88%
EV market penetration	EV share of passenger car stock: 4% in 2030; 8% in 2050 Share of electricity in passenger car energy demand: 1% in 2030; 3% in 2050
Electricity sector	
Total electricity demand	+0,5% p.a. until 2020 +1% p.a. 2020-2050 4130 TWh in 2050
Energy efficiency	Medium improvements
GHG emissions	Reduction of 70% (compared to 2005)
Renewable energy	50% RES-E in 2050 wind 26%, 9% solar and other fluctuating RES
Technology pathways	Fossil fuel production remains at 33% in 2050 Nuclear power decreases up to 2025 and remains at about 22% until 2050. CCS production plays a minor role with 7% in 2050

Source: Authors' own summary of Capros et al., 2013

With a substantial reduction of support schemes for wind and solar power across Europe after 2020, the continuing development of RES-E generation is projected to be driven mainly by market forces and increasing certificate prices in the EU Emissions Trading System (ETS). Carbon

[4] In the Reference Scenario, no distinction is made between hard coal and lignite.

Capture and Sequestration (CCS) is also employed to reduce the CO_2 emissions of fossil fuel combustion. Fossil fuel with CCS technology is projected to reach a generation share of 7% in 2050.

Going beyond the aggregate view, the characteristics of power systems at country level are very diverse and differ significantly from the EU average. These national trends are determined by national policies and strategies as well as by the availability of domestic resources (fossil and renewable).

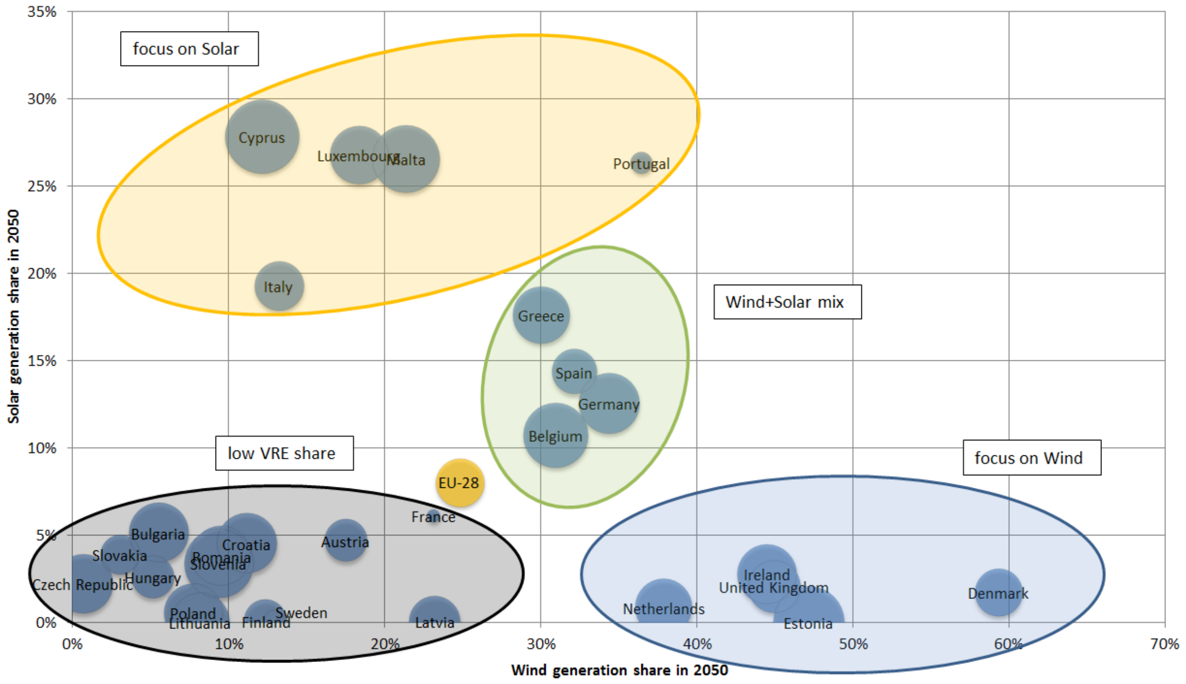
When assessing the impact of the charging of electric vehicles, there are two main power system characteristics that should be estimated:

- System flexibility: How flexible is the system with regard to additional power demand?
- Emission intensity: How many emissions are generated by satisfying additional power demand?

The generation side flexibility of power systems is strongly linked to the share of variable renewable energy sources (VRE). Availability of these energy sources depends on weather conditions. VRE resources adhere to an uneven regional distribution, follow certain characteristic patterns (like the day/night cycle of solar irradiation), and are linked with forecast uncertainty. The most important variable renewable energy sources are wind and solar energy. All other renewable energy sources (hydropower, biomass combustion) as well as thermal and nuclear power plants are – within certain limits – dispatchable.

Figure 8 shows the generation share of wind and solar power for the year 2050 across different countries, as well as the EU-28 average. It allows countries to be clustered into four groups:

Figure 8: Clustering of countries based on generation shares of wind and solar power in EU Reference Scenario 2013 (size of circles represents CO_2 intensity of power generation).



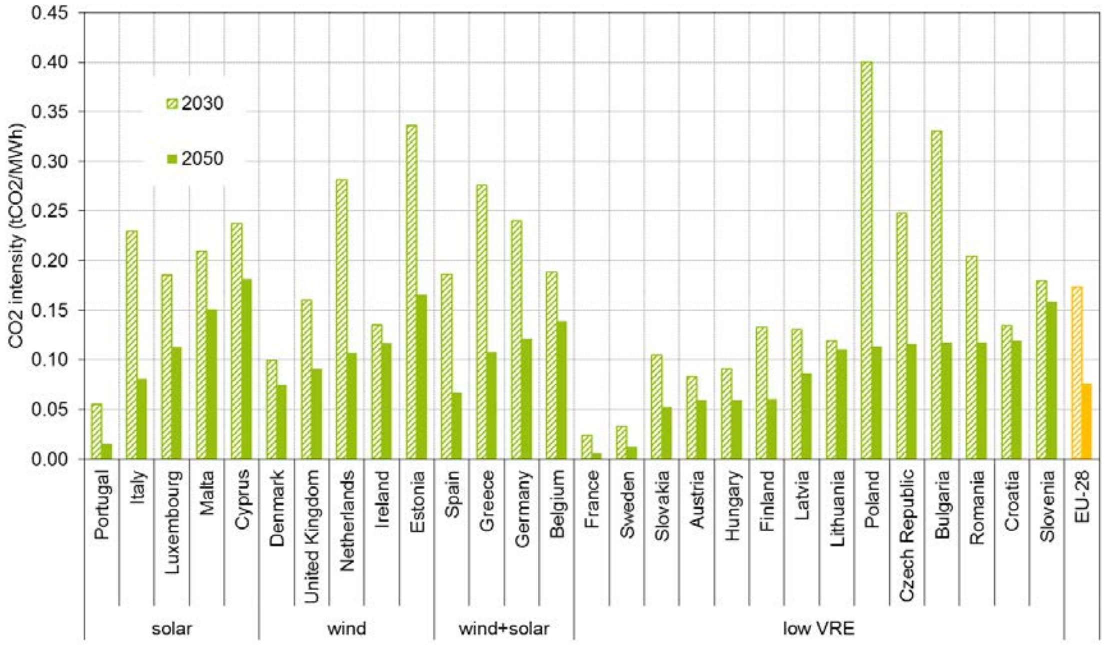
Source: Authors' own representation of Capros et al., 2013

- Countries with low VRE shares
- Countries that rely heavily on solar power
- Countries that focus on wind power
- Countries that rely on a mix of both solar and wind generation.

These groups face different challenges when integrating electric vehicle charging into the power system. The clusters also reflect the different renewable energy potentials of the country groups as well as their different existing energy system strategies.

The flexibility of a power system is crucial for its capability to integrate the additional demand by electric vehicles. This is especially the case if the electric vehicle demand share is high and it occurs concentrated in certain areas with high simultaneousness. Besides the VRE shares several other characteristics also affect system flexibility – e.g. degree of flexibility of different dispatchable generation technologies and demand side flexibility. But also a well-developed distribution grid infrastructure allows for better integration of EV demand and would therefore provide for an interesting analysis (see section 2.2.1); however, data availability (especially for 2050) is very limited. Therefore, the focus of the clustering process is on wind and solar shares of the electricity generation mix, which can be considered the most important characteristic regarding the flexibility assessment of a specific power system.

Figure 9: CO_2 emission intensities of electricity production in 2030 and 2050 by country

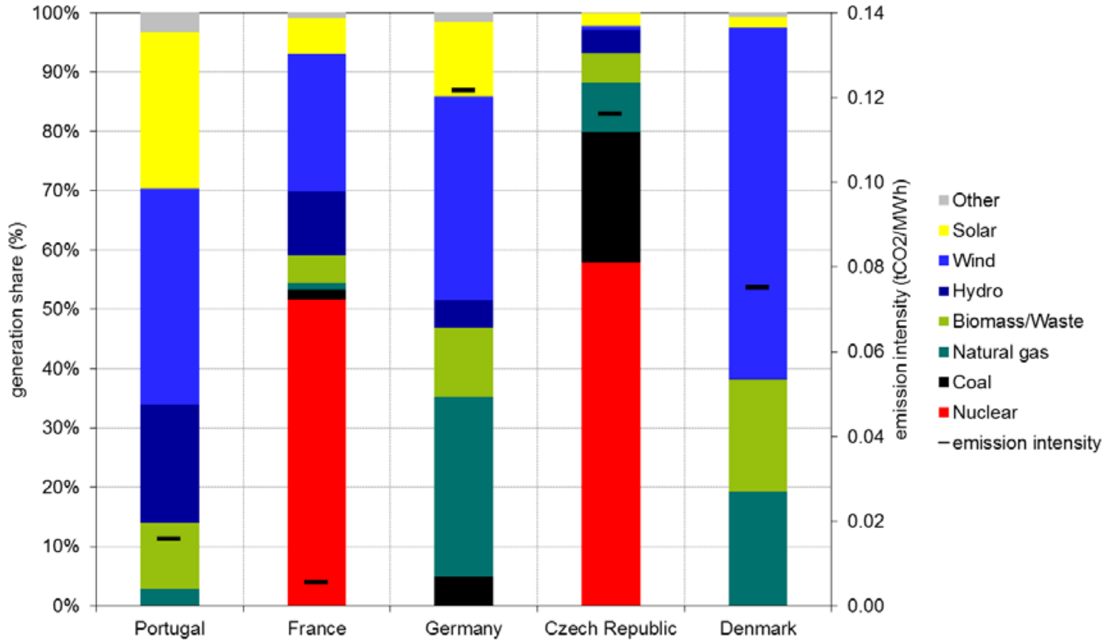


Source: Authors' own representation of Capros et al., 2013

The emission intensity of power generation is important for estimating the effect of electric vehicles on the overall emission balance – as avoided emissions in the transport sector may be partially offset by additional emissions in the power sector. The size of the circles in Figure 8 corresponds to the emission intensity of each power system. It should be noted that a high share of VRE does not necessarily result in low average emission intensities, as these are determined by the options that are chosen to cover the remaining generation shares. These can be dispatchable renewables (hydro power or biomass / waste combustion), non-renewable low carbon generation options (nuclear and CCS) or fossil fuel combustion plants with varying emission intensities.

Figure 9 shows average CO_2 emission intensities for 2030 and 2050 across all countries, sorted by clusters as described above. Emission intensities diverge strongly from the EU-28 average, and the spread across countries is significant. It can also be seen that emission intensities vary significantly inside each cluster. The emission intensity at EU-28 level is also more than halved from 2030 to 2050.

Figure 10: Electricity generation mix and CO_2 emission intensities in 2050



Source: Authors' own representation of Capros et al., 2013

To illustrate these differences, Figure 10 shows generation mix as well as emission intensities for the year 2050 across five different countries. Portugal achieves very high decarbonisation rates by means of an almost complete phase-out of non-renewable generation. France reaches similar emission intensities with only 45% renewable generation shares by relying heavily on nuclear power. In Germany, where renewable generation shares are about 64%, CO_2 emissions are much higher because coal and gas power plants are used instead of nuclear energy. Czech Republic achieves emission intensities that are similar to Germany, but it relies on a mixture of fossil and nuclear generation with almost no progress in renewable power. The Danish power sector is dominated by fluctuating wind power production (59%), but the overall emission intensity is not particularly low for a country with high shares of renewables. The residual demand in Denmark is satisfied by natural gas and biomass production.

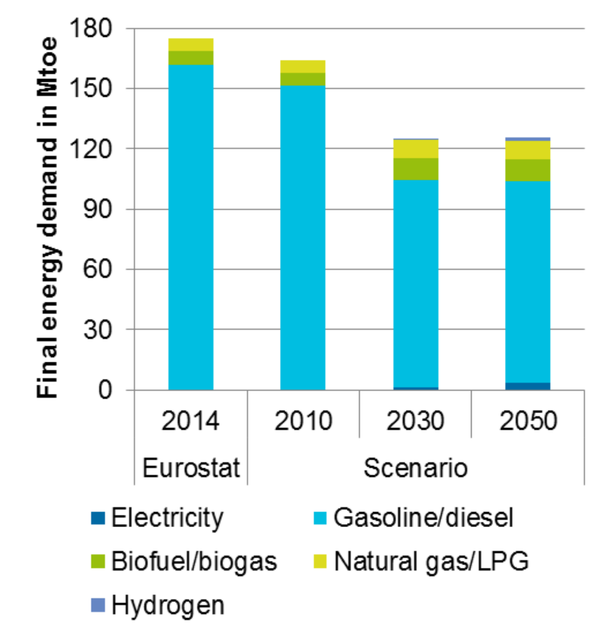
3.1.2. Passenger car transport

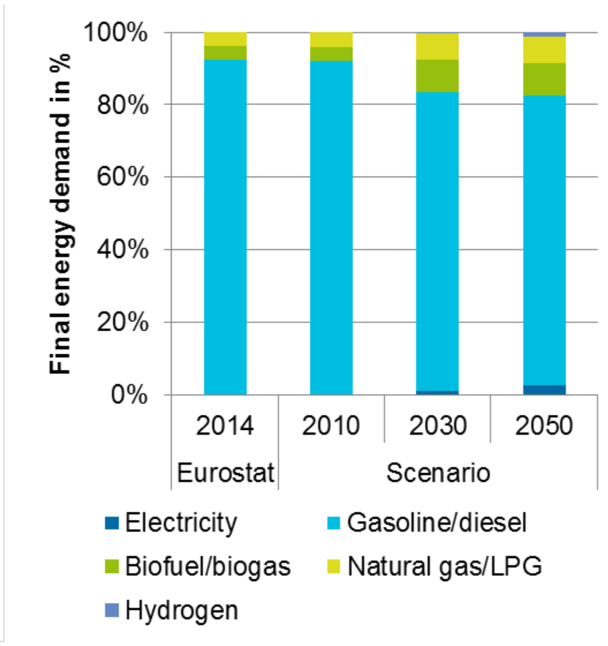
Passenger road transport activity increases steadily as a result of growing GDP and growing population. The yearly growth rate of around 0.7% p.a. cumulates to a total increase of transport activity by 29% in the period of 2010 2050. The energy demand of passenger road transport decouples over time from the increase in transport activity due to more efficient passenger cars. As a result of the fuel efficiency and GHG emission reduction policies the specific energy consumption of road transport (toe/pkm) drops by 21% by 2020 (compared to 2005). Thereafter, the efficiency improvement slows down in response to lacking efficiency policies after 2020. In 2050 the efficiency of passenger road transport is 41% higher than in 2005 due to higher vehicle energy efficiency.

The passenger car stock remains heavily dependent on fossil fuels (88% of energy consumption in 2050). First electric cars enter the vehicle stock around 2020 and the share of electric vehicles is rather small, i.e. 4% of total vehicle stock in 2030 and a bit more than 8% in 2050. Plug-in hybrids (PHEV) hold the larger share of electrically chargeable cars. It is estimated in the EU Reference Scenario that at the EU-28 level the proportion of pure battery electric vehicles (BEV) with regards to PHEV will increase from around 15% (2020) to reach almost 25% in 2030 and finally around 33% in 2050.

In the Reference Scenario 2013, total energy consumption of passenger car fleet is estimated to be around 164 million tons of oil equivalent (Mtoe) in 2010 which is around 6% lower than the 2014 real-world data from Eurostat (Figure 11). It drops to 125 Mtoe in 2030 (Figure 11) mainly due to the efficiency policies until 2020. From 2030 to 2050 this total energy consumption is estimated to remain at around this level. The structure of the energy demand from passenger cars also remains more or less equal over time. The passenger road transport relies heavily on liquid (fossil) fuels. Alternative energy carriers such as electricity and hydrogen enter the fuel market slowly and electricity constitutes approx. 1% of the fuel mix of passenger road transport in 2030. The share of electricity in the fuel mix increases to around 3% (1-4% spread among EU-28 countries) in 2050.

Figure 11: Final energy demand of passenger cars for EU-28 in EU Reference Scenario 2013





Source: Authors' own representation of Capros et al., 2013; Eurostat 2016.

How MOVEET calculates the energy demand and emissions from passenger cars

MOVEET model (Mobility, Vehicle fleet, Energy use and Emissions forecast Tool) is a tool for estimating transport demand and emissions, as well as forecasting the impacts of policy and technological measures in transport-related sectors, covering all transport modes from different regions in the world up to 2050. The model consists of all European countries. In the model, we consider all transportation modes that interact through four interrelated modules: Transport Demand, Fleet, Environmental, and Welfare.

Basically the model can:

- generate and project demand endogenously for all world regions,
- split this demand into the different most intensive energy consuming modes of transport,
- make use of the existing fleet data and project the world fleet dynamic in high level of detail into the future, and
- produce global impact assessment in term of emission and welfare.

The MOVEET model has been applied to EU-28 representation of passenger cars for this report. Using the EU Reference Scenario as the starting point of this project, MOVEET's passenger car module has been calibrated at EU-15 and EU-13 level to represent the reference scenario. For this purpose, at the beginning of the project, the reference scenario's economic assumptions and vehicle stock data of the base years 2005 and 2010 (PRIMES-TREMOVE model) have been adopted. After the calibration, MOVEET is able to reflect EU Reference Scenario 2013 transport demand prediction (kilometre-driven) and vehicle fleet structure in EU-28 for the period of 2010-2050.

The scenario simulation needs two exogenous adjustments of the model:

- Firstly, the vehicle fleet shares of the different car propulsion types have been fixed to the two alternative scenarios (EV-mid and EV-high). The shares of electric cars of the two scenarios defined for 2030 and 2050 were adopted for the EU-28. The number of electric cars for these two years were calculated at EU-28 level and then allocated to each of the 28 Member States.
- Secondly, a dataset of the EU Reference Scenario 2013 has been used to calibrate MOVEET to the average fuel consumption values and tank-to-wheel (TTW) CO_2 emission factors of the EU Reference Scenario 2013.

The model run concerns then basically calculation of fuel consumption, CO_2 emission and several air pollutions, i.e. PM_{10}, $PM_{2.5}$, NO_x and SO_2. The emission factors of the TTW air pollutions are based on emission factors derived from the Copert 4 emission calculation methodology (LAT, 2006). These emission factors were initially used in TREMOVE model (De Ceuster et al., 2007) before and have been adapted later on to MOVEET. Average 2030 emission factors are results of emission factor evolution in TREMOVE model taking into account all EURO standards that concern passenger cars entering into application before 2020. No new EURO standard is assumed to be implemented between 2020 and 2030. Beyond 2030 PM and SO_x emission factors are considered to remain at the EURO VI standard. PM and SO_x emissions are assumed to be determined by the development of the overall vehicle stock, its fuel consumption, and its structural composition. For NO_x, it is assumed that there is rather small additional mitigation potential from hypothetical EURO VII standards after 2020 i.e., -13% in 2030 -24% in 2050 (Amann, M. et al., 2012).

TTW emissions and pollution are obtained in principle by multiplication between transport demand and the fuel consumption, emission and pollution factors. Well-to-tank (WTT) emissions, on the other hand, are calculated by multiplying fuel consumption of each fuel type and the corresponding emission and pollution factors.

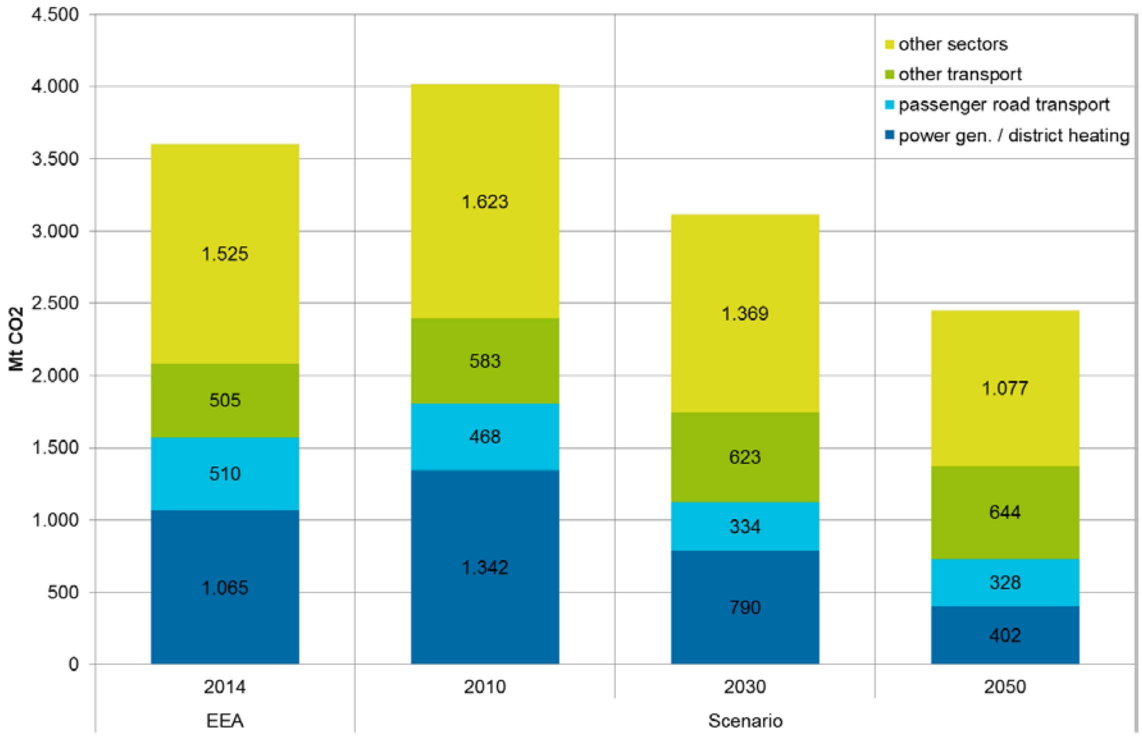
The average fuel consumption and the TTW CO_2 emission factors from the EU Reference Scenario 2013 are implemented in MOVEET. The CO_2 WtT emission factors are taken from Edwards et al. (2014) and are kept constant over time. The average fuel consumption and the TTW CO_2 emission factors from EU Reference Scenario 2013 are implemented in MOVEET. The CO_2 WTT emission factors in Edwards et al. (2014) are basically in line with those of IPCC as IPCC methodology (for example in calculating direct and indirect land use change emissions) are closely followed in Edwards et al. (2014).

3.1.3. CO_2 emissions from electricity generation and the transport sector

Figure 12 shows that the increased usage of renewable energy sources and the gradual decline of fossil fuel consumption lead to a decrease of CO_2 emissions. However, CO_2 emission reductions fall far behind the long term target of the EU (80% reduction until 2050 compared to 1990 levels). Emission trends in transport and power sector are diverging: While power sector emissions are reduced by about 70% (2050 rel. to 2005), despite the increase in power demand, transport sector emissions remain almost constant.

The CO_2 regulation is the driving force for GHG emission reduction of passenger road transport until 2020. The CO_2 emissions for passenger road transport decline by 29% until 2030 (compared to 2010) and remain at the same level up to 2050. Other applications such as freight transport and aviation have increasing GHG emissions over time and the transport sector GHG emissions are in fact higher than the emissions from electricity generation in 2050. The high GHG emissions of the transport sector are the result of increasing activity levels and the low penetration levels of low carbon transport solutions due to their cost-intensity.

Figure 12: CO_2 emissions by sector (EU-28 aggregate) in EU Reference Scenario 2013



Source: Authors' own representation of Capros et al., 2013; EEA 2016.

The opportunity to contribute to transport sector decarbonisation by coupling both sectors becomes clear. It should also be noted, however, that – in the reference scenario – the power sector is not decarbonized completely and additional electricity generation capacities are required. As a result electricity consumed by electric cars is not automatically CO_2 emission free and might lead to significant indirect CO_2 emissions if additional fossil capacities will be used to supply the demand from electric cars.

3.2. Other European energy and transport scenarios

Several alternative scenarios for the development of the European Energy system have been developed by a large range of actors. Most of the scenarios are target-driven scenarios with the goal to present different technical and economic feasible pathways towards a sustainable power system and highlight the required changes in technical infrastructure and policy frameworks.

To put the chosen reference scenario into perspective, four alternative scenarios developed by different actor groups are presented. For comparison with the reference scenario, the assumed or derived characteristics of the energy systems and the transport sector are highlighted.

3.2.1. Energy Roadmap 2050 (European Commission)[5]

In 2011 the European Commission published the Energy Roadmap 2050 that explores the challenges of the EU's decarbonisation objectives in the energy sector. The five scenarios of Energy Roadmap 2050 build on the same modelling framework as the EU Reference Scenario 2009 and reflect different possible technology pathways and related policy frameworks.

The scenarios are "high energy efficiency", "diversified supply technologies", "high RES", "delayed CCS" and "low nuclear". All scenarios are based on the same macroeconomic and demographic assumptions as the reference scenario, facilitating the comparison of the results across all scenarios. The model-based analysis of decarbonisation scenarios shows that decarbonisation in the EU is feasible. One of the main conclusions is that decarbonisation requires a virtually carbon free electricity sector by the year 2050, which can be achieved by varies technology combinations and related policy approaches.

[5] EC (2011)

Table 2: Fact Sheet of Energy Roadmap 2050 (decarbonisation scenarios)

General framework	
Overall GHG emissions	~85% compared to 1990
GDP development	+1.7% p.a. on average from 2010-2050
Population development	+0.1% p.a. on average from 2008 – 2050
Transport sector	
GHG emissions	Not mentioned
Main GHG abatement strategies	Massive shift to EV in road transport and energy efficiency gains Increasing share of sustainable biofuels
Final energy demand	-38 to -43% in 2050 compared to the EU Reference Scenario 2009
EV market penetration	80% of passenger car activity by electric cars in 2050 Share of electricity of passenger cars' and light duty vehicles' energy demand in 2050: ~65% in all scenarios
Electricity sector	
Total electricity demand	Significant demand reductions ranging from 32% (delayed CCS) to 41% (high energy efficiency) between 2005 and 2040.
Energy efficiency	Strong improvements with energy intensity reductions of about 2.5% p.a.
GHG emissions	Almost fully decarbonized
Renewable energy	RES-E share: 59.1% (diversified supply technologies) – 83.1% (high RES) Wind: about 33% in most scenarios (50% in high RES scenario). Solar and other fluctuating RES-E: about 10% in most scenarios (16% in high RES scenario)
Technology pathways	Energy efficiency and renewable energy are key strategies for achieving the decarbonisation targets in all scenarios. Considerable capacity for fossil fuel with CCS (about 25%) is required in all scenarios except the high RES scenario (below 10%). Nuclear power with almost 20% generation share remains dominant generation technology (delayed CCS).

Source: Authors' own summary of EC (2011)

3.2.2. World Energy Outlook 2015 (International Energy Agency)[6]

The World Energy Outlook (WEO) is the annual flagship publication of the International Energy Agency and one of the leading sources for projection of global energy markets. The WEO presents three scenarios with different underlying assumptions about the evolution of energy-related government policies. Projections are made for up to the year 2040. The central scenario of the 2015 edition is the "New Policies Scenario" (NPS) that is based on the current policies scenario but also takes into account climate protection targets presented by national governments for the UNCCC COP in Paris in 2015. Results of the NPS are presented below.

Table 3: Fact Sheet of World Energy Outlook 2015 for European Union (New Policy Scenario)

General framework	
Overall GHG emissions	-51% in 2040 (compared to 1990)
GDP development	1.7% p.a. on average between 2013-2040
Population development	0.17% p.a. on average between 2013-2040
Transport sector	
GHG emissions	-32% in 2040 compared to 2013 levels
Main GHG abatement strategies	Energy efficiency improvements in passenger cars and gradual shift to biofuels (especially second generation biofuels)
Final energy demand	-19% in 2040 compared to 2013 levels 15% biofuel share in 2040
EV market penetration	Small share of electric cars compared to other scenarios Share of electricity in transport energy demand: 4%
Electricity sector	
Total electricity demand	-0.4% p.a. (2013-2040)
Energy efficiency	Medium improvements
GHG emissions	65% reduction until 2040 (compared to 1990)
Renewable energy	About 51 % RES-E (23% wind, 5% PV)
Technology pathways	Strong reliance on gas-fired generation (21% in 2040) to replace coal and provide necessary flexibility. Nuclear production remains stable at about 23%.

Source: Authors' own summary of IEA (2015)

[6] IEA (2015)

3.2.3. Energy [r]evolution (Greenpeace/ *European Renewable Energy Council*)[7]

The energy [r]evolution scenario developed by the European Renewable Energy Council and Greenpeace International is a target-driven scenario, presenting a sustainable energy system that achieves the long-term EU CO_2 emission reduction goals. Based on comprehensive modelling by the Institute of Technical Thermodynamics of the German Aerospace Centre (DLR), cross-sector scenario results are presented.

Table 4: Fact Sheet of energy [r]evolution

General framework	
Overall GHG emissions	-95 % compared to 1990 (197 million tonnes in 2050)
GDP development	+1.6 % p.a. on average from 2009-2050
Population development	+0.05 % p.a. on average from 2009-2050
Transport sector	
GHG emissions	-94% compared to 2009 levels (51 million tonnes in 2050 Sector with highest emissions in 2050 (~26% of total emissions)
Main GHG abatement strategies	Decrease in transport activities (especially behavioural changes) Massive shift to electrical and fuel cell vehicles; strong energy efficiency improvements
EV market penetration	100% sales share of electric and fuel cell passenger cars Share of electricity in transport energy demand: 12% in 2030; 50% in 2050
Electricity sector	
Total electricity demand	Strong decrease in residential, industry and service sector Total demand significant increases due to electrification of transport and heat sector
Energy efficiency	Strong improvements in energy efficiency
GHG emissions	Almost completely decarbonized energy sector in 2050 (95% reduction of CO_2 emissions)
Renewable energy	96% RES-E (35% wind: 18% PV) in 2050 Installed capacities of RES-E more than twice as projected in EU Reference Scenario 2013
Technology pathways	No reliance on CCS technologies Complete nuclear phasing out of nuclear energy by 2040 Strong decentralization in power generation Significant expansion of grid infrastructure, demand side management and storage capacity

Source: Authors' own summary of Teske et al. (2012)

[7] Teske et al. (2012)

3.2.4. Roadmap 2050 (European Climate Foundation)[8]

The roadmap 2050 project is an initiative of the European Climate Foundation with the purpose to provide an independent and objective analysis of technical and economic feasible pathways to a low-carbon energy system in the EU. The roadmap 2050 projects distinguished itself from other studies by the extensive cooperation of a large variety of actors, including major utility companies, network operators, research centres and NGOs. Involved actors include McKinsey & Company and Oxford Economics. The pathways are elaborated backwards from the stipulated end-state in 2050 to today (back-casting approach).

Three different scenarios, all achieving an almost fully decarbonized power sector, are analysed. Road transport reaches also -95% in CO_2 emissions compared to 1990. All decarbonisation pathways are seen as feasible from a technological and economic viewpoint.

Table 5: Fact Sheet of Roadmap 2050

General framework	
Overall GHG emissions	80% CO_2 reduction in 2050 compared to 1990
GDP development	1.8 % p.a.
Population development	-0.08 % p.a. on average from 2010 – 2050
Transport sector	
GHG emissions	-95% in road transport; -50% aviation & sea transport
Main GHG abatement strategies	Extensive electrification in road transport and energy effiency improvements in cars Also second generation biofuels and carbon-free hydrogen
Final energy demand	Not mentioned
EV market penetration	All passenger cars electrified in 2050 (80 % BEV /20 % PHEV) Electricity consumption from road transport in 2050: 740 TWh
Electricity sector	
Total electricity demand	40% increase compared to 2005, reaching 4,900 TWh in 2050
Energy efficiency	Large improvements
GHG emissions	>95% reduction
Renewable energy	Scenario 1: 40% RES-E (21% wind, 17% PV and CSP) Scenario 2: 60% RES-E (21% wind, 17% PV and CSP) Scenario 3: 80 % RES-E (30% wind, 24 % PV and CSP)
Technology pathways	Nuclear and fossil fuel plants with CCS supply the remaining necessary generation share in equal parts. Significant expansion of electricity grid and doubling of backup generation capacities to accommodate fluctuating RES-E production

Source: Authors' own summary of ECF (2010)

[8] ECF (2010)

3.3. EV-mid and EV-high scenario

The Reference Scenario is a very conservative scenario with regard to electric car share in EU car stock. The overall GHG target of 80% emission reduction for 2050 is not reached in the reference case. The transport sector shows very little GHG reduction in the reference scenario and has higher GHG emissions than the power generation sector in 2050 (see Figure 12).

Several potential pathways to reach the GHG emission targets are presented in section 3.2. A higher share of electric cars and battery charging with renewable electricity sources is one of the favoured options – especially for road transport – for decarbonizing the transport sector to the required levels. Therefore two additional scenarios (EV-mid and EV-high) will serve for the discussion of the electric car integration into the European electricity system.

These two additional scenarios are implemented in the MOVEET model (see box on MOVEET model) in order to estimate their impact on the transport sector. Some basic assumptions of the reference scenario are also applied to the EV-mid and EV-high scenario:

Firstly, transport activity evolution of the whole EU-28 passenger car fleet in both additional scenarios is exactly the same as that of reference scenario. This means that transport demand in the whole EU-28 will grow from around 2,800 Giga vehicle-kilometers (Gvkm) today to around 3,160 Gvkm in 2030 and to around 3,480 Gvkm in 2050. Secondly, it is assumed that the average mileage per vehicle does not differ between electric and non-electric passenger cars and it is also assumed that this average mileage per vehicle is the same in all three scenarios.

The only parameter which has been altered is the electric car share of the passenger car stock in the EU. The EV-high scenario assumes 80% of electric driven cars in the passenger car stock in 2050 (see Table 6). 80% of electric passenger cars are pure battery electric vehicles; the remaining 20% of electric passenger cars are PHEV. The assumptions on electric car stock are loosely based on the available information of the Energy Roadmap 2050 from the European Commission (see section 3.2.1). The Energy Roadmap 2050 requires the total energy systems to achieve -80% in CO_2 emissions in 2050. Heavy electrification of passenger road transport is one of the main strategies for the transport in the Energy Roadmap 2050 scenarios. 80% of the activities in road passenger transport are undertaken with electric cars which is roughly reflected in the EV-high scenario.

Other scenarios (e.g. World Energy Outlook 2015 in section 3.2.2) require less GHG reduction from road transport and focuses more heavily on biofuels as a decarbonisation strategy. Therefore, GHG emission reduction pathways with less electric car penetration also seem plausible. The EV-mid scenario reflects the different approach to electric car market penetration and assumes a slower electric car penetration than the one of the EV-high scenario. Thus, the EV-mid scenario assumes 50% electric car share in passenger car stock in 2050 (see Table 6); the BEV to PHEV ratio is also considerably smaller. 60% of electric passenger cars in 2050 are pure electric vehicles due to the smaller market penetration of electric passenger cars.

The country-specific distribution of electric car penetration and the BEV to PHEV ratio per country were not available for the alternative scenarios which are presented in section 3.2. The assumed market penetration of electric vehicles among EU-28 countries in the EV-mid and EV-high scenario considers information on typical new car registration structure and second-hand car flows among these countries.

The remaining non-electricity energy demand from passenger cars (e.g. fossil gasoline, fossil diesel) is relevant for the GHG emission calculations of the transport sector. Both the EV-mid and the EV-high scenario assume the same fuel mix of non-electricity energy carriers as in the reference scenario. Thus, the GHG intensity of the non-electricity fuel mix is equal in all three scenarios.

Table 6: Summary of EV-mid and EV-high scenario

	2030	2050
EV-mid scenario		
EV total share	20%	50%
BEV share in EV	50%	60%
PHEV share in EV	50%	40%
EV-high scenario		
EV total share	30%	80%
BEV share in EV	60%	80%
PHEV share in EV	40%	20%

Source: Authors' own assumptions

3.3.1. EV-mid scenario

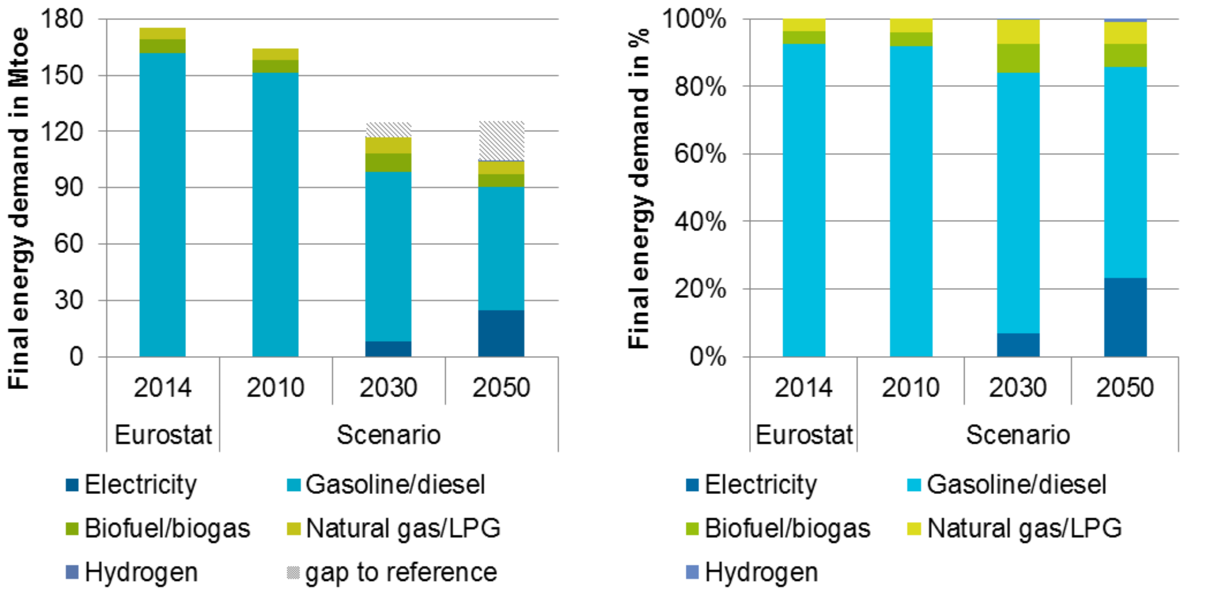
At EU-28 level, reaching 20% of electric car penetration in the total passenger car stock will drop the energy consumption of the passenger car stock by more than 6% in comparison with the reference case in 2030, i.e. a fall from 125 Mtoe to 117 Mtoe (see Figure 13). Reaching 50% share of electric vehicles in the total passenger car stock in 2050 will more intensively drop energy demand from passenger cars (see Figure 32 for national EV penetration rates). The total estimated energy demand from passenger car stock should decrease from around 125 Mtoe in the EU Reference Scenario 2013 to around 105 Mtoe in the EV-mid scenario (-16%) which can be attributed to the higher electric car penetration in comparison to the reference scenario.

Comparison to the base year 2010 includes electric vehicle car fleet penetration and energy efficiency gains of conventional cars, which are also assumed in the Reference Scenario 2013. The main reduction of energy consumption is evidently recognizable until 2030 due to efficiency gains of conventional cars (-29% between 2010 and 2030). Unlike the reference scenario, the higher energy efficiency of electric drive train[9] causes a drop in energy demand after 2030 (-36% between 2010 and 2050).

The higher share of electric cars also results in higher electricity share in passenger car fuel mix. It increases from no electricity demand in 2010 to 7% in 2030 and to 23% of total final energy demand in passenger road transport in 2050 (Figure 13). The fossil fuel share drops below 70% in 2050 and is considerable smaller than in the reference case.

[9] The specific energy consumption per distance travelled of electric drive trains is generally lower in relation to combustion engine drive trains. As a result, the final energy demand decreases with a higher share of electric vehicles.

Figure 13: Final energy demand of passenger cars for EU-28 in EV-mid scenario



Source: Authors' own assumptions applied to MOVEET model; Eurostat 2016

At country-level, highest electric vehicle car stock penetration rates are in the order of 65% to 85% by 2050 while other countries have an electric vehicle share in the passenger car stock that is well below 40%. As a result, highest country-specific electricity shares in passenger cars fuel mix constitute approx. 35% of total final energy demand. It reduces to 10-15% for countries with small electric vehicle penetration rates.

3.3.2. EV-high scenario

The EV-high scenario assumes stronger electric car penetration than in the other two scenarios and car stock shares of 30% in 2030 and 80% in 2050 will be reached (see Figure 34 for national EV penetration rates). Additionally, the BEV to PHEV ratio of electric cars shifts stronger to BEV than in the EV-mid scenario and 80% of the electric cars are pure electric vehicles in 2050.

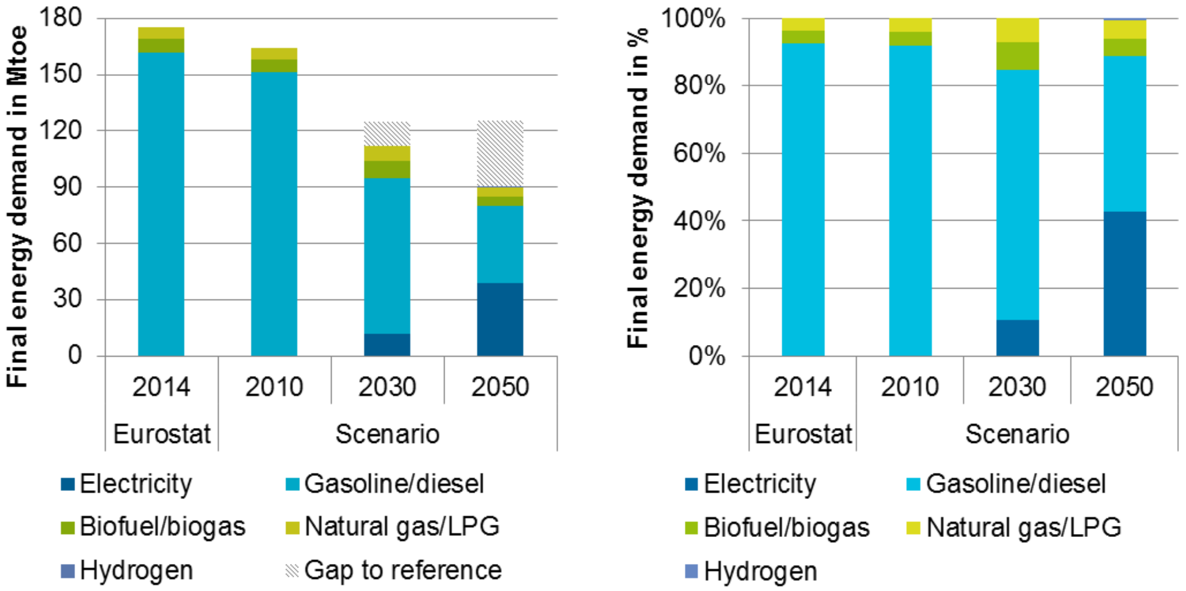
The better energy efficiency of the electric drive train becomes clear again in this scenario. The higher market penetration of electric cars increases the fall of total energy consumption from passenger car stock compared to the EV-mid and the reference scenario. At EU-28 level, it is expected that the total energy consumption will drop by 10% (relative to the reference case) in 2030 from 125 Mtoe in the EU Reference Scenario 2013 to 112 Mtoe in the EV-high scenario. In 2050, the drop increases to 28% (125 Mtoe to 90 Mtoe).

Again, the CO_2 regulation for cars is the main cause of final energy demand reduction until 2030 (-32% by 2030) when compared to the 2010 base year. However, the high share of electric vehicles causes a continuous drop of energy demand up to 2050 (-45% compared to 2010).

The change in electric car penetration results in an increased electricity share in the fuel mix. In 2030, more than 10% of the final energy demand from passenger cars in the EU-28 is electricity (Figure 14). The electricity share reaches a similar level to those of fossil liquid fuels (electricity: 43%; gasoline/diesel: 46%) in 2050. In total, the fossil share of fuels is reduced to around 50% of the final energy demand from passenger cars which results in considerable abatement of direct emissions from road transport.

On a national level, some countries reach a fully electrified passenger car stock (BEV and PHEV) in 2050. The lowest national electric vehicle shares in car stock vary from 37% to 55%. The electricity share in the national fuel mix for passenger cars ranges from 15% to 74%.

Figure 14: Final energy demand of passenger cars for EU-28 in EV-high scenario



Source: Authors' own assumptions applied to MOVEET model; Eurostat 2016

3.4. How the additional electricity demand can be covered

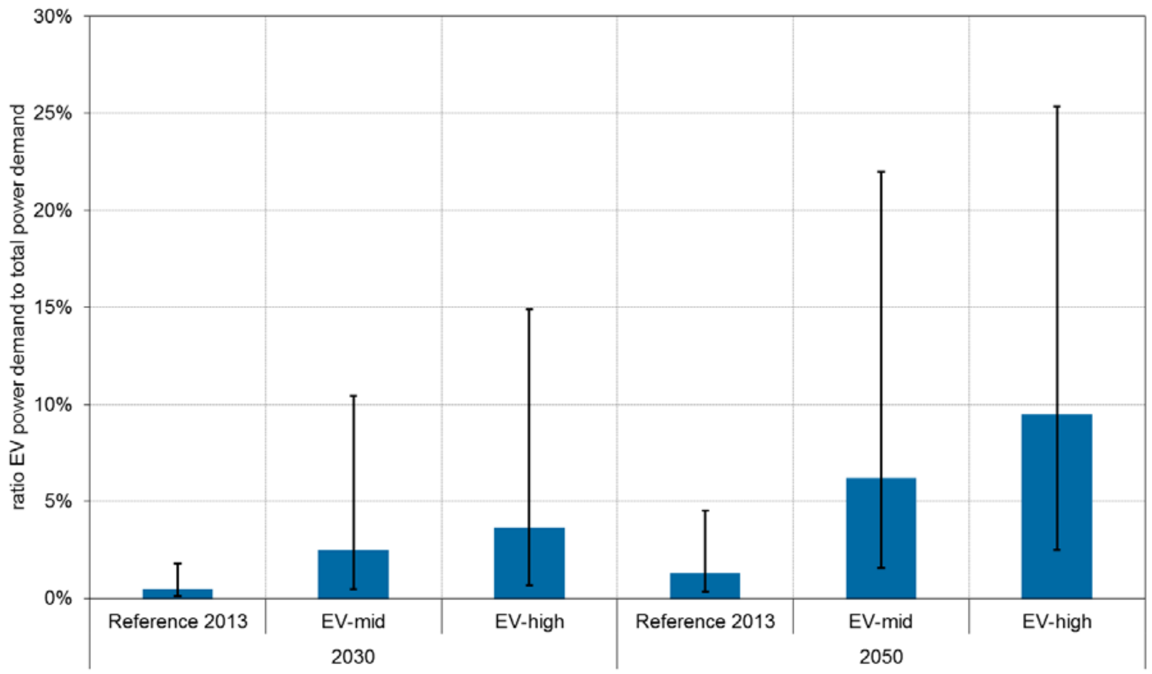
Electric vehicles, obviously, need electricity to run. Charging electric cars results in additional demand for electricity that needs to be satisfied by additional power generation. Sufficient generation capacities need to be available at the right time and the right location to satisfy demand at all times. Additional demand may be met by increasing the full load hours of existing power plants or by building new generation capacities. The electric cars have to be connected to the grid, and they must be available for charging in order to charge the car. And as a result, the additional generation may lead to additional emission of greenhouse gases and air pollutants.

This section examines how the additional power demand (caused by electric car charging) can be met – on the aggregate EU-28 level as well as on the level of different countries.

3.4.1. Ratio of electric car demand and total power demand

An important indicator for assessing the impact that electric car charging has on electricity systems is the ratio of electric car power demand to total electricity demand. Figure 15 shows this data for the EU-28 aggregate, across the three electric car penetration scenarios (reference, EV-mid and EV-high), and for 2030 and 2050. It also indicates the spread across different countries. In the reference scenario, the EU-28 average of this ratio is well below 1% in 2030 and increases slightly above 1% in 2050 – as transport sector electrification only plays a minor role in the Reference Scenario 2013, its effect on the power system is almost negligible. This is not the case if higher penetration rates are assumed: In the medium and high scenarios, electric car demand shares increase to about 6% and 9.5% until 2050, respectively (see Figure 33 and Figure 35 for country-specific data). Electric car demand shares across countries vary significantly and deviate strongly from the EU average. In the high penetration scenario, they vary between 3% and 25% (in 2050).

Figure 15: Electric car share of total electricity demand (EU-28 average). The spread markers indicate differences between countries



Source: Authors' own illustration of Capros et al., 2013; authors' own assumptions applied to MOVEET model

The overall demand increase of up to 25% (depending on the country analysed) would not require a complete restructuring of the power system. From a top-down perspective, in some countries, increased utilization of existing power plants may even be able to compensate the demand increase. Depending on the availability of existing (fossil) power plants, and on the objectives regarding which power sources should be used (e.g. climate and RES targets), it may also require additional generation capacities (see discussion in section 3.4.2).

A demand increase in the discussed order of magnitude would affect power sector emissions, and they would be very relevant for climate policy specific to the power sector. The demand increase should also be seen in the context of potentially increasing power demand in other sectors as well (e.g. heating and cooling) – it is unlikely that the additional power demand of electric vehicles will be compensated by demand reductions in other sectors.

Moreover, not only the aggregated annual demand changes matter. Power demand needs to be satisfied at the right time and place. Electric vehicles constitute a new type of power consumer, with specific load patterns and spatial distributions, and increasing the overall demand share of this consumer type to more than 10% would require adaptation efforts to maintain system stability and adequacy (see section 2).

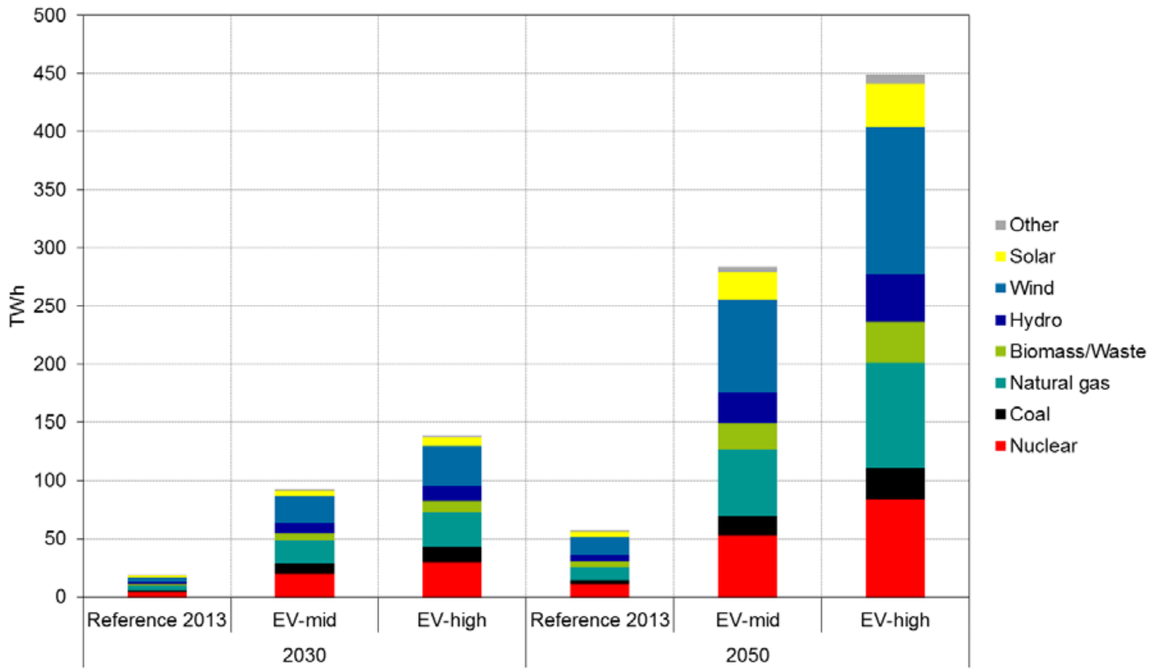
Electricity demand from electric cars in road passenger transport is not negligible and impacts the electricity system. It has to be integrated into the electricity system and the system has to be adapted to charging electric cars.

3.4.2. A closer look at additional power generation

Section 3.3 discussed how much additional electricity would be required to charge electric vehicles in ambitious electric vehicle scenarios. Section 3.4.1 compared these numbers to overall power demand and showed that – at an EU-28 average – EV charging would increase power demand by up to 9.5%, and up to 25% in some member states.

Figure 16 shows how much additional power needs to be generated to satisfy electric car demand, and it also gives an estimate for which sources might be used to generate this power. This data has been calculated based on the average generation mix for each country in 2030 and 2050 as reported in the reference scenario. It is assumed that this generation mix remains unaffected by increasing electric car power demand relative to the reference scenario. This implies that an increase in demand is met by an adequate, proportional increase of generation capacities to ensure that sufficient generation capacity is available and the generation share of each technology remains unchanged. In policy terms, this effect could be the result of renewable targets that are formulated not in terms of installed capacity, but as relative shares of total power generation or demand[10].

Figure 16: Additional generation required to satisfy electric car power demand (EU-28 aggregate)



Source: Authors' own calculations

The assumption of fixed generation mixes also constitutes a significant simplification of the complex interplay between generation and load profiles (see box on electric car charging and power generation profiles). As described in section 2.2, the additional generation necessary for electric car charging depends in particular on the time of charging and can be influenced by smart

[10] The German EEG (the law governing renewable power support in Germany) is an example of national legislation which uses this type of target setting (Bundesrepublik Deutschland, 2014). Instead of defining absolute targets (in terms of generation capacity), it requires 55%-60% of total power demand to be met by renewable sources by 2035. If power demand would increase (e.g. because of increased EV shares), higher renewable generation capacities would be required to meet the target.

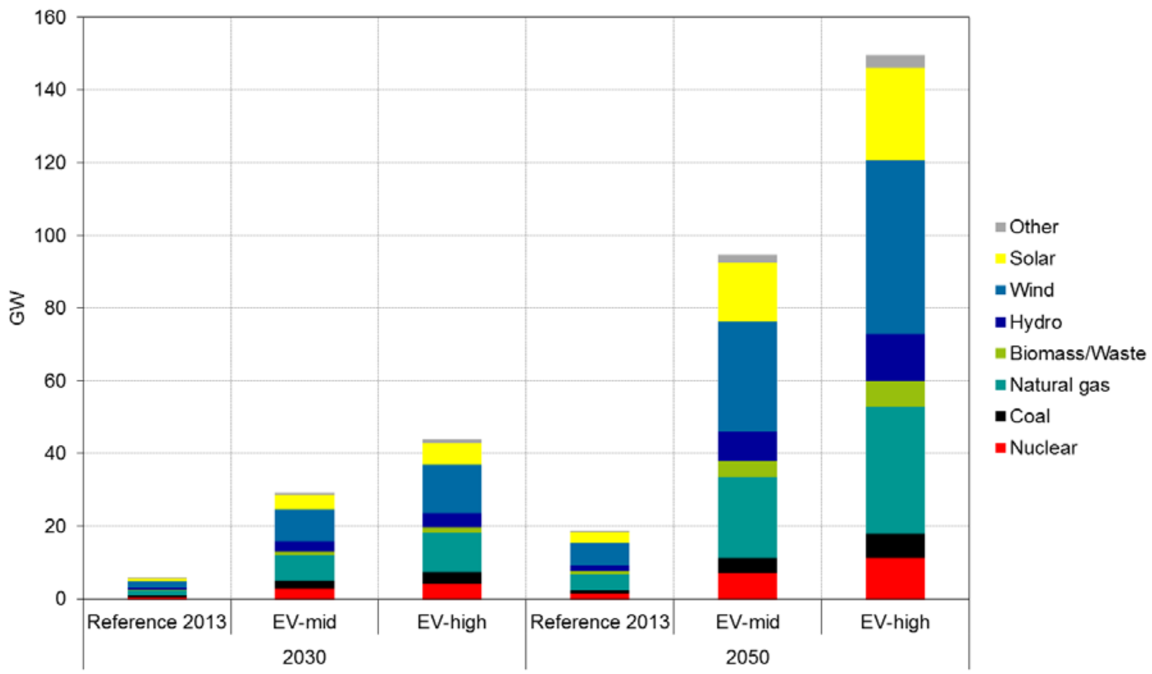
charging approaches. As a first-order estimate, however, the assumption of constant load factors and constant full-load hours is reliable. More detailed analyses with dispatch modelling approaches and different smart charging strategies could result in slightly different load factors and a different integration of VRE.

The total annual generation for electric cars in 2050 amounts to 57 TWh in the reference scenario and increases to 283 and 448 TWh in the medium and high penetration scenarios, respectively. More than half of this demand is met by generation from renewable sources (solar, wind, hydro and biomass). Under the above described approach for the average generation mix almost 20% is met by additional generation from nuclear power plants.

Figure 17 indicates how much additional generation capacity needs to be put in place in order to provide this additional generation. It is assumed that the average load factors derived from the reference scenario are not affected by increasing electric car demand, thus neglecting the effect of electric car demand increasing load factors of dispatchable generators or using surplus VRE generation[11].

The total needed additional capacity in 2050 is significant. In the medium scenario it amounts to 95 GW and in the high scenario to almost 150 GW. Increases in capacity are the greatest for wind, natural gas and solar power plants. In the high scenario a total of 48 GW in wind, 35 GW in natural gas, and 25 GW in solar capacity are required to satisfy the additional EV demand.

Figure 17: Additional generation capacity required to satisfy electric car power demand (EU-28 aggregate).



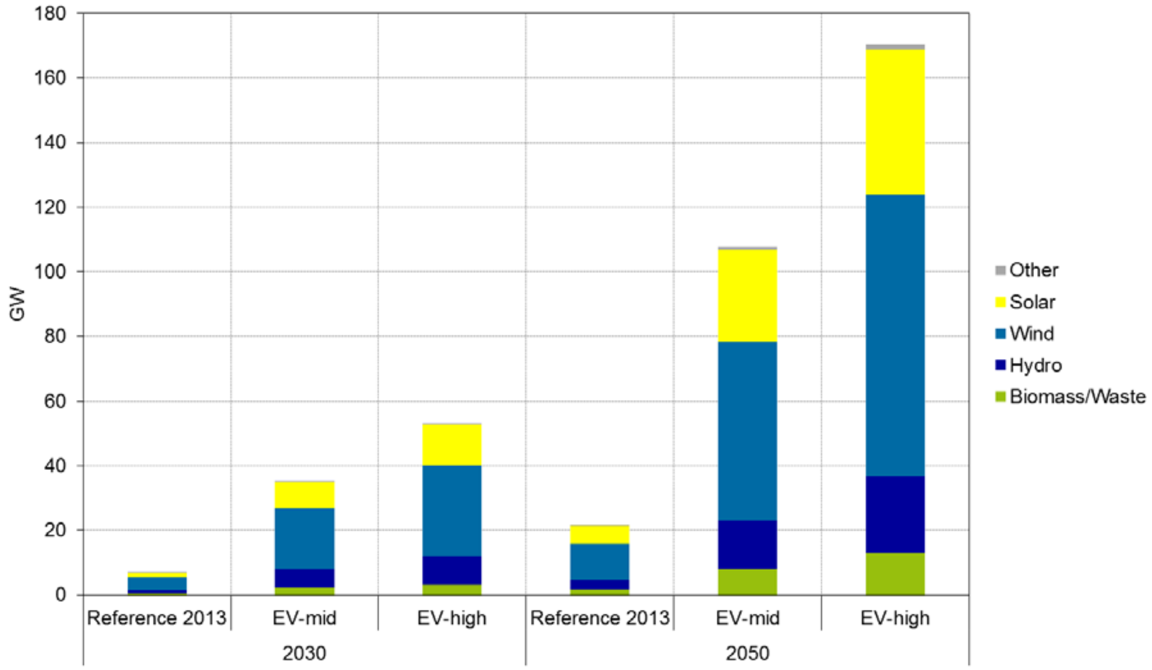
Source: Authors' own calculations

[11] The impact of electric car charging to load factors of dispatchable generation capacities and to integration of VRE generation is very much depending on the ability of the electricity system to shift the charging to favourable hours. The smart charging approach and the willingness of car users to participate in smart charging are relevant factors for load factors and VRE integration (see section 2.2). The assumption of constant load factors and constant full-load hours is a reliable estimate for a general analysis. More detailed analyses with dispatch modelling approaches and different smart charging strategies could result in slightly different load factors and different integration of VRE.

Only by covering the entire electricity electric car demand with renewable energy, electric cars can be reasonably considered as a zero-exhaust emission and environmentally sustainable transport option. Furthermore, only by adding the necessary renewable energy capacities required to cover total electric car demand, the need for additional fossil and nuclear power plant capacities can be avoided and the transport sector would not put an additional burden on the energy sector in terms of CO_2 emissions.

Figure 18 shows the required additional capacities necessary to satisfy electric car demand completely with renewable energies. Again, load hours of thermal power plants and renewable energy capacities are assumed to be equal to the reference scenario. To fully cover electric car demand in the EV-high scenario by renewable production a total amount of 170 GW of renewable energies is required in 2050 (including 87 GW wind, 45 GW solar, 24 GW hydro and 13 GW biomass capacities). To put these numbers in perspective: In the reference scenario, renewable generation capacities increase from 227GW in 2010 to 786 GW. Fully covering electric vehicle power demand by renewable sources would require increasing renewable generation capacities by 22% in 2050 (relative to the reference scenario). These numbers illustrate the significant level of additional investments in renewable energy that is necessary to ensure that electric mobility does not negatively impact CO_2 emissions of the energy sector and does not result in the addition of rather inflexible thermal power generation units.

Figure 18: Additional generation capacity required to satisfy electric car power demand – only renewable generation capacities added (EU-28 aggregate).



Source: Authors' own calculations

How EV charging affects power generation profiles

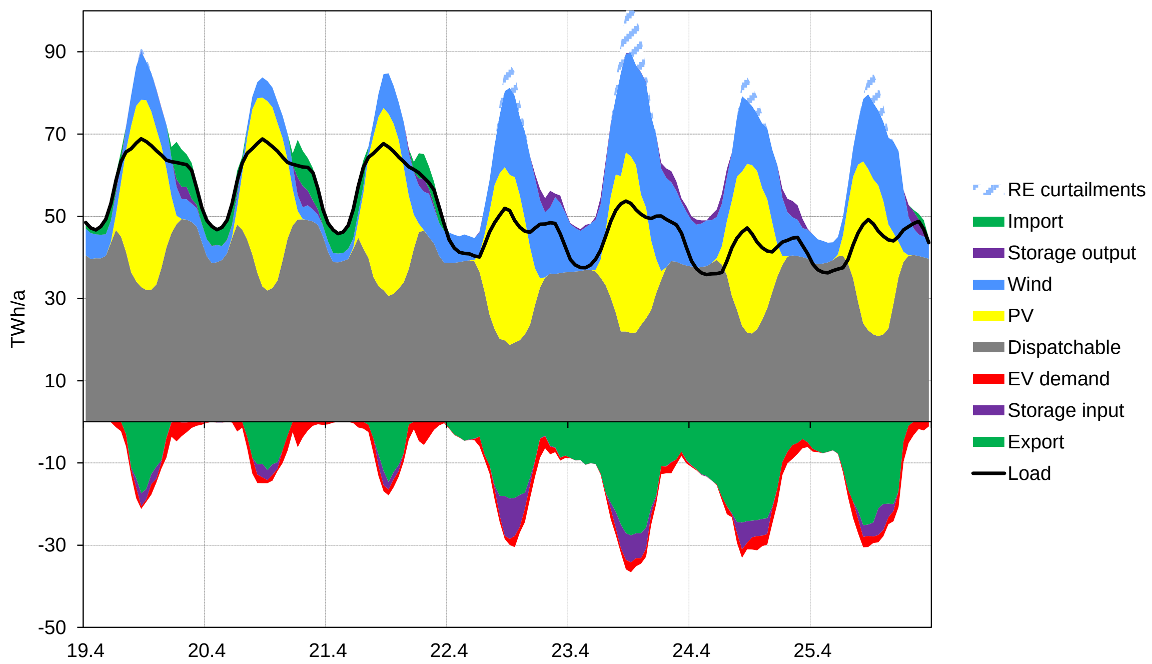
The level of electricity demand and the mix of generation options that is used to meet this demand are far from constant over time. This needs to be considered when analysing how EV power demand can be satisfied.

The simulation results depicted in Figure 19 show the hourly variations of these parameters over the course of one week. Demand is usually highest during the day and low at night, and it is higher on workdays than on weekends. Renewable energy plants that rely on fluctuating energy sources generate power whenever they are available. This results in typical daily peaks for solar power plants, and in irregular profiles for wind turbines that follow meteorological conditions. Dispatchable power plants (e.g. coal, gas, and nuclear) fill the gap (also called ‘residual demand’) that remains between demand and variable renewable generation (VRE). At times when residual demand is small, dispatchable power plants – preferably flexible natural gas power plants – only run on partial load. Surplus VRE generation can be stored or exported, or it may be disconnected if it cannot be absorbed by the system.

This way, the generation mix changes significantly over time, and the generation mix used to power electric vehicles depends on when (and where) they are charged. If managed properly, EV demand can be used to absorb surplus VRE generation. It can also lead to an increase of dispatchable generation that is operated on partial load.

Often, electric vehicles are used during the day and connected to the grid overnight. In this case, uncontrolled charging leads to typical demand peaks in the evening. In power systems with high solar generation shares (as in the example above) EV power demand could be shifted towards midday to match the daily generation peaks – but this would require adequate charging infrastructure and smart charging strategies.

Figure 19: Hourly variation generation mix and demand (one week). German power system 2030, 65% renewable share



Source: Authors’ own calculations

As described in section 2, electric cars can significantly impact the operation of national power systems when electric car penetration reaches significant levels and the share of electric car demand in total electricity demand is high. If these countries also exhibit high levels of wind or solar generation, the coordination of electric car demand and electricity supply through smart charging approaches becomes increasingly important and could constitute a significant challenge. Furthermore, the different national and local generation mixes require divergent types of smart charging approaches.

To illustrate the different consequences of varying national generation portfolios and their specific challenges for integration of high shares of additional electric car demand, we take a closer look at the power sectors of five countries from all renewable energy clusters: Portugal (solar), France and Czech Republic (low variable renewable share), Germany (wind+solar mix), and Denmark (wind) (see also Figure 8 and Figure 10).

Portugal (solar cluster) is an interesting example of a country with high electric car demand combined with fluctuating renewables. The country reaches a high electric car demand share of 12% in 2050 (EV-high scenario), while at the same time, fluctuating renewables provide more than 60% of the electricity supply. Balancing energy demand and fluctuating supply will therefore become increasingly challenging and electric car demand will play an important role in providing the required flexibility. As solar production has a share of 26% the load profile of uncoordinated electric car charging (mostly overnight) will not automatically overlap greatly with renewable energy supply. Therefore, providing opportunities for day-charging (e.g. at the working place) and pursuit of corresponding smart charging approaches will become indispensable to match electric car demand with daily supply curves.

The generation mix of Denmark (wind cluster) is characterised by a very high share of wind power (59%), but as the remaining demand is satisfied by natural gas and biomass plants, the emission intensity is at an intermediate level. In contrast to Portugal, the matching of electric car charging patterns with renewable energy supply in Denmark is more complicated due to the more heterogeneous generation profiles of wind. In order to be able to utilize the large wind production for electric car demand, maximizing times when electric cars are connected to the grid and are ready for smart charging is crucial during day and night. Although the electric car demand share is very high (14%, 2050, EV-high scenario), the power system is relatively well prepared for the additional demand due to the large share of flexible natural gas power plants.

France (low VRE cluster) also has a high electric car demand share of 11% in 2050 (EV-high scenario) but with over 50% nuclear energy production the supply profiles are completely different. Nuclear production is relatively inflexible and has low marginal costs; therefore, the production is characterized by homogenous load profiles that cannot easily ramp up production in times of high energy demand. In order to avoid prolonging operation of older plants or even investments in additional nuclear capacity to provide the required electricity for electric car charging, smart charging strategies should facilitate electric car load profiles that maximizes the utilization of the remaining electricity sources.

Germany (wind & solar cluster) is an example of a country with a relatively high average emission intensity of 0.12 t CO_2/MWh (see Figure 9) and a large share of fluctuating renewable energy (47%). In this case, the specific CO_2 emissions for electric car supply can be significantly lowered if RES-E oriented charging approaches are applied. Electric cars can become an important flexible demand option, allowing for the integration of otherwise unused renewable surplus production instead of stimulating additional production from fossil power plants.

Another example for a power system with a relatively high emission intensity is the Czech Republic (low VRE cluster) due to large shares of coal power. However, in this case the potential to reduce CO_2 emissions for electric car supply are minimal. On the one hand, renewable energy generation is very low (12%) and more than 50% of the total generation is produced by nuclear plants that operate already at the production limits and in addition have similar generation profiles than coal power plants. Under these circumstances smart charging provides few opportunities to improve the environmental performance of electric cars.

3.5. Emission balance of the transport and the energy sector

The increasing penetration of electric cars affects the emission levels of CO_2 and other air pollutants in both the transport and the energy sector: In the transport sector, Electric vehicles reduce emissions by replacing emission intensive combustion engine vehicles. Less fuel use also reduces the WTT emissions from fuel production. In the power sector, they increase emissions by generating additional power demand that leads to additional utilization of conventional power plants. For the overall environmental evaluation of increasing electric car penetration in Europe the emission balances of both sectors need to be assessed.

This section first describes changes in CO_2 emissions and thereafter analyses the impact of electric cars on the air pollutants particulate matter (PM), nitrogen oxides (NO_x) and sulphur dioxide (SO_2).

3.5.1. CO_2 emissions

When comparing CO_2 emission changes in the transport and power sector, it needs to be considered that in the power and industry sector (unlike the transport sector), CO_2 emissions are subject to regulation via the EU Emissions Trading System (ETS). Following the cap-and-trade mechanism, a system wide cap limits all emissions within the ETS. Actors need to acquire allowances for all emissions they generate, and the allowances can be traded to guarantee that overall emissions are reduced in a cost-efficient manner.

If one assumes that the ETS remains in place, and that it is implemented in an effective manner, different emissions in the power system and from refineries will not lead to a change of overall system emissions: The emission cap will be retained, the price for CO_2 allowances will increase or decrease, and emissions will be reduced or increased somewhere else in the system to guarantee that the emission cap is met.

There has been heavy criticism regarding the effectiveness of the ETS. In the past and at present, the over-supply of allowances has led to very low carbon prices. If over-allocation is avoided, an ambitious, binding cap is implemented and maintained, and if other design deficits are addressed, the ETS may guarantee that the mitigation targets are achieved, with or without additional electric vehicle power demand. However, these developments should not be taken for granted.

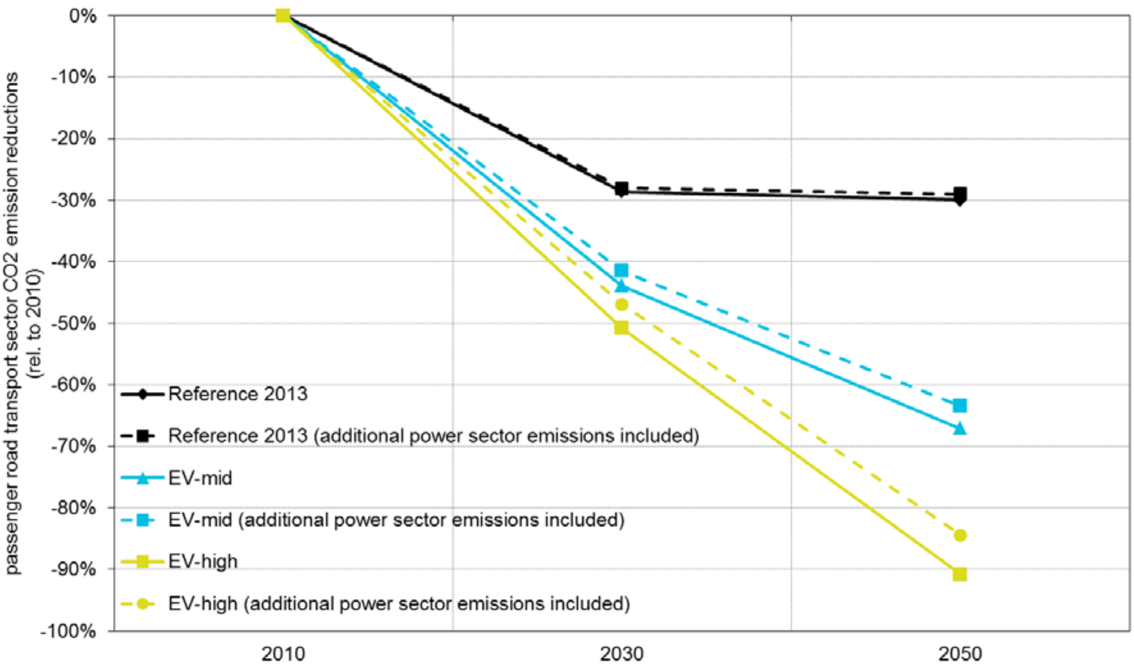
For the following section, the compensation effect of the ETS is not taken into account – that is, different emissions of the scenarios from the power and industry sector do not affect emissions in other parts of the overall system in any way. It shows the impact of higher electric vehicle penetration without the interaction of sectors that could be achieved through a functioning ETS.

Figure 20 shows how CO_2 emissions (TTW and WTT emissions of car use) in passenger road transport change over time. Emission reductions (relative to 2010) occur in all three scenarios. They result from the combined effect of efficiency improvements (which are assumed to be identical in all scenarios) and different assumptions regarding the market share of electric vehicles.

Electric vehicles can make a significant contribution: CO_2 emission reductions (relative to 2010) in passenger road transport increase from 30% (reference scenario) to 91% (EV-high scenario).

The figure also indicates how emission reductions are affected if additional CO_2 emissions related to power generation are taken into account. The order of magnitude of these additional emissions depends on how electric vehicle power demand is satisfied (see section 3.4.2). The effect increases with electric vehicle penetration levels, but additional emission in the power sector are considerably smaller than emission reductions in the transport sector. In the EV-high scenario, emissions reductions are reduced by more than 6% points in 2050.

Figure 20: Passenger road transport sector CO_2 emission reductions (WTT and TTW emissions) relative to 2010 (EU-28 aggregate). The dashed lines take additional power sector emissions into account



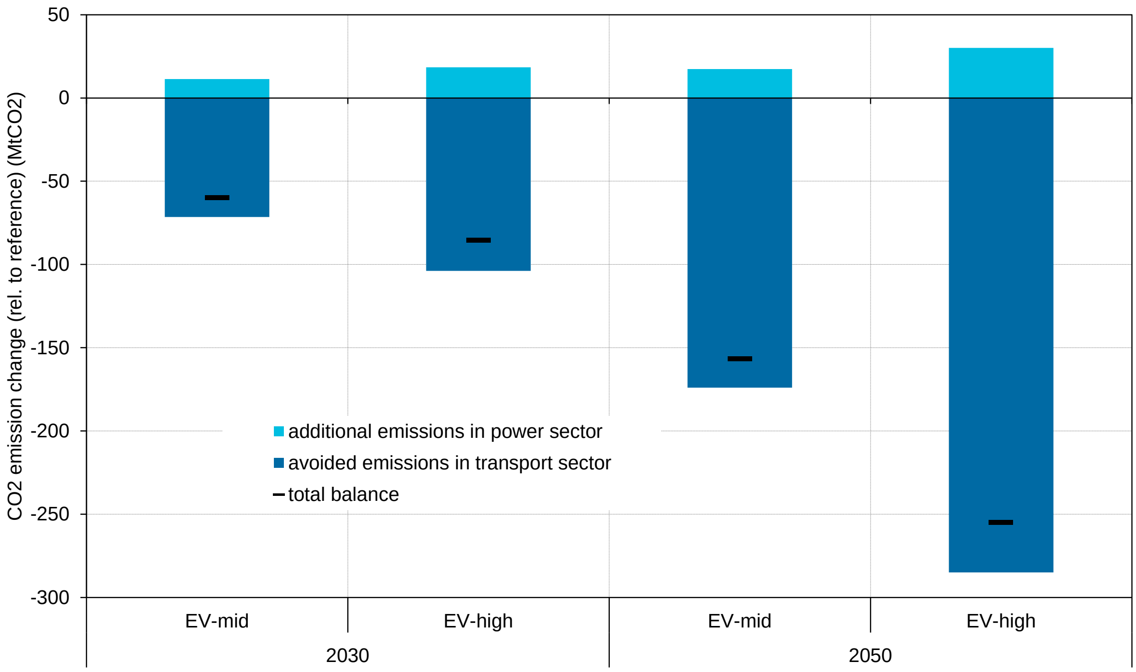
Source: Authors' own calculations

In the following, we take a closer look at how CO_2 emission trends in the EV-mid and EV-high scenarios. To distinguish between the effect of efficiency improvements and increasing EV shares, we will show emission differences not relative to a base year, but relative to the reference scenario, thus isolating the effect of increasing EV market shares beyond the reference scenario.

Figure 21 shows how the increasing penetration of electric cars affects CO_2 emissions in both power and transport sector. The figure shows CO_2 emission changes relative to the reference scenario. The avoided emissions in the transport sector strongly increase between 2030 and 2050 due to the increasing electric car penetration levels. At the same time the additional emission in the power sector caused by the additional production necessary to cover electric car demand increase. However, the emissions in the power sector increase at a much slower rate due to the increasing shares of renewable energy generation. In 2030 the ratio between the additional emissions in the power sector and the avoided emissions in the transport sector is approx. 1/5 on the European level (see Figure 22). As the emission intensity in the power sector decreases strongly between 2030 and 2050 due to increasing share of renewables, this ratio improves further and the additional emission in the power sector are only 1/10 of the avoided emissions in the transport sectors (Figure 23).

In terms of CO_2 emissions, electric car penetration has a strong positive impact compared to conventional vehicles despite the fact of large share of CO_2-intensive generation of coal and gas plants in the power sector. However, electric cars cannot simply be considered as emission-free transportation as the required electricity demand causes additional emissions in the power sectors. Emissions in the production and end-of-life phase cannot be neglected as well and need to be taken into account in the environmental assessment of electric cars. Furthermore, the improved CO_2 balance of passenger road transport is grounded on additional electricity generation capacities which results in higher costs of the electricity system and increased acceptance issues (e.g. additional VRE capacities, additional nuclear capacities).

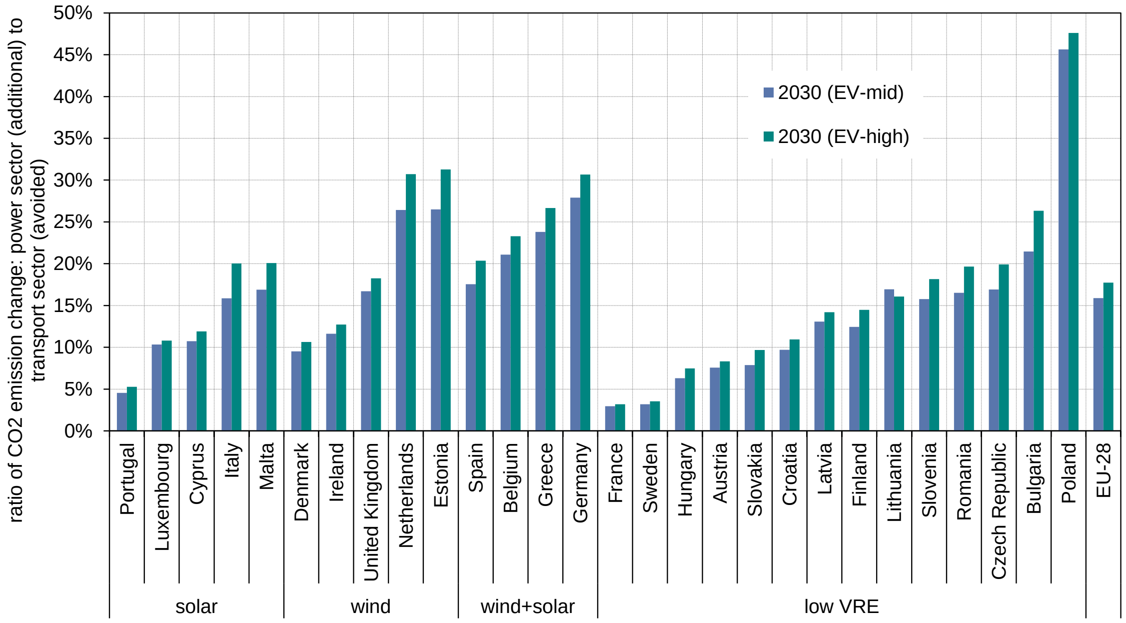
Figure 21: How electric vehicles affect CO_2 emissions in transport (TTW and WTT emissions) and power sector (EU-28 aggregate)



Source: Authors' own calculations.

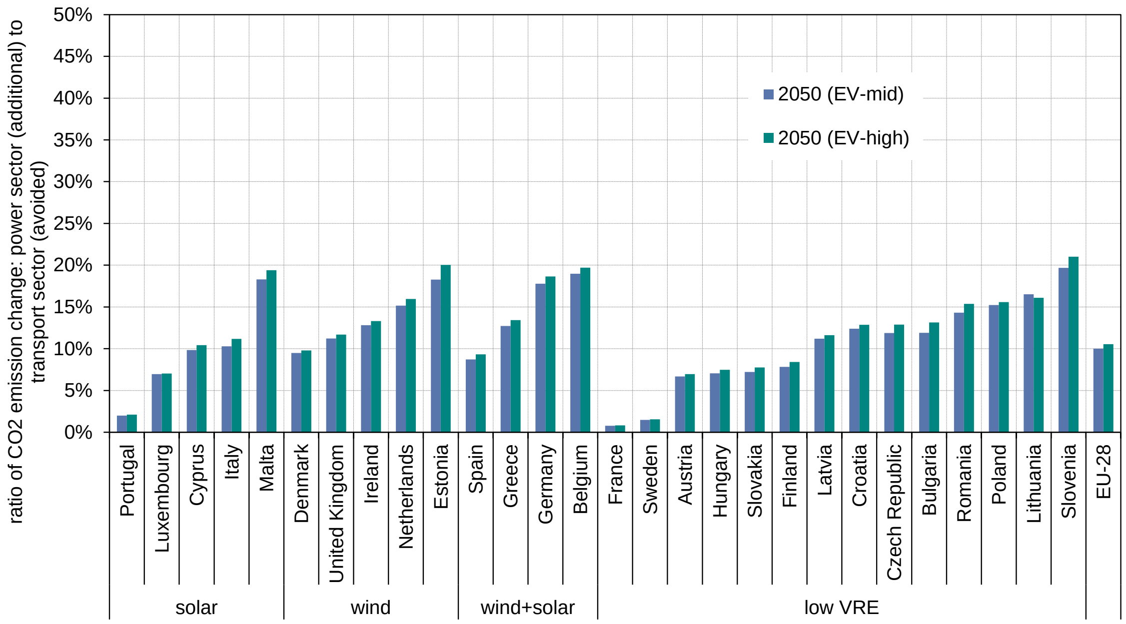
National power systems and emission intensities of power generation are very diverse. Accordingly, the degree to which CO_2 emission reductions in the transport sector are offset by additional emissions in the power sector differs largely across Member States. Figure 22 and Figure 23 provide an indication of how strong these differences are. They show the ratio of CO_2 emission changes (caused by increased EV market shares) in both transport and power sector. The numbers indicate degree of the offset of the avoided emissions in the transport sector by the additional emission in the power sector.

Figure 22: Percentage of avoided transport sector CO_2 emissions (TTW and WTT emissions) that are offset by additional power sector CO_2 emissions (2030) – by country



Source: Authors' own calculations

Figure 23: Percentage of avoided transport sector CO_2 emissions (TTW and WTT emissions) that are offset by additional power sector CO_2 emissions (2050) – by country



Source: Authors' own calculations

For example, in 2050, in Portugal about 2% of the avoided emissions in the transport sector are offset by additional emissions in the power sector. In several countries, such as Estonia, Germany and Slovenia, nearly 20% of the avoided emissions are offset by the additional emissions in the power sector. The numbers differ not only between countries but also within the clusters of renewable energy portfolios as the CO_2-intensitity of the non-renewable production greatly affects the additional emission in the power sector. For example, the ratio for France is below 1% despite low shares of wind and solar power as the remaining power generation is mostly covered by nuclear generation. On the other hand, the ratio for Germany with higher wind and solar generation shares is about 18% due to the large generation of CO_2-intensive coal-based generation. This highlights the importance of the overall CO_2-intensitiy of the national generation mix required to charge electric cars.

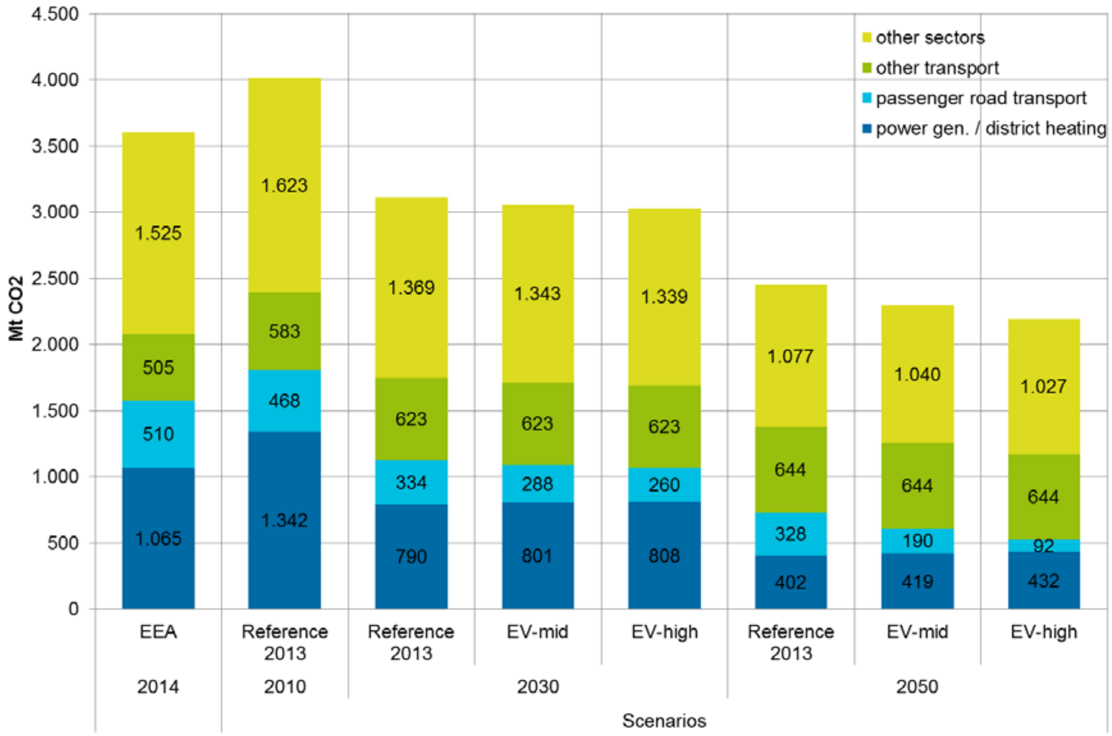
In 2030, the importance of additional power sector emissions is larger than in 2050 – this is because in 2030 renewable power generation shares are still low and many fossil power plants remain in place. Also, the differences between countries are significantly larger in 2030. This reflects that in 2030, national generation mixes are still very heterogeneous. For example, in Poland (where coal dominates the power generation portfolio), in 2030 almost 50% of CO_2 emissions reduced in the transport sector are offset by additional emissions in the power sector. This value drops to about 15% in 2050, when more and more coal power plants are being phased out.

Figure 24 illustrates the development of the CO_2 emissions from all sectors over the course of 2010 to 2050. The difference of cross-sectoral CO_2 emissions among the three scenarios is small since the number of electric cars is the only variation between the three scenarios. By contrast, the impact of electric car penetration is evident for the transport sector-specific emissions. The CO_2 emission regulation on new registered cars up to 2020 and smaller energy efficiency improvements beyond 2020 are considered in all scenarios. Thus, the CO_2 emissions of passenger road transport (TTW) decline by around 35% in 2030 and stay more or less constant thereafter. In 2030, in EV-mid and EV-high scenario CO_2 emissions of passenger road transport (TTW) are 44% and 49% smaller than in 2010, respectively (see Figure 20). The spread of CO_2 emissions between both scenarios is higher in 2050 due to the larger number of electric cars and the larger emission reduction impact of each electric car. The passenger car emissions are only 37% of the 2010 value in EV-mid scenario (63% reduction). In EV-high scenario, the emissions are reduced to 18% of the base value in 2010 (82% reduction).

The emission reduction in passenger road transport is partially offset by the additional emissions of power generation. In contrast, both EV scenarios are characterized by less liquid fuel use and WTT emissions of fuel production are reduced over time[12]. The overall emission balance is calculated by adding all WTT emission changes attributable to varying electric vehicle penetration rates to the TTW passenger transport emissions. In accordance with this, the overall emission reduction in relation to the 2010 level of passenger road transport emission is similar. In EV-high scenario, the overall balance would result in CO_2 reduction for passenger car transport of 84% (-395 Mt CO_2/a) in 2050; in EV-mid scenario the emission abatement for passenger cars is 63% (-297 Mt CO_2/a) in this case.

[12] WTT emission reduction of passenger road transport is fully attributed to other sectors of EU-28 in Figure 37. According to Edwards et al., (2014), roughly 40% of the WWT emissions of gasoline and diesel occur outside the EU-28. A detailed analysis of the share of the WTT emissions of fuel which occur within the EU-28 lies beyond the scope of this study. However, the emission reduction impact on the CO_2 balance of the EU-28 might be smaller than shown in Figure 37.

Figure 24: CO_2 emissions by sector (EU-28 aggregate) in EU Reference Scenario 2013, EV-mid and EV-high



Source: Authors' own representation of Capros et al., 2013; authors' own calculations; EEA 2016

The emission reduction compared to 2010 is based on the effect of energy efficiency improvements which are also considered in the reference case and the introduction of electric vehicles. The isolated impact of electric vehicle integration is smaller and corresponds to the comparison of the EV-mid and EV-high scenario emissions to the reference case. The EV-high CO_2 emissions of passenger road transport and electricity generation are 255 Mt CO_2/a lower by 2050 than in the Reference Scenario 2013; the CO_2 emission reduction impact of electric vehicles reduces to 187 Mt CO_2/a (2050) in the EV-mid scenario.

The emissions from additional electricity generation are of the same magnitude of order than the WTT emission reduction of less liquid fuel use. The impact on carbon prices within the ETS shall therefore be small. However, the interactions of different sectors are not considered in this study and a more detailed analysis would require overall energy sector modelling which goes beyond the scope of this study.

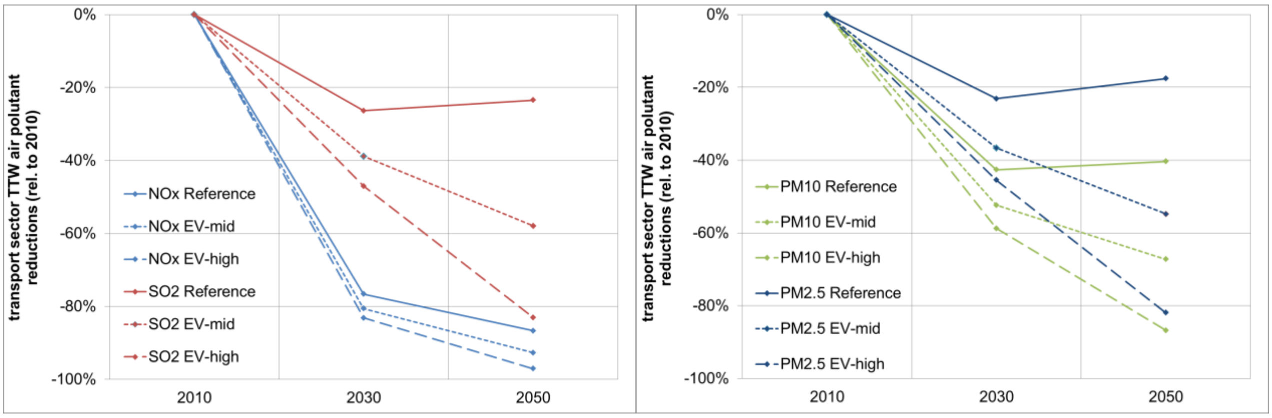
3.5.2. Air pollutants

Electric car penetration does not only affect CO_2 emissions but also has an impact on air pollutants. The major air pollutants in this regard are particulate matter (PM), nitrogen oxides (NO_x) and sulphur dioxide (SO_2). The reduction of air pollutant emissions is considered as a major driving force for electric vehicle introduction in some heavy polluted areas (e.g. China, California).

On the one hand, the decrease in conventional cars and burned fuel leads to a significant tank-to-wheel (TTW) emission reduction in the transport sector; especially in urban areas in which the people are heavily exposed to the air pollutant emissions. On the other hand, the increase in electricity production caused by the additional demand from electric vehicles leads to an increase of air pollutants in the electricity sector. The foreseen emission trends are described separately for each sector since the exposure to the air pollutants and the health impact cannot be compared. Changes in air pollutant emissions in other phases of the life-cycle (e.g. vehicle production, fuel production) are not considered in the calculations.

All pollutants decrease from 2010 to 2030 in the reference case. Two measures cause this drop. The CO_2 regulation for new cars leads to a reduced energy consumption (see Figure 11). Additionally, the air pollutant regulation[13] in transport results in decreasing air pollutant emission factors up to 2030 (see box on MOVEET on page 23). From 2030 to 2050, only NO_x emissions decrease since improved emission factors are assumed for NO_x. According to Amman, M. et al. (2012), only minor improvements in air pollutants emission factors are possible beyond the current legislation for other air pollutants than NO_x. Thus, the air pollutant level is following the minimal increase of energy consumption of the reference case between 2030 and 2050.

Figure 25: Passenger road transport air pollutant TTW emission reduction in relation to 2010 (EU-28 aggregate)



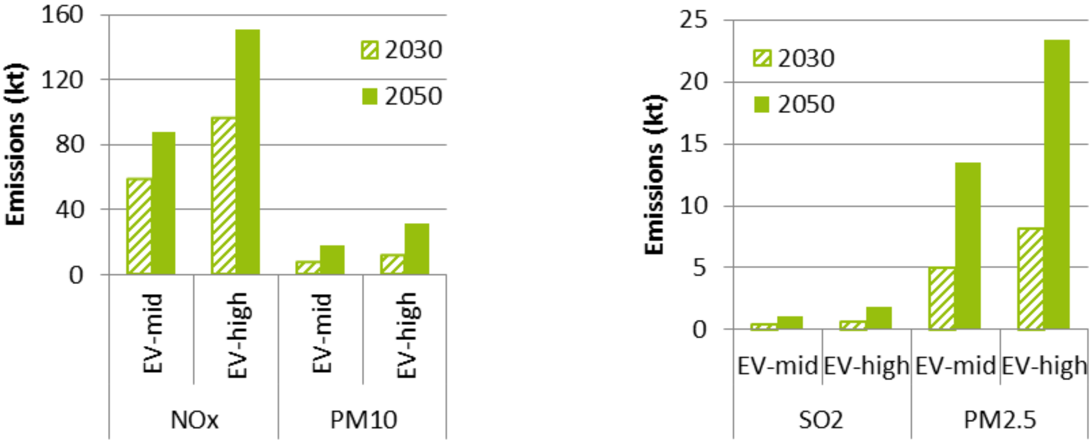
Source: Authors' own calculations (MOVEET).

The impact of electric vehicles on the local TTW emissions of transport is evident in Figure 25. In the EV-high scenario all pollutants achieve an emission reduction of more than 80% in 2050 if compared to the 2010 level. The reduction is between 55 and 67% for SO_2, PM_{10} and $PM_{2.5}$ in the EV-mid scenario and their emission level is 30 to 40% points lower than in the reference case. Thus, also smaller penetrations rates of electric vehicles result in relevant positive effects on local level.

Figure 25 shows the effect of all measures of the scenarios (energy efficiency gains, air pollutant regulation and introduction electric vehicles). Figure 26 compares the air pollutant emissions of the EV-mid and EV-high scenario to the reference case and illustrates the impact of electric vehicles introduction only.

[13] A fully implemented and well-functioning regulation for real-world impact has been assumed.

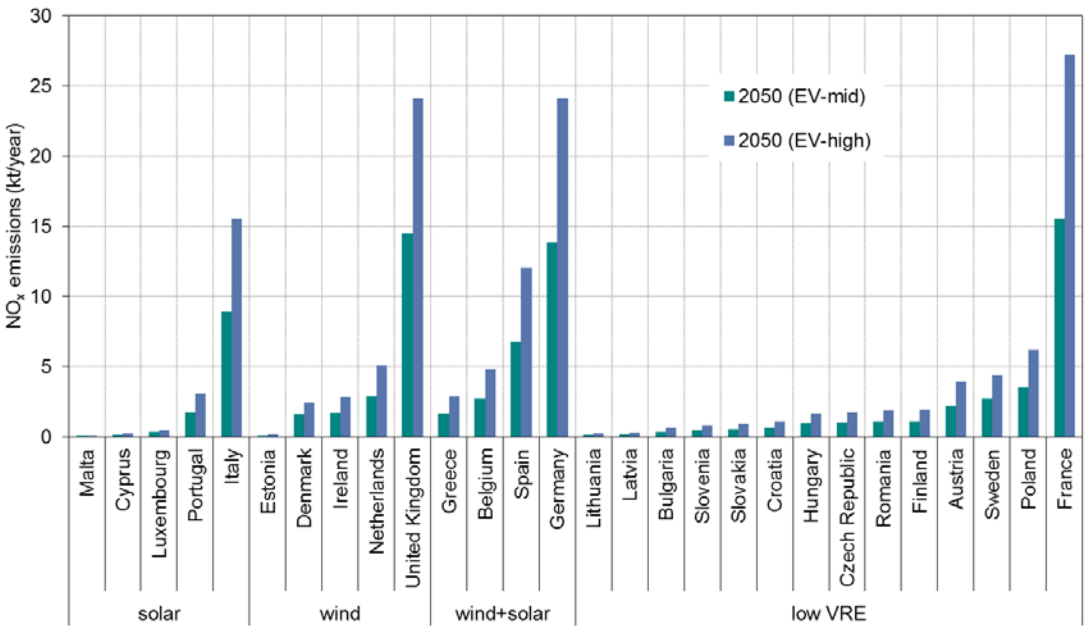
Figure 26: Avoided TTW emissions in passenger road transport (impact of electric vehicle integration) – EU-28 aggregate.



Source: Authors' own calculations (MOVEET)

Figure 27 and Figure 28 illustrate the country-specific effect of increased electric vehicle penetration on NO_x and PM_{10} emissions[14]. The country-specific fuel structure of passenger road transport is less diversified than that of the power sector in all scenarios. This rather homogeneous fuel structure leads to a similar reduction distribution among the EU-28 countries for all considered air pollutants.

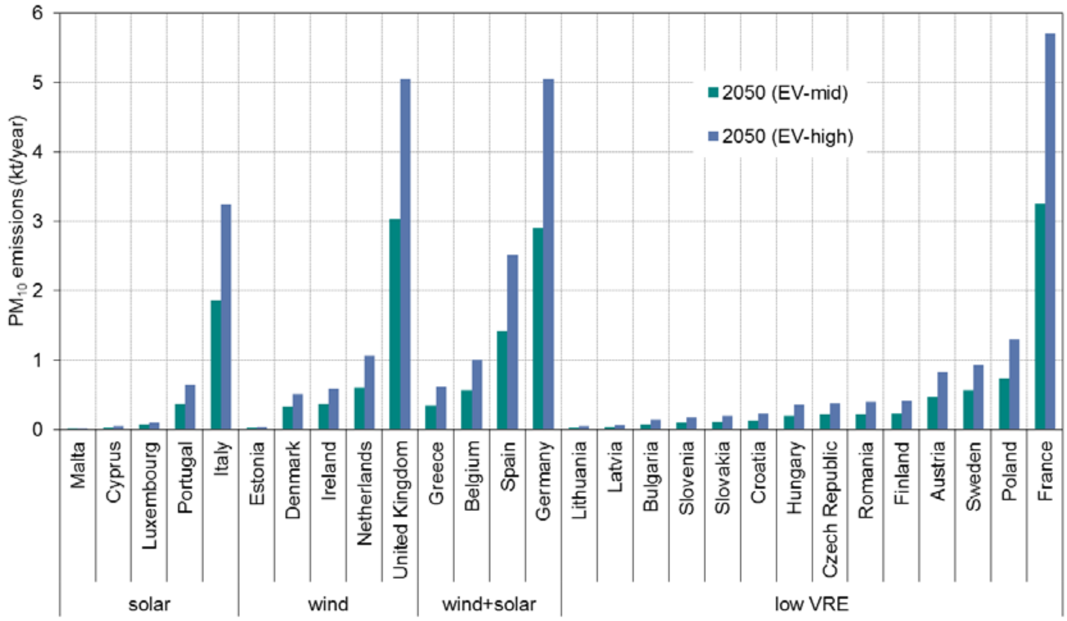
Figure 27: Avoided TTW NO_x emissions in passenger road transport (impact of electric vehicle integration) in 2050 – by country



Source: Authors' own calculations (MOVEET)

[14] The country-specific figures for SO_2 and $PM_{2.5}$ are found in the appendix of this report.

Figure 28: Avoided TTW PM_{10} emissions in passenger road transport (impact of electric vehicle integration) in 2050 - by country



Source: Authors' own calculations (MOVEET)

As a result, air pollutant reduction depends very strongly on the absolute amount of fuel reduction and the number of kilometres driven. Countries with a high traffic volume and high ratios of electrification in the fuel mix show the highest reduction in air pollution. As an example, France and the UK have a higher or similar absolute reduction level in comparison to Germany as a result of higher electrification rates.

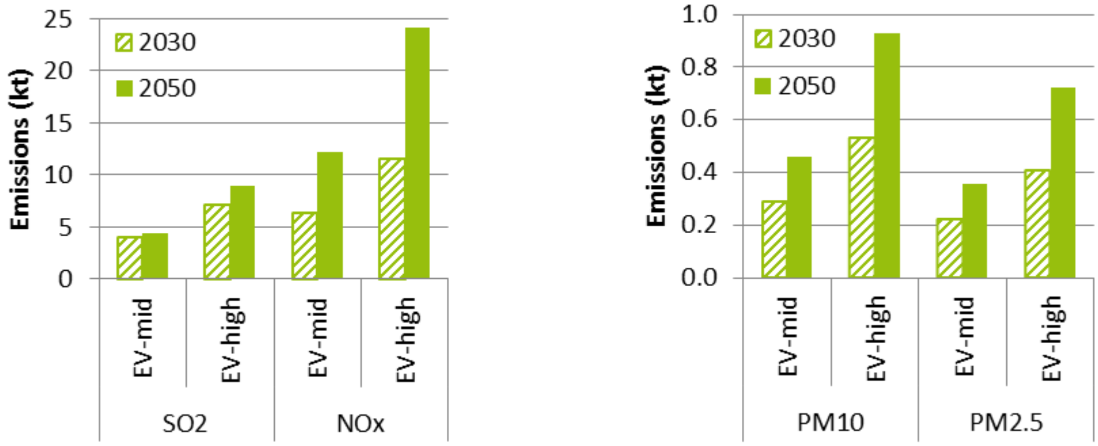
In the electricity sector, the emission levels depend mainly on the production levels of fossil fuels and the applied emission control technologies. The emission intensity of electricity for the respective air pollutants strongly decreases up to 2030 and decreases even further up to 2050. The main influencing factors are the increasing share of emission-free solar and wind generation, the growing application of NO_x/SO_2 scrubbing technologies and the implementation of emission control legislation.

Based on the electricity production levels for each technology the amount of additional emissions caused by EV electricity demand are quantified for 2030 and 2050. The calculations of the electricity sector emissions are based on emission factors derived from data of the GAINS model developed by the International Institute for Applied System Analysis (IIASA)[15]. For 2030 emission factors for each pollutant (SO_2, NO_x, PM_{10} and $P_{2.5}$) are calculated based on results of the Current Legislation Scenario that takes into account emission control legislation adopted by 2014 and assumes their full implementation according to the foreseen schedule (e.g. 2010/75/EU Industrial Emissions Directive). As the model only provides projections up to 2030, emission factors for 2050 are calculated on the basis of selected emission factors from the year 2030. In order to reflect continuous technical progress the calculations of the emission factors for 2050 exclude older plants that went into operation before 2005 as it can be assumed that these plants will mostly be retired by 2050.

15 http://gains.iiasa.ac.at/models/index.html.

Given the assumed constant generation mix in the electricity sector (see section 3.4), the relative increase of power demand that is caused by electric vehicle charging leads to a proportional increase of air pollutant emissions in the power sector. Figure 29 illustrates the additional emissions in the energy sector in absolute terms for the year 2030 and 2050 for both EV scenarios.

Figure 29: Additional emissions in energy sector (impact of electric vehicle integration) – EU-28 aggregate.



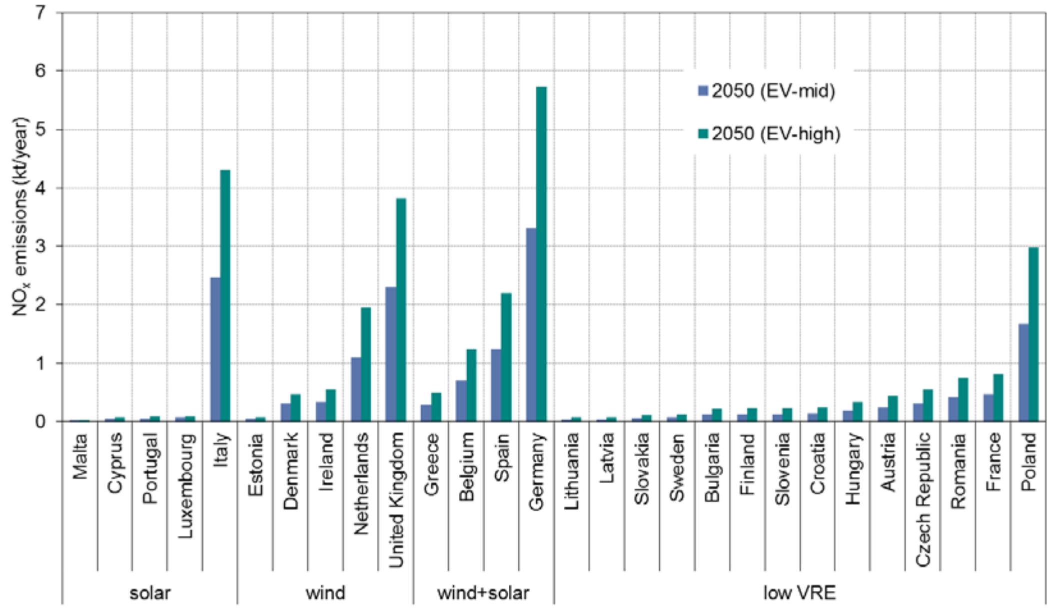
Source: Authors' own calculations

Additional emissions are also calculated on country-level based on the country-specific generation mix. However, country-specific calculations exhibit a relatively high level of uncertainty as the calculations do not distinguish between lignite and hard coal despite their differences in emission intensity. Countries also vary greatly in the application of emission reduction technologies and in the ambition level of emission control policies. As no comparable data on country-specific application of emission reduction technologies is available, the calculations are only based on the European average emission factors and do therefore not reflect national differences in application of emission reduction technologies.

Figure 30 and Figure 31 show the levels of the additional NO_x and PM_{10} country-specific emissions resulting from electric vehicle demand in 2050.[16] The data clearly indicates that EV demand causes additional NO_x and PM_{10} emissions mainly in a few countries that have high levels of EV demand and relatively large shares of fossil fuels generation. For example, in Poland the additional demand by electric vehicles leads to an increase of electricity production of more than 6%. Since the Polish generation mix in 2050 is still dominated by coal power (about 48%) and renewables contribute only 18%, the additional emissions of air pollutants are the highest in Europe in absolute terms. In Italy the generation mix is far less dominated by coal power in 2050 (15%). However, due to the larger absolute number of electric vehicles in Italy and the associated increase of electricity production (about 10%), Italy also exhibits high emissions of air pollutants. The case of Ireland highlights the relevance of natural gas power plant shares for air pollutant emissions. The generation mix in Ireland is dominated by natural gas power plants (39%). As this technology caused significant amounts of NO_x but almost no PM_{10} emissions, Ireland levels of NO_x are relatively high but PM_{10} emissions are low.

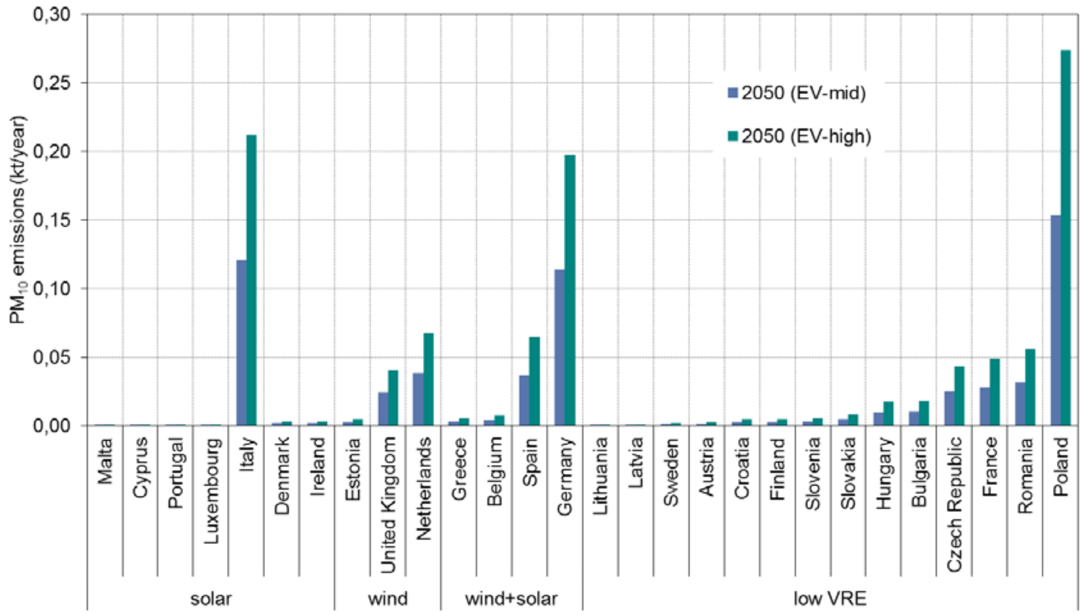
[16] See appendix for figures on SO_2 and $PM_{2.5}$ emissions.

Figure 30: **Additional NO_x emissions in the electricity sector by country (impact of electric vehicle integration) in 2050.**



Source: Authors' own calculations

Figure 31: **Additional PM_{10} emissions in the electricity sector by country (impact of electric vehicle integration) in 2050.**



Source: Authors' own calculations

The general picture for the emission balances of transport and energy sector for each air pollutant is similar for NO_x, PM_{10} and $PM_{2.5}$. The overall impact of electric car penetration has a positive effect on the pollutant emissions as the avoided emissions in the transport sector are only offset by relatively small additional emissions in the power sector. The offset for PM_{10} and $PM_{2.5}$ is around 3% in 2050 in all scenarios; for NO_x the offset is higher and increases to around 15% in 2050. This positive environmental performance with its overall significant reduction of air pollutant emissions comes about mainly for three reasons. Firstly, the share of renewables in the electricity sector is far larger than in the transport sector. Secondly, the total energy consumption per km is much lower due to the higher efficiency of electric engines compared to ICE. Lastly, emission reduction technologies in large scale power plants are more economical and effective than small-scale applications in the transport sector.

The emission balance of SO_2 differs from the other pollutants. Use-phase SO_2 emissions are generally low in transport compared to those from power production with coal. The additional demand of electric vehicles increases the electricity production from coal power plants and the SO_2 emission increase in power production is 4 (EV-mid) to 5 (EV-high) times higher than the reduction of TTW SO_2-emission in the transport sector.

While emission balances are a meaningful indicator for the environmental performance of different transport options in case of CO_2, the environmental evaluation of air pollutant emission, in particular PM, is more complex. The impact of NO_x, SO_2 and PM emissions on human health and the environment depends to a large degree on the location, intensity and type of emission sources. In particular, the spatial distribution of these emissions and human exposure plays an important role for the impact on human health. As the characteristics of the emissions in the transport and power sector are different, a simple comparison of emission changes in both sectors is insufficient for a comprehensive environmental evaluation of these air pollutant emissions. For example, the transport sector is characterized by many small distributed emission sources located close to the population. In contrast, emissions in the power sector occur at large point sources, often in less populated areas.

With regard to the environmental impact this can mean that a concentration of PM emission sources (e.g. large fossil fuel power plants) in environmentally sensitive areas can increase the negative impact on plant and animal life. In regard to human health, the shift of emitting sources (e.g. coal power plants) from densely populated cities to less populated rural areas tend to further improve the already positive impact of the overall reductions of emission levels on human health. These examples illustrate that a more detailed spatial analysis that takes into account the type and location of emission sources is required for a comprehensive analysis of the effects of the changes in air pollutants. Nevertheless, it can be concluded that electric vehicle penetration leads to significant reductions in emission levels of NO_x, PM_{10} and $PM_{2.5}$. In contrast to that, the SO_2 level increases if the additional demand of electric vehicles results in increased use of coal power plants.

4. Conclusions

The introduction of electric vehicles will inevitably lead to greater interaction between the mobility and the electricity sector. When electric car penetration reaches higher levels, the electricity demand from electric cars will become a relevant factor within the energy system and impacts the operation of power plants and the grid infrastructure. Assuming a relatively fast development of electric cars (EV-high scenario), the demand share of electric cars to total electricity demand will reach levels of 4% to 5% in several European countries by 2030. The electric vehicle demand increases with higher share of electric vehicles until 2050 and the electric vehicle to total electricity demand varies between 3% and 25% among the EU-28 countries by 2050. It will increase to more than 10% in many countries. On EU average, it will make up 9.5% by 2050 with an electric car stock penetration of 80%. As a transport fuel, electricity would become a relevant energy option with roughly 50% (around 450 TWh/a) of the passenger car fuel mix by 2050.

The increase in electric cars leads to reductions in CO_2 and local air pollutant emissions in the transport sector. Depending on the electricity generation mix (constant electricity generation mix to Reference Scenario 2013 assumed) these positive effects will be (partially) offset by additional emissions in the energy sector caused by the additional electric demand of passenger cars. However, with a net reduction of 255 Mt CO_2/a in total (avoided emissions in the transport sector and additional emissions for electricity production) in 2050, high electric car penetration by 2050 has a strong positive CO_2 impact in comparison to the EU Reference Scenario 2013 (effect of electric vehicle integration).

For 2050, the total emission reductions including WTT emission changes of fuel and power production implies a CO_2 abatement in passenger transport of 84% compared to 2010 (-395 Mt CO_2/a).

The impact of local air pollutant emissions from electric vehicles and emissions from power generation cannot directly be compared as the human and animal exposure to the air pollutants is different for both sectors. Nonetheless, the net balance of passenger road transport and power generation emissions provides an overall picture of the emission effects. Electric vehicle penetration of 80% results in local air pollutant emissions reduction (PM, NO_x and SO_2) in passenger transport (TTW) of more than 80% for all pollutants in comparison to 2010 levels. The offset of additional emission in the power sector for NO_x and PM is small compared to the reductions in the transport sector. By 2050, it is 3% for PM and around 15% for NO_x. The offset of additional emissions in the power sector is different for SO_2. The increased use of coal in power generation results in additional SO_2 emissions, which surpass the emission reduction in passenger road transport by the factor 5.

The positive impact on CO_2 and most air pollutant emissions is obviously smaller with less penetration of electric cars (EV-mid scenario). The CO_2 emission reduction of 157 Mt CO_2/a in total (impact of electric vehicle integration) is a reduction of 63% compared to the reference scenario (2050).

The comparison to 2010 includes also the impact of energy efficiency gains of conventional cars. Compared to the 2010 CO_2 emission level of passenger road transport, the emissions are 297 Mt CO_2/a smaller (-61%). The air pollutant TTW emission drop of passenger road transport reduces to 55 to 67% for SO_2 and PM in comparison to 2010. Thus, other measures would be needed to achieve the same emission levels as in the scenario with a strong penetration of electric cars.

The impact on CO_2 emission reduction of fuel production and the emission increase of power production are of the same order of magnitude. As both are integrated in the EU ETS, no crucial impact on the carbon prices shall be expected due to higher electric vehicle shares under this assumption.

In order to satisfy the additional electricity demand of 80% car stock penetration significant additional generation capacity could be required. Up to 150 GW of generation capacities are added to the energy system due to electric cars (130 GW more than in the reference case). Assuming constant generation mixes, this includes up to 47 GW wind, 25 GW solar, 41 GW fossil and 11 GW nuclear capacities. These capacities require significant additional investments in particular for wind and solar power and increase land use for electricity generation. As nuclear and coal power plants have negative environmental impacts and they do not fit into a future energy sector due to their inflexible generation, higher nuclear and coal capacities should be avoided. Instead, additional renewable capacities should be installed to replace the required additional coal and nuclear capacities. This would include 87 GW wind, 45 GW solar, 24 GW hydro and 13 GW biomass capacities.

The intensity of electric vehicle charging could potentially also put local grid infrastructures under substantial stress and lead to severe technical problems in network operations. The critical number of electric vehicles for grid operation depends on the local context and no general threshold can be set. Case studies show that severe operation problems can occur with electric vehicle car stock penetration of around 10%.

However, due to possibility of altering electric vehicle charging profiles through smart charging approaches these negative effects can partially be counteracted. Depending on the chosen goal of electric vehicle demand management, smart charging need to follow different goals such as reducing grid constrains by smoothing load profiles, maximizing utilization of renewable energy production to reduce CO_2 emissions or minimizing charging cost by shifting charging to low-costs periods of electricity generation. The potential to use electric cars as an aggregated large scale storage option appears very limited due to low overall storage capacity and the competition with other more cost-efficient storage options. However, electric cars could potentially provide important system services to contribute to grid stability. Most importantly, as smart charging approaches imply reduced freedom compared to user-driven charging, it depends strongly on the user acceptance of smart charging concepts.

As generation mixes and the grid infrastructure are very diverse across countries and across regions, electric vehicle penetration leads to diverse integration issues. Even between countries with similar renewable energy shares, the appropriate strategies for charging can be very different depending on the renewable technologies and the remaining types of generation capacities. In countries with high fluctuating renewable energy supply, the coordination of the electric vehicle demand with fluctuating supply will become a major challenge. Electric vehicles also provide a valuable source of flexible demand that can foster the integration of renewable energy (e.g. Portugal, Denmark and Germany). In countries with high shares of fossil power plants as part of electricity production strategy (e.g. Poland, Czech Republic), electric vehicle demand could lead to substantially higher CO_2 emissions (e.g. through additional coal power plant generation) in the electricity sector. Smart charging could increase renewable electricity integration in such countries as well. Furthermore, in regions with a weak network infrastructure, additional grid reinforcement or implementation of specific smart charging approaches might be required to ensure the stable functioning of the infrastructure.

However, with the implementation of smart charging approaches, the required new capacities for specific technologies can be reduced. For example, by renewable energy-oriented charging patterns the additional capacity for dispatchable plants such as coal and nuclear and renewable generation plants, could potentially be reduced by harvesting renewable surplus-production and by increasing production of existing plants.

Overall, the analysis reveals that an increasing electric vehicle penetration heavily impacts the operation of the energy sector and integration of electric vehicle demand poses very diverse challenges on the management of power system at local, national and European level depending on the respective status of the energy system. Thus the transport and energy sector development will be more closely coupled and policy making for both sectors has to be made integrated in the future. However, in terms of total emission balances in the long run, electric mobility can lead to significant reductions in CO_2 and most air pollutant emissions. It will be a relevant part of a future sustainable transport system. Nonetheless, integration of electric vehicles does not address all negative effects of the transport system. Improvements in road safety and reduction of congestion, land use and noise levels require a more systematic transformation of the transport system to achieve modal shift and traffic avoidance.

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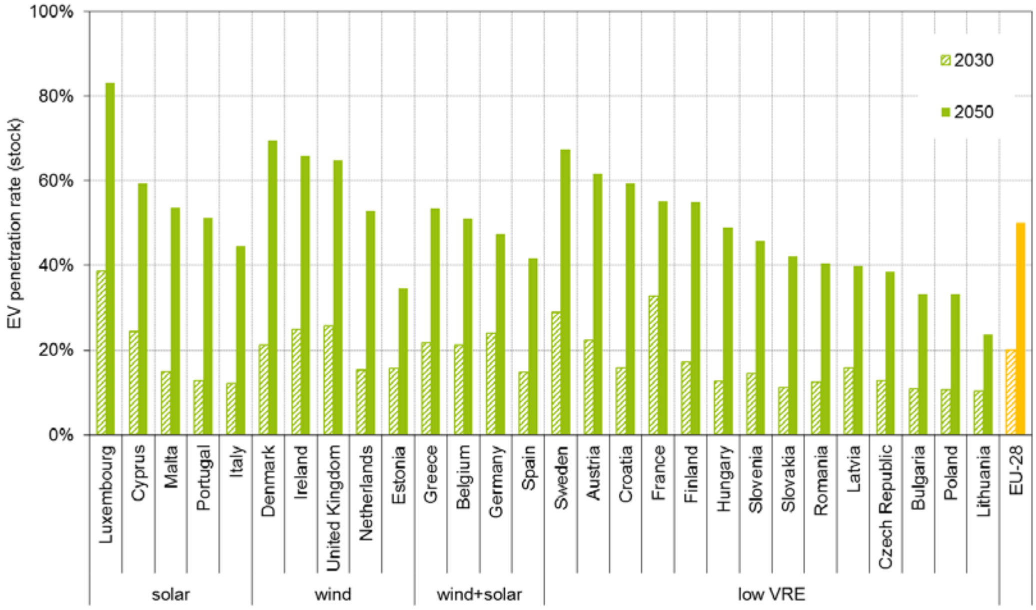
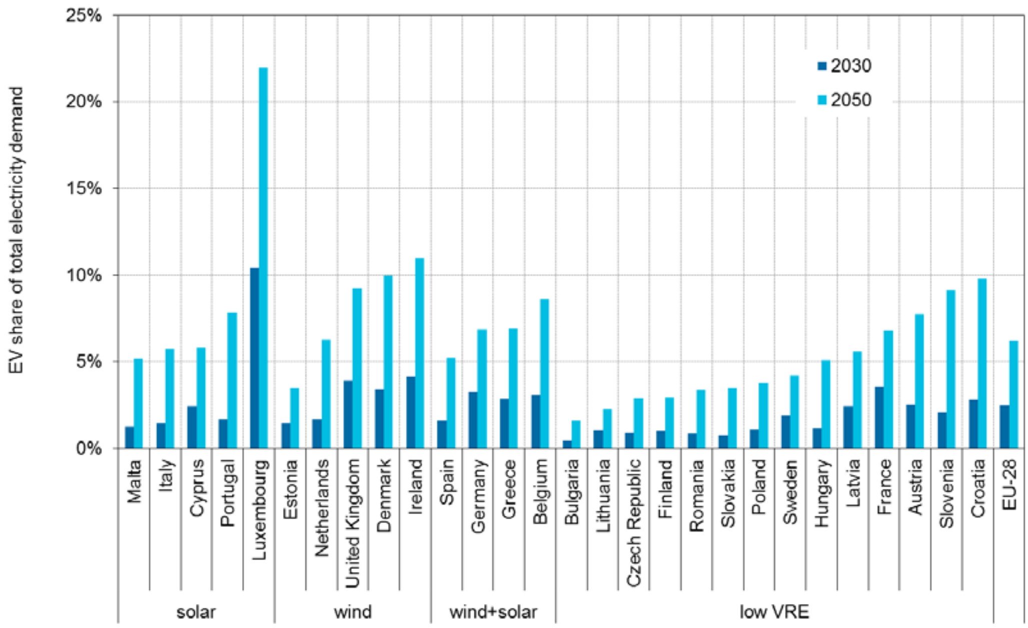
Appendix

Figure 32: EV penetration rate of EV-mid scenario by 2030 and 2050 – by country



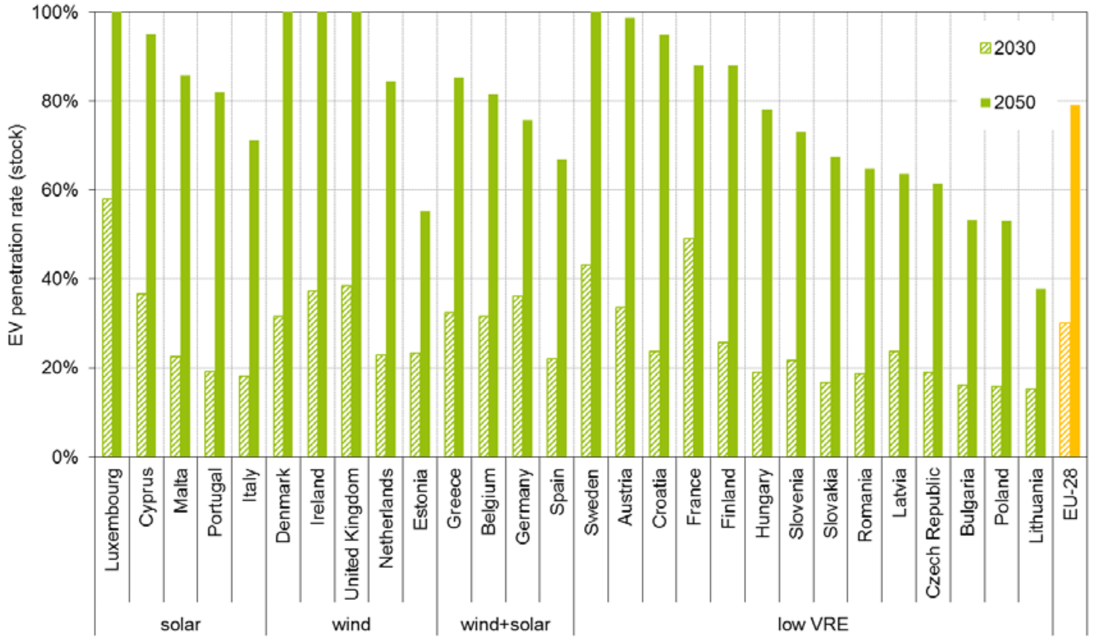
Source: Authors' own scenario

Figure 33: EV share of total electricity demand of EV-mid scenario by 2030 and 2050 – by country



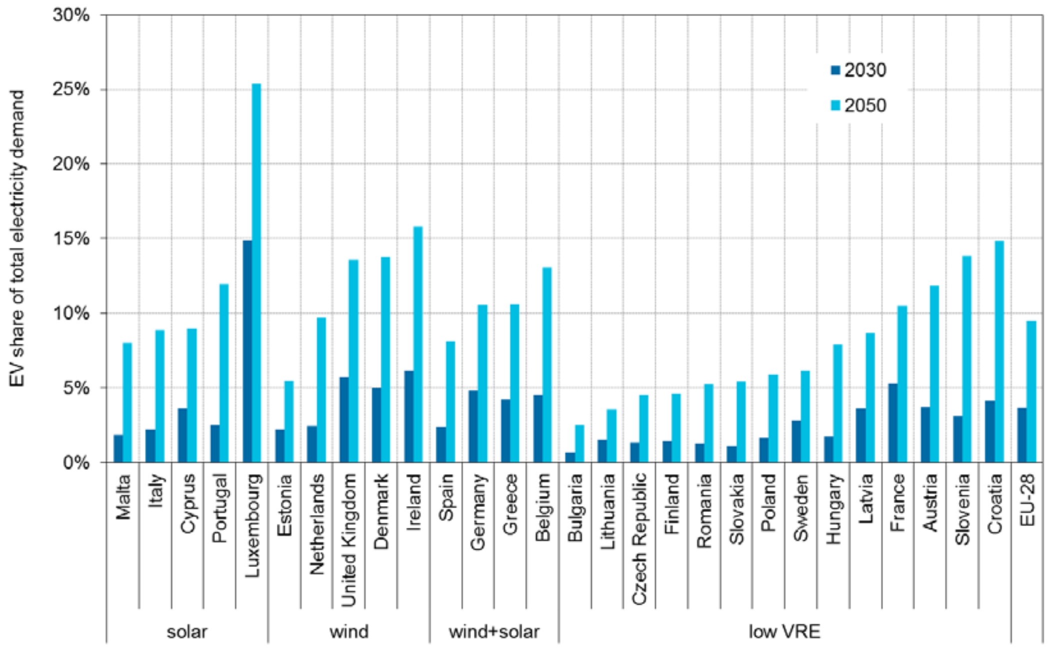
Source: Authors' own calculations

Figure 34: EV penetration rate of EV-high scenario by 2030 and 2050 – by country



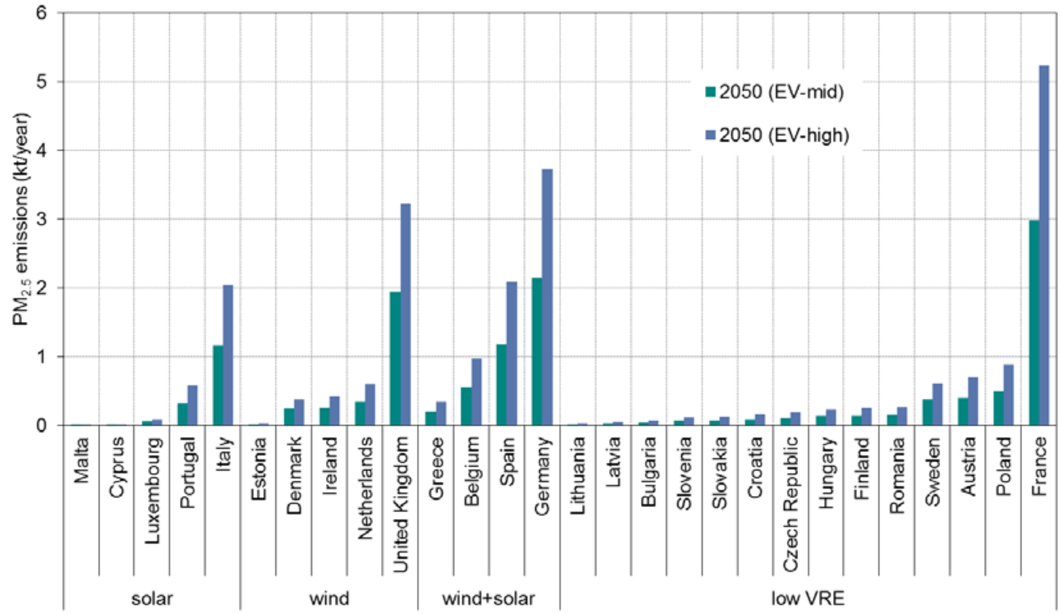
Source: Authors' own scenario

Figure 35: EV share of total electricity demand of EV-high scenario by 2030 and 2050 – by country



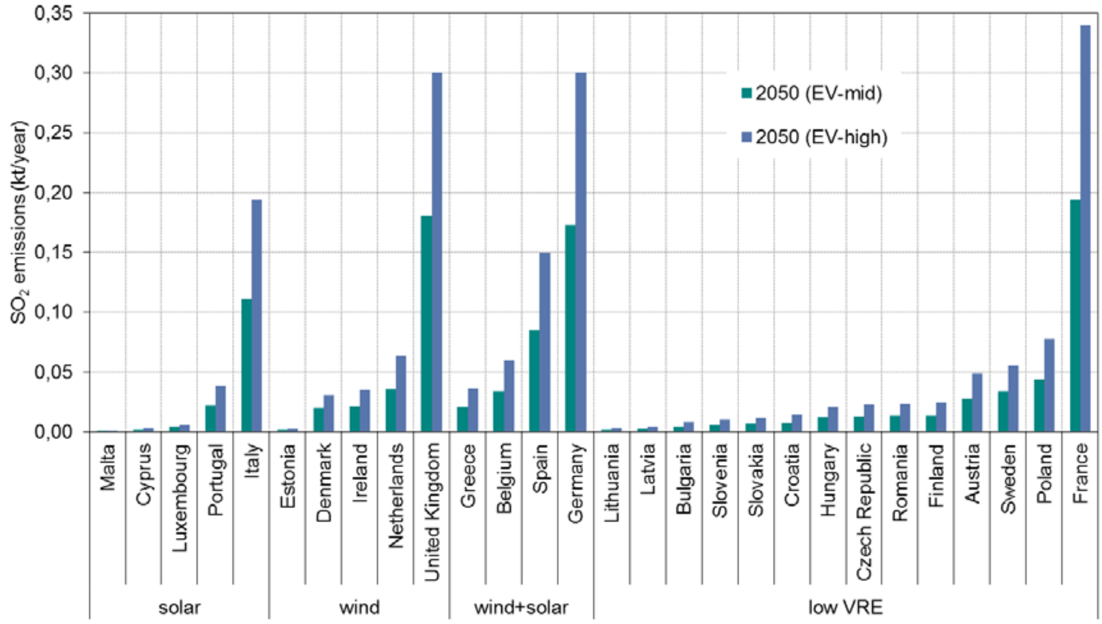
Source: Authors' own calculations

Figure 36: Avoided TTW $PM_{2.5}$ emissions in passenger road transport (impact of electric vehicle integration) in 2050 – by country



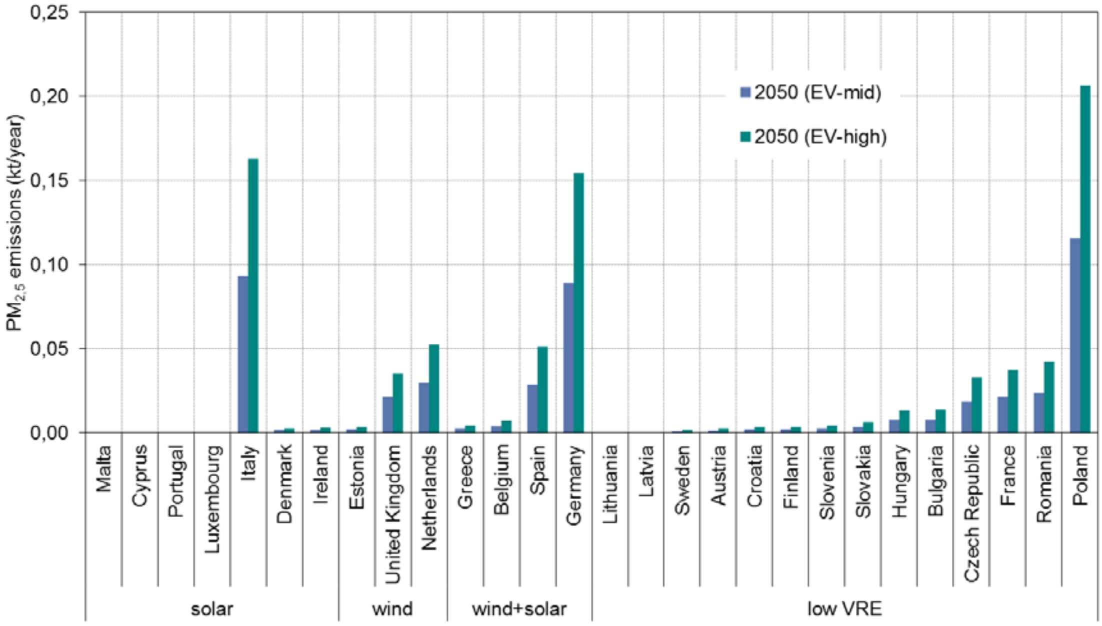
Source: Authors' own calculations (MOVEET)

Figure 37: Avoided TTW SO_2 emissions in passenger road transport (impact of electric vehicle integration) in 2050.



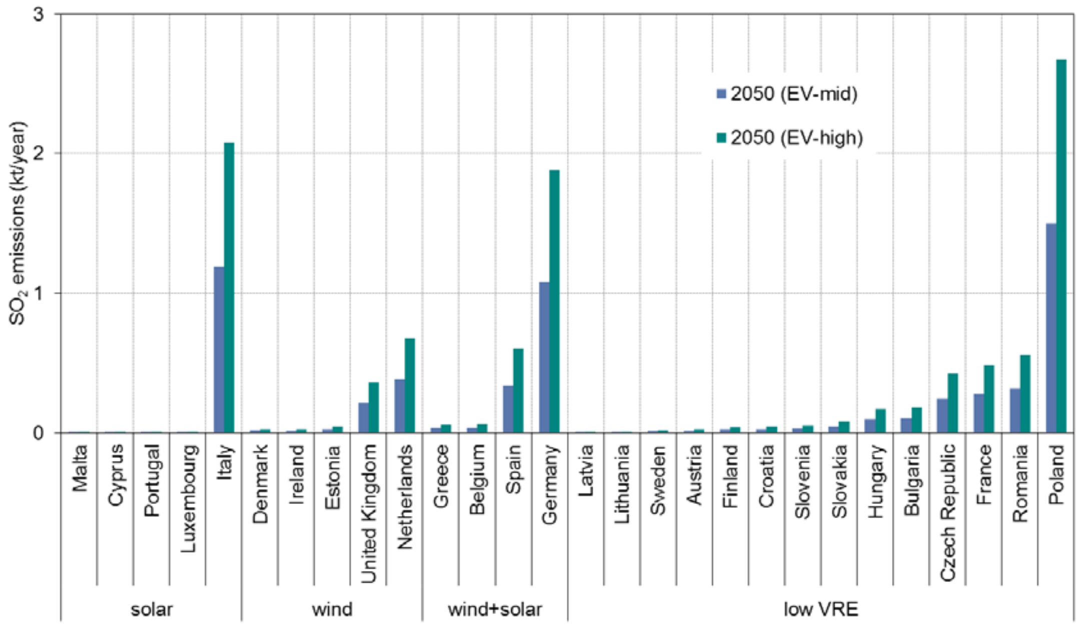
Source: Authors' own calculations (MOVEET)

Figure 38: Additional $PM_{2.5}$ emissions in the electricity sector by country (impact of electric vehicle integration) in 2050



Source: Authors' own calculations

Figure 39: Additional SO_2 emissions in the electricity sector by country (impact of electric vehicle integration) in 2050



Source: Authors' own calculations