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1 Introduction/Background

Ambitious carbon reduction targets combined with the concerns over energy security and sustainability in Europe have lead to the evolving concept of low-carbon energy economy. Electric and plug-in hybrid vehicles (EV, PHEV) have the potential to contribute significantly to solving contemporary and future environmental challenges of energy system. In order to secure affordable and sustainable future energy supplies it is also imperative that the dependence on imported fuels is limited. Shift of energy demand due to electrification of transport sector into the electricity system potentially offers a more secure energy solution. However, to support mass electrification of transport resulting in reducing future fuel import dependence would require generation of electricity from clean energy sources such as; renewables, carbon capture technologies and nuclear.

The increased demand of electricity as a result of the roll out of EV and PHEV will make a significant impact on the electricity system operation and development and require the development of a comprehensive recharging infrastructure. Shifting significant amounts of energy demand from transport sectors into electricity, if not properly managed, would lead to require significant infrastructure investment and could massively reduce already low system capacity utilisation levels if the paradigm of the system operation is unchanged. On the other hand, a monumental transition in this strategic development of two key energy sectors i.e., transport and electricity, could offer great business opportunities and contribute to revitalisation of Europe’s economy.

One of the key concerns for future low-carbon electricity systems is that they may be characterised by much lower generation and network asset utilisations given; (i) a significant penetration of low capacity value wind generation combined with (ii) a potential increase in peak demand that is disproportionately higher than the increase in energy, which may be driven by shifting of the transport sector demand into electricity. However, the transport sector based on EVs is characterised by significant inherent storage capability, and this opens up opportunities for utilising more efficient charging strategies, not only to optimise electricity production capacity, but also to enhance the utilisation of network and generation assets.

Delivering the carbon reduction targets cost-effectively through appropriate EV charging will require a fundamental shift from a passive to an active philosophy of network control. This shift, enabled by the incorporation of demand management into system operation and design, can be achieved by the application of an appropriate information, communication and control infrastructure.

Currently no system for the smart integration of a large number of EV and PHEV into the electricity grids exists. Europe could evolve into a cost-effective and “Smart” electricity system by embracing electro-mobility. To address this strategic evolution of an integrated transport and electricity system, it is necessary that its fundamental economic, environmental and security performances of the system with various levels of penetration of EV are fully understood.

1.1 Objective of the report

In order to comprehend the role of electric vehicles in optimal development and operation of the electricity systems and to quantify the various impacts that EV and their alternative operational (charging) strategies may have on the cost and environmental performance of the system an advanced modelling framework has been developed. The framework is applied to perform a wide range of quantitative analysis for different EV penetration scenarios (0% – 100%), which include;

- Evaluating the impact of EV and their alternative operational (charging) strategies on overall demand of the electricity system (demand profiles, peak power demand, energy requirements, and corresponding generation capacity requirements necessary to maintain system reliability.

- Assessment of the economic performance of the system under alternative vehicle charging strategies while considering the trade-offs between various operational cost elements (efficiency losses, fuel costs, CO_2 costs etc) for different electricity systems.

- Quantifying the additional value and economic benefits of EV/PHEV through complementing ("firming up") the intermittent generation and in provision of ancillary services.

The report presents an introduction to the detailed modelling framework and elaborates several studies and the corresponding results. The results highlight the impacts of coordinated charging of a large number of EV in future electricity systems to enable the potential contribution of EV towards more efficient and cost-effective operation of the system.

1.2 Scope and structure of the report

The work presented in this report is based on quantitative as well as qualitative analysis. Quantitative analysis covers the economic and environmental impact assessment of the integration of EV in electricity system operation and its future development. It involves application of advanced dynamic generation and network operation and expansion planning optimisation models to simulate real time system operation under various generation technology, electricity system as well as electro-mobility related constraints. While the qualitative analysis is based on expert analysis for assessment of future market, policy and regulatory requirements pertinent to efficient integration of EV in future electricity systems in order to propose relevant recommendations.

The developed model is first implemented on a Great Britain (GB) equivalent electricity system including future demand and generation projections. In order to take account of various uncertainties in penetration of EV, intermittent generation and a likely outcome of the operational (charging) strategies of EV a range of alternative scenarios are considered in each case. This gives a broad range of outputs to be generalised to a degree keeping in view the underlying input assumptions and the system specific nature of results.

All of the above studies have been conducted within the operation constraints associated with the supply and demand balance in the electricity system and dynamic characteristics of plants, as well as considering the satisfying the mobility requirements of the electric vehicle users inline with the detailed GB transport surveys [NTS09]. Therefore, the results are primarily representative of the vehicle users in GB.

It is also to be noted that the aim of this work is to identify the key ‘system-level’ impacts of various penetrations of EV in different system conditions and operational strategies. Key drivers that influence the value of EV in future electricity systems ere determined within a power system domain. Therefore, the external factors such as life cycle costs, life cycle emissions (including fuel chain), impacts on battery life and associated costs are not considered within the scope of this work. Also the analysis of the network issues has been carried out in other work packages within the G4V project.

Successful integration of EVs on a European scale also requires the establishment of a clear regulatory framework, appropriate market structures and complementary policy measures to support the efficient deployment of EVs. Transparency of the regulatory regime is needed to ensure the market confidence of relevant stakeholders to take advantage of the range of opportunities brought along by the transformation of transport and electricity systems due to EVs.

The remainder of this report is structured as follows:

- Chapter 2 describes the overall methodology including the various constraints used in simulating power system operation with EV, a brief description of EV journey data, the structure of the input data and the various scenarios analysed through case studies.
- Chapter 3 outlines the key modelling inputs for the case studies analysed, in particular system demand data, generation parameters etc.
- Chapter 4 lays out the results of the detailed studies, elaborating the economic and environmental performance of the system under a range of EV penetrations, generation portfolios (including different levels of intermittent generation in the system).
- Chapter 5 discusses key regulatory and policy challenges related to large-scale integration of EVs into future European electricity systems. Key areas of interest include: charging infra-

structure, impact on the distribution grid, provision of ancillary services by EV, and application of ICT in the integration of EVs.

- Chapter 6 concludes the report highlighting key findings, summarise the results and suggest future research in this area.

2 Methodology

The existing electricity systems in most of the European countries have been designed for moderate annual load growth. However with the anticipated growth of electrical loads in the form of electric vehicles (EVs), the electricity supply system may be required to accommodate significantly larger load growth and different loading patterns in the future. This will lead to a range of impacts on the power system development and operation. The intensity of these impacts will depend on the characteristics of the incumbent system and on the penetration level of EVs in the system. Furthermore, these issues will depend on the timing, location as well as the rate and strategy of battery charging processes.

The nature of impacts and the relevant requirements for secure and cost efficient operation of the power systems will vary among the generation, transmission and distribution segments of the power system. This section describes the modelling approach employed to quantify the potential impacts of EVs on the development and operation of the overall (generation) systems.

2.1 Modelling framework

The model developed at Imperial College as shown in figure 1, minimises the total electricity production costs while maintaining the required level of system reliability and respecting various operating constraints of the individual plants, electric vehicles and the overall system.

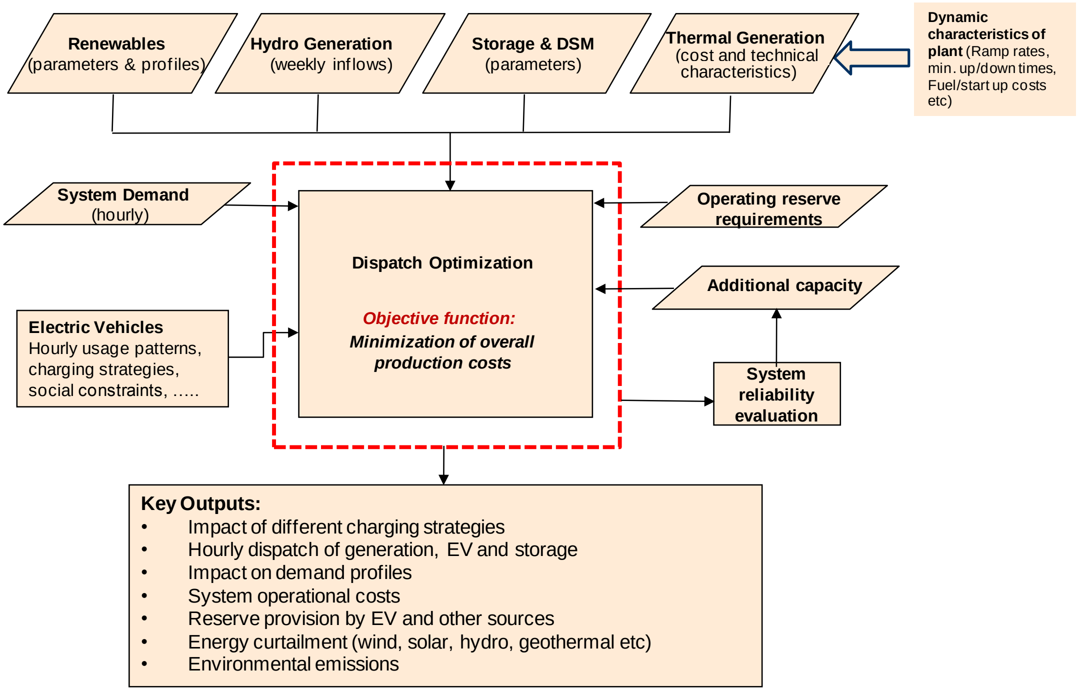

Figure 1. Simplified representation of generation scheduling model

The detailed production and reserve optimisation model minimises the generation production cost subject to multiple constraints associated with the dynamic characteristics (stable generation levels, ramp rates, minimum up/down times etc.) and cost parameters of various technologies, behaviour of intermittent generation while maintaining adequate level of additional operating reserves in the system.

This cost minimisation process incorporates various tradeoffs between the production cost of modelled technologies, operating reserve provision by alternative sources and associated costs (no-load and efficiency loss costs), renewable energy curtailment and CO_2 emissions. It is based on a mixed integer linear programming (MILP) algorithm implemented using FICO Xpress solver [FICO11].

The overall cost which is minimised includes: (i) generators' operation cost, (ii) start-up cost, and (iii) cost of load shedding (if that option is necessary in any time interval).

In order to deal with the uncertainties associated with conventional generation availability, demand fluctuations and variability of output of (intermittent) renewable generation, two types of operating reserve have been modelled;

- Short-term reserve (for seconds to a few minutes time periods) for automatic frequency regulation requirements, which corresponds to primary and secondary reserve as defined by former UCTE and G4V Project Manual,
- Long-term reserve (from a few minutes to a few hours time periods) to mitigate unforeseen imbalances between demand and supply over longer time horizons in each region; corresponds to tertiary reserve as defined by the Project Manual.

EVs are modelled to contribute to provision of primary and secondary reserve in optimised charging strategies. A conservative approach has been followed by not including the contribution of frequency sensitive loads towards frequency regulation (such as e.g. smart refrigerators).

Primary and secondary reserve requirements are typically defined by the Transmission System Operator in a given area, based on short-term dynamic analysis of system behaviour during an unforeseen disturbance (e.g. loss of large generation unit). These requirements are a function of system demand level prior to disturbance, and the nature of disturbance event that the system is expected to successfully withstand. Due to frequency sensitivity of demand, response requirements decrease with higher demand levels. For instance, in the UK system the primary reserve requirement (also called frequency response in the UK) for the demand level of 35 GW is 800 MW, in order to contain the frequency drop below 0.8 Hz following a largest foreseeable generation loss of 1.32 GW, while at 55 GW this requirement is only about 400 MW.

Primary and secondary reserve requirement curves have been further modified to account for the effect of short-term wind fluctuations for a given installed wind capacity. The updated primary reserve requirement ensures that the risk of violating frequency limits remains unchanged compared to the case without wind.

The tertiary reserve requirement needs to take into account the uncertainty of wind output and demand forecast errors, as well as any credible generation outages. The approach from [SILVA10] is adopted here, where reserve requirements are set using an analytical method incorporating the stochastic behaviour of wind and demand. Upward and downward reserve levels are chosen to be able to handle deviations from forecast of wind and demand that occur in 99.73% of the cases within a 4-hour horizon (i.e. which are within three standard deviations from the forecast, assuming normally distributed errors). For upward reserve this is further increased by the amount of largest foreseeable generation loss (1.32 GW in the current UK system).

An extensive range of sensitivity studies can also be performed to test the robustness of results and to understand the main cost drivers and their tradeoffs over a range of system conditions. These include:

- Impact of alternative charging strategies of EV
- Various penetration levels of EVs in the system
- Different penetration level of renewables in the system
- Varying degree of flexibility from (flexible) generation resource.

2.2 Main inputs requirements and outputs of the model

Key inputs to the optimisation model include; generation capacity of various technologies in the system, dynamic characteristics and operating cost of generation plants, annual time series (hourly) of electricity demand profiles and renewable energy outputs and hydro energy inflows for run-of-river and hydro reservoir types. Also a detailed representation of the EVs including their driving patterns and associated temporal electricity demand is also required as a key input to the model. Further details of the input data requirements are discussed at length in Chapter 3.

The key outputs of the dynamic scheduling and reserve model include:

- Unit commitment schedule of all plants in the system;
- Hourly dispatch of each generation technology;
- Hourly charging and discharging (in case of bi-directional optimisation) of EVs;
- Hourly allocation of operating reserves;
- Renewable energy curtailment;
- Total system annual operational costs and its components including; start-up, no-load, fuel, losses; and
- Environmental emissions from electricity production.

2.3 Modelling Constraints

The objective function is formulated as cost minimisation, as described above, and is optimised against a set of constraints which are categorised in the following text. Those constraints along with the objective function constitute a Mixed-Integer Linear Programming (MILP) problem.

2.3.1 System-level constraints

Key constraints on the level of the electricity system are as follows:

- *System power balance*: ensures that the sum of conventional generator output, hydro and wind generation matches the sum of original system demand and total net charging of EVs (charging minus discharging, adjusted for appropriate efficiencies). Any shortage of available energy is resolved through expensive load shedding (no export or import of electricity is foreseen in the model).
- *Available wind energy*: the output of wind generation cannot exceed total available wind energy in any given time instance; any difference between the two is reflected in wind energy curtailment that might be necessary to maintain system security.

- *Short-term and long-term operating reserve requirements*: sufficient long-term and short-term reserve needs to be provided by generators (and if allowed other providers such as flexible demand) to meet the system security of supply criterion (valid for both upward and downward reserve).

2.3.2 Generation technology-related constraints

The following constraints apply at the generator level:

- Total output of thermal generators is constrained by the minimum and maximum output of units that are switched on at a particular time.
- Output of hydro generators, in addition to maximum capacity, is constrained by the available energy from hydro inflow (run-of-river plants) or the energy content of hydro reservoirs.
- Energy balance of hydro reservoirs is related to the hydro inflows, water usage for generation and possible spillage of excess water.
- Minimum up and down times for thermal generators (i.e. the necessity to keep a generator on or off for a few hours after switching it on or off).
- Ramping constraints ensuring that the output of a generator cannot change by more than the allowed ramping rate (both upwards and downwards).
- Boundaries on individual generators' abilities to provide primary, secondary and tertiary reserve.

2.3.3 Vehicle-related constraints

The ratings and the energy storage content of the EV battery are modelled as inflexible constraints. Battery ratings here refer to the maximum allowed charging or discharging power with respect to the grid.

The assumption is made that each vehicle makes two journeys per day. The modelling ensures that the following parameters are taken into account when considering EV behaviour:

- Start time of 1st journey
- End time of 1st journey
- Start time of 2nd journey
- End time of 2nd journey
- Type of 1st journey (short/medium/long)
- Type of 2nd journey (short/medium/long)

For any particular combination of journeys, with given start and end times of two journeys and corresponding durations of both trips, we keep track of all time intervals within a day when a vehicle following this combination is not in use, i.e. when it is available for charging (or discharging). Obviously, charging (and discharging) power of all vehicles within a given combination of journeys can only be non-zero at times when vehicles are stationary.

The total net energy delivered to a particular vehicle group over the course of one day needs to match the energy requirements of their two journeys, while respecting the efficiency of battery charging.

State of charge of EV batteries is also accounted for, so that hour-to-hour changes in the state of charge result from charging and discharging decisions, and electricity consumption for completing the two journeys. Total energy stored in batteries of vehicles in a given category at any given time interval is bounded from below and above by its minimum and maximum values.

Simplified linear charging and discharging curves have been assumed for the batteries. Although realistic (dis)charging curves tend to be slightly different, a linear curve still provides a satisfactory approximation given the time resolution of the model (typically one hour) and the observed time horizon of one year.

Finally, the economic and environmental assessment model also considers the contribution of electric vehicles to frequency regulation through providing primary and secondary reserve. Contribution from EV charging is assumed to be limited by total charging power drawn at a given time, scaled down using a factor to account for the fact that not all vehicles will be in a position to interrupt their charging to provide frequency regulation services. This may be due to reasons such as: unwillingness to provide service, lack of time available before the next journey etc. Based on expert judgment, this factor has been estimated at 80%.

Provision of frequency regulation as a result of energy stored in EV batteries that is available for discharging is also accounted for; this contribution is limited by the total energy remaining in EV batteries at a given time, divided by the expected duration of frequency regulation service (typically 30 minutes), and further scaled down using a factor to account for the fact that only part of that energy will be available for service provision, and that a part of vehicles are on the road at the time. Again, based on expert judgment, the value of this scaling factor used for the analysis has been estimated at 20%.

EV contribution to frequency regulation is then included into constraints on frequency response requirements, so that they can displace some or all of the response provided by conventional generators (if it is assumed that such functionality is available on the side of EVs).

EV-related constraints are constructed for each day when running the day-ahead optimisation for the entire year; this procedure can include various approaches to EV charging and discharging (e.g. cost-optimised vs. non-optimised charging). Along with seasonal variations in basic system demand and wind availability, seasonal differences in driving patterns can also be accounted for in this manner (e.g. distinguishing between different seasons, workdays and weekends, etc.). These differences would primarily be reflected in numbers of vehicles across different categories, as well as the energy needed to complete their trips.

2.3.4 Emission constraints

The model is capable to introduce specific constraints on emissions resulting from electricity production. However, for the studies performed in this analysis the cost of CO_2 emissions is internalised in the overall cost optimisation process. This leads to an optimised dispatch of generation taking into account (minimising) the CO_2 emissions.

CO_2 emissions from fossil fuel-based electricity generation have been modelled considering International Panel on Climate Change (IPCC) emission factors for different fuels [IPCC11]. The emission factors establish a proportional relationship between primary energy used for generating electricity and the CO_2 emissions caused by the process. They also imply that CO_2 emissions per unit of electricity output depend on the efficiency of the technology, meaning that emissions per megawatt-hour of electricity generated increase when power plants are part-loaded.

It has been assumed that an opportunity cost of CO_2 exists in the amount of £20 (€23) per tonne[1]. This value has been incorporated into generators' fuel costs, to account for the additional cost of carbon emissions when determining the optimal dispatch of fossil fuel-based thermal generators.

2.3.5 Social constraints

The developed modelling framework also represents constraints associated with the social aspects of the EV users. Some of these social aspects identified as more relevant for this work include:

- Percentage of the EV car users willing to allow the system operator control the charging (in either unidirectional or V2G modes) of their vehicles when connected during stationary periods.
- Minimal charged battery levels (the minimum distance to be covered as percentage of the battery storage capacity) that EV users would like to always retain for any emergency (or otherwise) needs.
- Time before a journey (if any) that an EV user would like his battery to be fully charged.

2.4 Modelling vehicle charging strategies

EV loads are particularly well placed to support system operation, for the following reasons:

- The additional energy requirements for EV charging is relatively modest compared to the original electricity demand,
- Short driving times generally associated with small passenger vehicles (most of the time over 90% of vehicles are stationary, as indicated in Figure 2), and
- Given that the batteries have relatively high power ratings and significant amount of inherent storage in aggregation.

Clearly, there is considerable flexibility regarding the time when the vehicles can be charged and this can provide significant benefits both to the operation of distribution and transmission networks as well as to the efficient dispatch and utilisation of generation. This flexibility can be further enhanced by so called vehicle-to-grid (V2G) applications that involve discharging car batteries (exploiting stored energy in the battery) to support the grid. EVs could also make a contribution to the provision of instantaneous reserve services through being disconnected while charging or injecting power from car batteries.

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[1] An exchange rate between British pound and Euro in this report has been assumed in the amount of 1 GBP = 1.15 EUR.

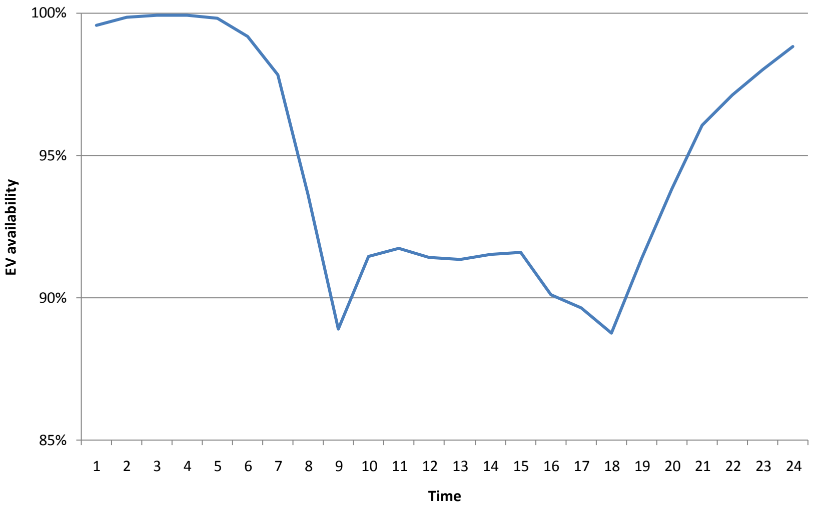


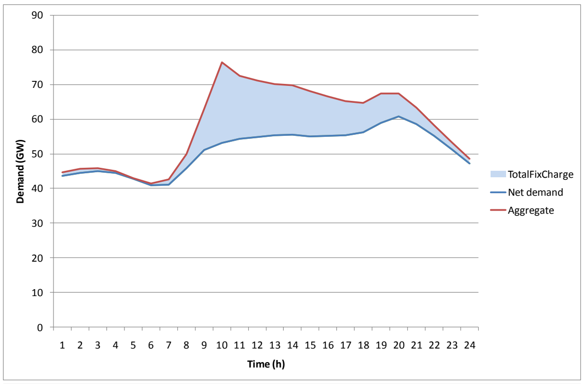
Figure 2: Percentage of stationary vehicles during a typical day for the UK (Source: [NTS09])

As mentioned earlier, the impacts of EV integration in the electricity systems are linked to the way the charging process of EVs is managed i.e. the charging strategy. In order to test the boundaries of impacts, two main strategies of EV charging are investigated in this work. In each of these the vehicles should have enough stored energy in the battery during the stationary periods to suffice their forthcoming journey needs. It is envisaged that a number of charging strategies may emerge as a consequence of user requirements and availability of charging infrastructure. The impacts of these charging schemes and their comparison for various scenarios are presented in Chapter 4.

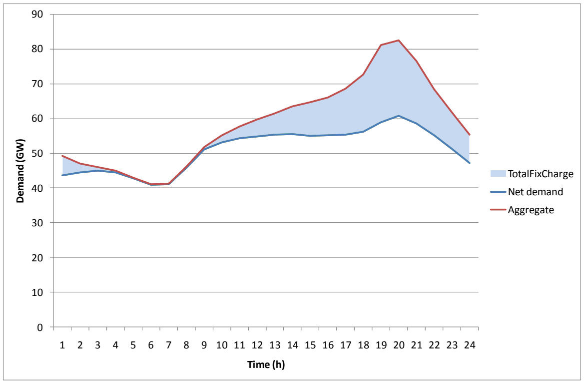
a) Uncontrolled (non-optimised) charging

Under this charging scheme all users are allowed to charge their vehicles as and when they wish i.e., no control is exercised on the charging process by the system operator or any other third party. In Figure 3 below a few examples of user selection-based charging schemes are shown. In an uncontrolled charging regime a more likely situation may emerge in the form of a combination of these choices. The strategies shown are based on an average representation of two journeys per vehicle per day. Although the shapes of charging load are given for illustration purposes only, we note that the maximum assumed charging power per vehicle has been 6 kW, EV penetration has been 100%, and charging has been assumed to take place anywhere, depending on the time when journeys are completed (as the analysis is made on the system level, no specific assumptions have been made as to where the vehicles would actually be charged). Sensitivity analyses conducted indicate that the aggregate charging load shape does not change significantly with higher or lower maximum charging power.

a: Energy stored in batteries just after the first journey to last for both journeys of the day.



b: Energy stored in batteries just after the second journey to last for both journeys.



c: Energy storage takes place immediately after each journey equal to the energy consumed during the journey completed.

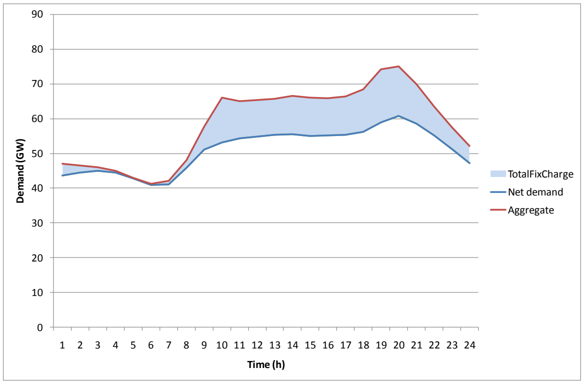


Figure 3. Examples of non-optimal charging strategies for the UK system

b) Controlled charging

In this charging scheme EV charging (or discharging to the grid) can be managed by the system operator or by a third party (aggregator) to make this process economically efficient or to support the operation the system. This can be achieved by exploiting the electricity price variation during peak and off peak demand periods, as well as through provision of ancillary services by EV when EVs are stationary and connected to the grid. This scheme can be further applied in two modes.

i. Unidirectional charging of EVs

In this case EVs can only be charged from the grid during their stationary periods, at times when it is considered most beneficial to charge from the system point of view. In other words, the power flow takes place in one direction only i.e. from grid to EVs, and what is controlled is the timing of delivering this energy to EV batteries.

When controlling vehicle charging, it is assumed that all vehicles sharing the same driving pattern also follow the same charging profile. Charging profiles from all journey categories, when added together, form an aggregate charging curve that is optimised from the system perspective. (A more detailed treatment of various charging strategies is provided in G4V deliverables compiled in WP6.)

ii. Bidirectional control of EV charging process

In order to support the system, bi-directional flow of power between the grid and the electric vehicles is being considered a potential option. Therefore, we have investigated this mode of application of EVs in detail. This charging strategy allows provision of electricity injections back to the grid (called vehicle to grid, V2G) when required, besides charging of the EV by the grid. In other words power flow is possible in either direction i.e. power injections into the grid using stored energy in the EV batteries are also possible. This increases significant additional complexities in the system operation and hence in the modelling framework. However, this offers further flexibility to the system operator by allowing him to exploit EV charging as well as discharging processes to support system balancing tasks.

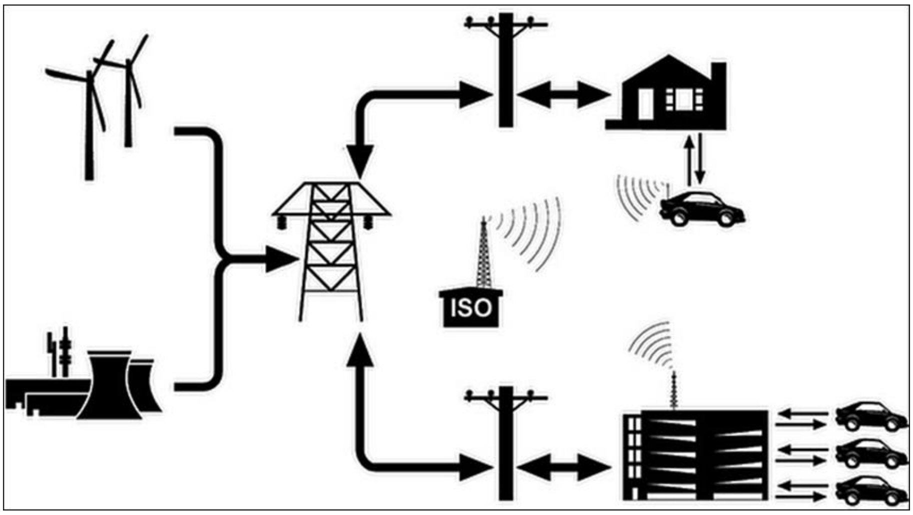


Figure 4. Example of interaction between EVs and the power system (Source: [KEMPT05])

Charging as well as discharging of EV can also be managed to achieve alternative objectives from the electricity system’s perspective. For example in order to limit the system peak demand it may be required that the charging is shifted away from high demand periods towards low demand periods of the day. Also EV can be applied to supply part of the peak demand using discharge of the stored energy during these periods thus saving some of the peaking generation capacity as well as reducing the transmission congestion on constrained circuits.

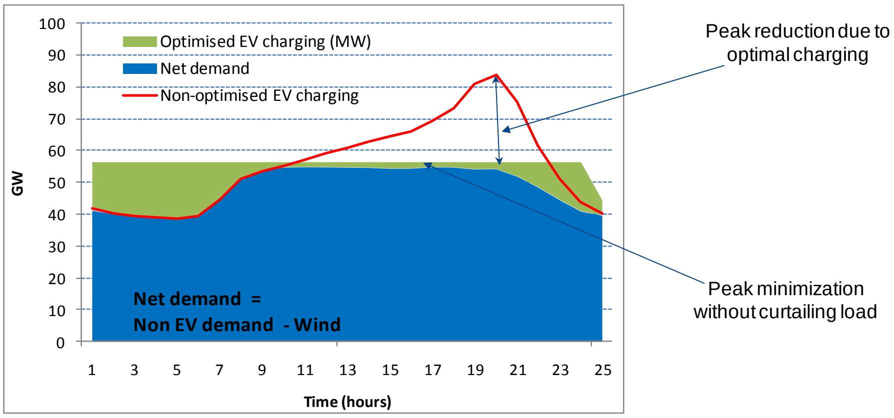


Figure 5. Optimal charging strategy to minimise the overall UK peak demand

In order to improve the efficiency and utilisation of capacity in the system we developed two formulations for optimising EV charging patterns:

- Optimal charging that would minimise peak demand (capacity-driven management)
- Optimal charging that would minimise generation system operating cost (energy-driven management)

3 Description of Key Modelling Input

Due to the complexity and the detailed nature of the developed model, extensive input data are required that includes both the electricity system information as well as the transport (vehicles) system statistics. We have analysed three different electricity systems in Europe which include; Great Britain (GB), Spain and Sweden. Selection of these systems (countries) was based on an approximate representation of different parts of Europe i.e. Northern, Southern and Central, as well as on the consideration of the ease of data availability. The novelty of this work demanded specific type of information and data in particular related to the transport sector, raised several challenges. GB system data has been acquired and prepared for the model in relatively greater detail, while that for Spain and Sweden involves certain simplifications as explained in the following sections.

3.1 Electricity demand

The overall electricity demand to be managed by the power system is divided into two major parts: i) system demand which arises from conventional sources of electrical load and, ii) the demand arising due the electrification of road transport. Both of these are discussed in detail in the following two sections.

3.1.1 System demand

System demand here represents the electricity load to be served by the supply system and it does not include the additional demand due to EV charging which is modelled separately in this analysis. The time horizon of this work is focused on year 2030 (and beyond); therefore, the forecasted increase in electricity demand (both energy and peak demand) is accounted for in the analysed systems. This excludes the demand served by the embedded generation or that which is served by import links, which are beyond the scope of this analysis.

For the GB system the National Grid “Base case” demand growth forecast is taken as reference [NGRID11]. The hourly electricity demand for the year 2008/09 is linearly scaled according to annual peak demand (GW) increase rate of 0.1% per annum and electricity demand (TWh) increase rate of 0.7% per annum. For Spain and Sweden the corresponding system’s demand were provided by G4V consortium members (Endesa and Vattenfall, respectively) based on their national sources. These hourly annual profiles for electricity demand for GB, Spain and Sweden (equivalent[2]) system is modelled for each scenario under study.

Key system demand-related statistics are given in Table 1 below. As mentioned earlier, this demand does not include any demand from electric vehicles, which are modelled separately as explained in the next section.

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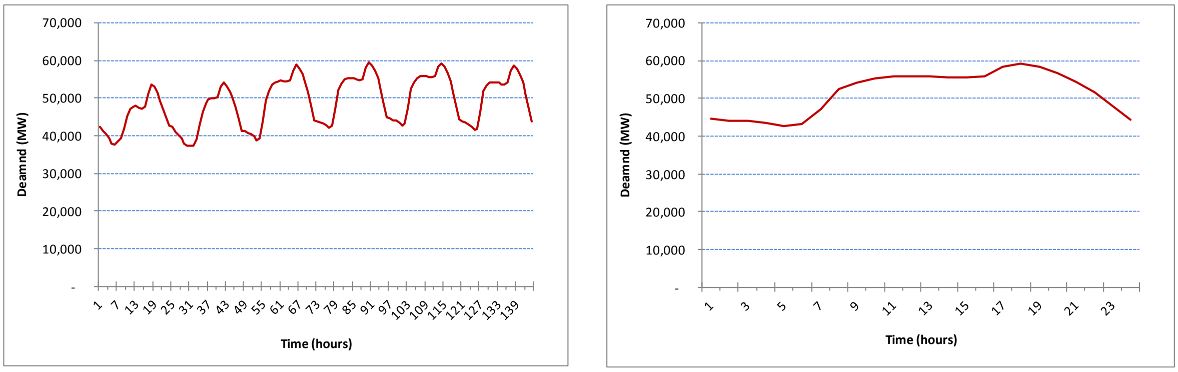
[2] The term ‘equivalent system’ is used here to avoid any future forecasting controversies. Also for the completeness of data input to the model, certain assumptions were also made where relevant information was not available, and which may differ to an extent from the existing conditions.

Table 1. Annual projected demand (excluding EV demand) – 2030

Demand	Great Britain	Spain	Sweden
Minimum demand (GW)	25.2	21.7	8.7
Peak demand (GW)	60.0	52.9	26.5
Average demand (GW)	41.6	35.6	16.4
Energy demand (TWh)	364.0	312.2	144.0

No significant variations in the daily demand patterns of the three systems were observed which in general follow the every day consumption patterns inline with user requirements. Typical daily and weekly demand patterns for GB are shown in Figure 6 below.



Weekly demand profile Daily demand profile

Figure 6. Typical winter demand profiles for the GB system

The seasonality effect is significantly pronounced in all the three systems and is a major reason for differences in the monthly consumptions patterns of selected countries.

Significant differences have also been found in the load duration curves of the three selected countries which illustrate the relationship between generating capacity requirements and capacity utilisation.

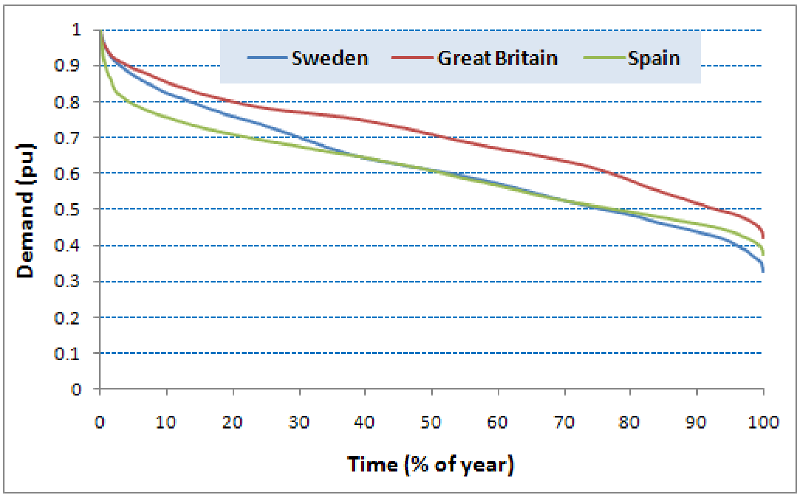


Figure 7. Annual load duration curves of selected systems

3.1.2 Electricity demand due to electric vehicles

The increase in electricity demand due to electric vehicles is dependent upon the level of electrification of the vehicle fleet in a system. Due to significant uncertainties regarding the attainable penetration of EV in different countries we have analysed a complete range 0% to 100% penetration of EV in selected systems[3]. It is also important to observe that the impact of same penetration of EV on electricity peak demand (GW) in a given system could vary widely depending upon the applied EV charging strategy; however, the corresponding variation in additional electricity demand (TWh) may not be large.

Depending upon the overall number of vehicles (cars) in the system, Figure 8 below depicts the possible increase in electricity demand for various penetration levels (0-100%) of EV in the selected three systems.

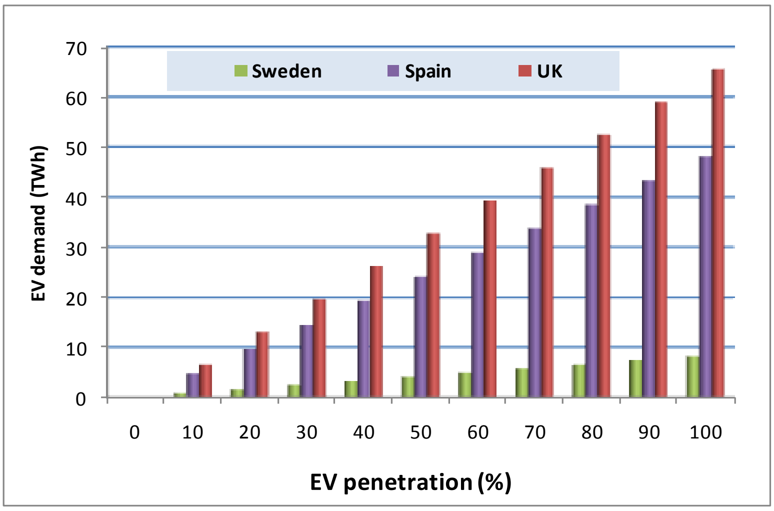


Figure 8. Additional electricity demand due to EV

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[3] This is also in accordance with the Project Manual [G4V10] (p. 55) and the overall approach within the G4V project.

3.2 *Key statistics for transport system data*

A comprehensive analysis of the transport statistics was required to deduce the information necessary to represent the driving patterns and corresponding electricity requirements. The transport system data for the GB system, as applied in this model, have been deduced from detailed transport surveys and their comprehensive analysis.

Database records for the UK include 67.4 million journeys undertaken by around 34 million vehicles on an average business day. Total daily distance travelled is slightly less than 30 kilometres per vehicle. The average energy consumption per unit of distance travelled is assumed to be 0.15 kWh/km[4]. This gives the total daily energy requirement of approximately 4.4 kWh per vehicle. Efficiency losses incurred during battery charging as well as other on-board consumption such as air conditioning etc are included in modelling.

Input to our modelling of EVs is based on the National Transport Survey (NTS) database in the UK [NTS09]. Data extracted from the database contain information on all journeys conducted by a sample of light vehicles, including starting and ending times of individual journeys grouped according to the distances travelled. Data is typically classified into distance bands (e.g. less than 1 mile, 1 to 2 miles, 2 to 3 miles etc.). An illustrative sample of the required data set is presented in Table 2.

Table 2. Driving patterns data

Start time	End time	Distance band	No. of journeys (daily)
00:00 – 00:59	00:00 – 00:59	Under 1 mile	6922
00:00 – 00:59	00:00 – 00:59	1 to under 2 miles	15987
00:00 – 00:59	00:00 – 00:59	2 to under 3 miles	14848
…	…	…	
00:00 – 00:59	01:00 – 01:59	2 to under 3 miles	1277
00:00 – 00:59	01:00 – 01:59	3 to under 5 miles	4938
00:00 – 00:59	01:00 – 01:59	5 to under 10 miles	3209
…	…	…	
00:00 – 00:59	02:00 – 02:59	50 to under 100 miles	474
00:00 – 00:59	03:00 – 03:59	100 to under 200 miles	492
00:00 – 00:59	04:00 – 04:59	200 miles and over	388
…	…	…	
23:00 – 2359	23:00 – 23:59	25 to under 35 miles	7750
23:00 – 2359	23:00 – 23:59	35 to under 50 miles	1458
23:00 – 2359	23:00 – 23:59	50 to under 100 miles	923

Based on the NTS data, journeys are further classified into journey categories. These are characterised by the number of vehicles included, start and end times of each journey, as well as the energy needed for each journey within each journey category. This leads to a significantly large number of journey categories requiring extensive computational time to simulate the system and subsequently analyse results.

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[4] Reference [LUND08] uses a specific energy consumption of 0.16 kWh/km, although the value of 0.11 kWh/km is also reported; while reference [ELEME09] uses 0.20 kWh/km. On the other hand, [G4V10] defines consumption ranges as: 0.13-0.25 kWh/km for BEV, 0.12-0.16 kWh/km for City BEV, and 0.15-0.25 kWh/km for PHEV. In this work, we have assumed the consumption of 0.15 kWh/km as a central value.

In order to reduce the number of journey categories, we group the distance bands (as shown in Table 1 above) into three clusters; Short, Medium and Long, as specified in Table 3. The concept of “equivalent distance” is introduced here which serves as the representative distance driven within a particular type of journey. For instance, all journeys classified as short, i.e. between 0 and 15 miles, are represented by an equivalent distance of 9 miles each. Similarly, the values of 20 and 100 miles are represented by Medium and Long journeys, respectively. These values have been calibrated to ensure that the total distance driven remains similar to the one in the respective vehicle fleet.

Table 3. Distance band clusters and equivalent distances

Journey type	**Distance band [mile (km)]**	**Equivalent distance [mile (km)]**
Short	≤ 15 (24)	9 (14.4)
Medium	15 (24) ÷ 50 (80)	20 (32)
Long	≥ 50 (80)	100 (160)

The NTS data suggest that each vehicle on average makes two journeys a day. In order to facilitate the application of developed modelling framework, we assume that each vehicle in the fleet completes exactly two journeys, and journey data have been processed accordingly. For each combination of journeys and journey categories, specific information is necessary for the optimisation procedure, such as:

- Start and end times of journeys define when the vehicle is on-road to know that the rest of the time the vehicle is parked and thus potentially available for power (charging/discharging) management.
- The number of vehicles involved and their energy needed for each journey provides the EV related power and energy constraints to be managed for the category involved within their stationary period.

Journey data prepared as described above allow for the simulation of alternative charging strategies, given that the energy consumed during the journey is specified together with the times when vehicles are stationary and hence being potentially available for charging. Our simulation and optimisation algorithms would ensure that the state of charge of batteries would not compromise the ability of vehicles to carry out their intended journeys.

Given that in the statistics obtained the total number of vehicles is approximately half the total number of journeys, it may be appropriate to assume that each vehicle completes on average two journeys; for example, driving to work in the morning (first journey) and driving back home in the evening (second journey). This is illustrated in Table 4 that specifies, for each journey combination, the number of vehicles and corresponding energy requirements.

Table 4. Final journey data table

1st journey		2nd journey		No. of veh.	E1	E2
start1	end1	start2	end2	(from 1st to 2nd)	kWh	kWh
1	1	2	2	64.93	87.881	88.456
..	..	..	..	..	..	..
8	9	17	18	4900.83	6705.441	6880.413
..	..	..	..	..	..	..
22	23	23	24	8.24	11.156	11.321

3.3 *Generation system data*

The generation capacity in the selected systems is represented by groups of technology types such as; nuclear, coal, gas, hydro storage, hydro run-of-river, wind, solar etc. Each technology group is characterised by specific number plants (units) according to their projected installed capacities. All plants within each thermal technology group are characterised by generic ratings, availability, and dynamic as well as cost characteristics. Renewable generation representation is explained in the next section.

The basic information obtained regarding projected generation capacity levels for the three selected systems is given in Figure 9 below. These capacity levels do not consider the additional demand due to EV. Therefore our reliability assessment model evaluates the reliability of each system under each EV penetration scenario and augments the generation capacity to satisfy the system reliability requirements. This additional capacity is assumed to be open cycle gas turbines (OCGT) being the least expensive to build capacity. Section 4 will elaborate these additional capacity requirements and their sensitivity of different penetration levels of EV and the applied charging strategies.

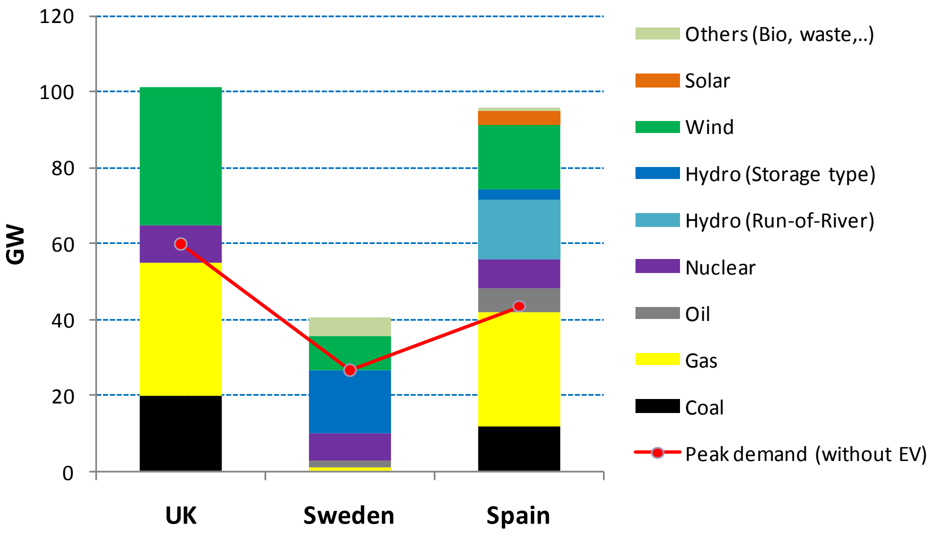

Figure 9. Generation capacity of the analysed systems

Detailed representation of the generation system required following key characteristics of each plant in the system which include:

- Unit rated capacity
- Minimum stable generation level
- Maximum annual generation or plant load factor constraints (if any)
- Fuel source and Marginal cost of power production
- Plant efficiency
- No-load cost
- Start-up costs
- Operating reserve provision characteristics including ramping up and down rates
- Minimum up and down times
- Plant emission factors

For the UK system, generator data was based on recent studies [UKERC09] and relevant UK energy statistics [DUKES10], while for the Spain and Sweden he relevant data has been provided by respective consortium members.

Furthermore, sensitivity studies regarding the impact of generation composition (mix) were performed for the UK system. Therefore, three alternative generation mixes for the UK were investigated in detail, which were mainly differentiated on the basis of the overall operational flexibility available in each case. Three scenarios for generation system flexibility were developed ranging from low to high flexibility generation systems as depicted in Figure 10. They primarily differ in terms of the relative share of Nuclear (assumed inflexible) and Gas (assumed flexible) in the system.

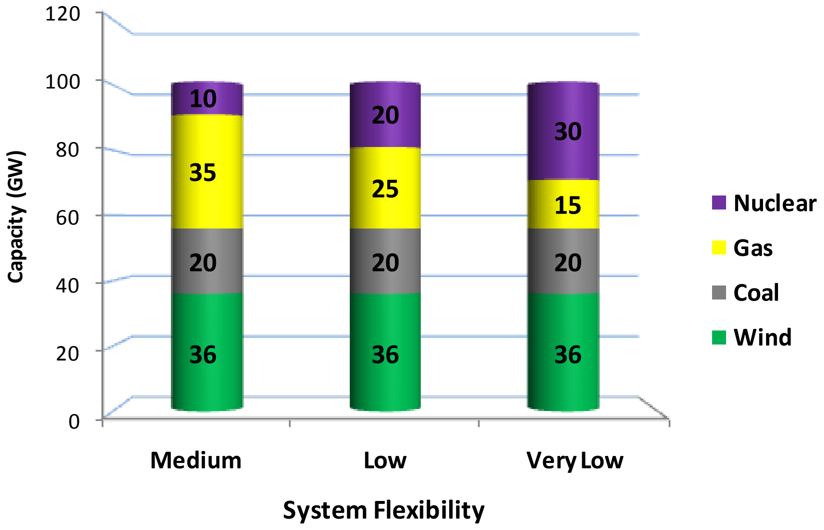

Figure 10. Alternative (UK equivalent) generation systems for flexibility impact analysis

Additional sensitivity analysis is also performed by varying the penetration of wind generation in the above given medium flexibility scenario.

Renewable generation

For the studies presented in this report only wind generation is included to represent renewable generation in the system which is envisaged to be the main saleable renewable technology in Europe within the considered time horizon. However, the model is capable to include other main renewable technologies such as solar (photovoltaic as well as Concentrated Solar Power – CSP).

Wind power is modelled as a zero marginal cost energy source. Consequently, it is prioritised in generation merit order of the plants wind generation will be fully utilised unless constraints related to other plant (must-run generation like the minimum stable generation level constraints of reserve providing plant) or system load conditions lead to the curtailment of some wind energy. For example, curtailment may happen during periods where there is a coincidence of low demand, high wind and/or solar power output while thermal plant are also operating due to their “must run” constraints or to provide reserve.

Representative wind profiles have been obtained for all three systems that have been analysed in the case studies (GB, Spain and Sweden). The profiles have the form of 8760 hourly values spanning one year, and the installed wind capacity which is expected to be online in 2030 has been estimated according to relevant long-term projections.

3.4 System reliability criteria

The amount of generation capacity in a power system is considered to be adequate if it meets electricity demand with an “economically efficient” level of reliability. Conceptually this “optimal” level of capacity to be installed would be determined by balancing generation investment costs against benefits associated with the improvements in reliability of supply, i.e. the reduction in loss of supply to consumers. Instead of conducting such a cost benefit analysis, generation system planners traditionally aim to maintain a certain level of capacity margin that would deliver a minimum reliability performance as measured by various reliability indices.

In a centrally planned system having both; conventional thermal generation technologies and intermittent renewables, the most frequently used index is “Loss of Load Expectation (LOLE)” which represents an expected number of hours in a year when demand may exceed the available generation (resulting in disconnections of demand). Given that LOLE is calculated for all hours of the year, rather than a single peak demand period, LOLE captures all correlation that exist among demand, intermittent (wind) generation as well as energy limited hydro generation sources.

We have evaluated the amount of adequate generation capacity at various levels in different generation portfolios of the incumbent systems while applying the Loss of Load Expectation (LOLE) reliability standard. In the system capacity assessment model a LOLE level of 3 hours/year was applied to evaluate the amount of adequate generation capacity in respective systems. Many recent generation adequacy studies have exercised similar reliability standards such as; France[5] (LOLE: 3 hours/year) and Republic of Ireland[6] (LOLE: 8 hours/year).

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[5] Generation Adequacy Report on the electricity supply-demand balance in France, RTE 2007

[6] Generation Adequacy Report, Republic of Ireland, EirGrid 2007

3.5 *Input cost assumptions*

Fuel costs assumed for coal and gas for the UK system are given in Table 5 below. These costs were assumed to be the same throughout the year i.e. no seasonal variation of the fuel costs has been assumed.

Table 5: Fuel cost assumptions[7]

Fuel	Unit cost	Energy cost
Coal	£65 (€75)/tonne	£2.50 (€2.88)/GJ
Natural gas	£0.18 (€0.21)/m^3	£4.74 (€5.45)/GJ

The cost of CO_2 was assumed to be around £20 (€23) per tonne of CO_2 emitted. Due to different emission factors of different types of plants, CO_2 emissions and corresponding costs per unit of electricity produced vary for each technology.

The generation cost from the modelled technologies are determines from their representative marginal cost curves according to their output level in each hour of simulation. These costs added with the corresponding CO_2 costs yield the overall production cost of the technology under consideration. These production costs corresponding to full output level of main technologies are given in Table 6 below.

Table 6: Generation costs

Generation technology	Fuel cost at full output	CO_2 cost at full output	Total cost at full output
Coal	£25.0(€28.8)/MWh	£18.5(€21.3)/MWh	£43.5(50.0€)/MWh
Gas	£33.4(€38.4)/MWh	£7.9(€9.1)/MWh	£41.3(€47.5)/MWh
Nuclear	£21.0(€24.2)/MWh	-	£21.0(€24.2)/MWh

Fuel costs for Spanish and Swedish system have been assumed at the level used in the TRANS-CSP project [TRANS06].

3.6 *Emission Factors*

Emission factors for greenhouse gases (CO_2, CH_4 and N_2O) from fossil fuel combustion, along with their Global Warming Potential (GWP) values have been obtained from internationally acknowledged databases and manuals [IPCC11, DEFRA09]. They have been used to estimate the GHG emissions arising from electricity generation for various case studies on the impact of EVs, which also enables the quantification of the environmental impact of a large-scale deployment of EVs.

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[7] The price of gas was obtained from the Intercontinental Exchange (ICE) Monthly Natural Gas Futures at the beginning of 2011 (www.theice.com). Price of coal has been estimated from the average price in 2010 as reported in Financial Times.

4 Economic and Environmental Analysis

Electrification of transport system through the introduction of electric vehicles is a pragmatic attempt at decarbonising the transportation sector, yet their integration with the electricity system requires an in-depth scrutiny. This is due to the non-conventional form and usage patterns of this new (mobile) form of electrical load.

This work studies the impact of the electric vehicles on electricity system by analysing system-wide, hour-by-hour, all year round, cost-optimised system operation, featuring different penetrations of EV in the electricity system. An integrated simulation and optimisation framework has been applied, which encompasses an EV model, a unit commitment and balancing model, a demand side management algorithm, and a system reliability valuation model, as explained in Chapter 2. The key objective is to analyse the cost, reliability and environmental performance of the future electricity systems when coping with supplying various levels of EV under their alternative charging strategies.

Simulations for a wide range of EV and generation scenarios are carried out. Results show how an uncontrolled EV load comes along with increased system peaks requiring significant amount of additional generation capacity as well as operational cost, along with the curtailment of large amounts of intermittent (wind) generation. On the other hand, controlled EV charging management, in both unidirectional or bidirectional (V2G) modes, leads to significant benefits in terms of reduced additional generation capacity requirements and lower operational costs to serve EV load.

Environmental emissions from power sector are linked to the generation mix of the incumbent system. The controlled charging of EV can lead to enhanced emission savings from electricity production compared to uncontrolled EV charging case. Major emission savings can be achieved in a non carbon-intensive system through coordinated management of EV charging.

This chapter provides a detailed description of various case studies carried out in this work. The studies examine a number of factors which could influence the economic and environmental performance of the electricity system under various uptake scenarios of EVs, the elements of which include:

- Penetration level of electric vehicles in the system
- Charging control strategies
- Generation mix and share of intermittent (wind) generation in the system
- Generation system flexibility
- Fuel and CO_2 costs
- Characteristics of the incumbent electricity systems (UK, Spain, Sweden)

Nevertheless, the studies performed based on these scenario assumptions do not represent forecasts or estimates of future developments, but have rather been designed to understand the impacts of potential magnitude of electrical energy required over time due to EV under alternative control strategies of the EV load. The following sections elaborate the quantified impacts.

4.1 *Impact on overall electricity demand*

Penetration of EV into the system introduces new form of electricity demand which mainly differs to conventional demand sources on account of its consumption patterns and inherent flexibility. On the one hand EVs represent mobile electric loads which existing power systems have never experienced while on the other hand they come with significant built-in electricity storage capacity. The fact that most of the EVs are stationary during major part of a day, combined with their sizeable storage ability offers temporal shift of EV related electricity demand across time. This provides the system operator with additional potential to maintain demand and supply balance exploiting the charging (or discharging in case of V2G) process of EV.

Regarding the impact of EV on overall electricity demand a key question is: At what time would the EV users recharge their vehicles? From the system perspective the optimum time for electricity providers is typically at night (off-peak hours) when demand is low and low-cost plants are the marginal providers. Charging cars during the off-peak periods, particularly at night (or when wind/renewable output is high) is an efficient use of the generating sector, and by flattening the daily demand profile this will improve generation efficiency. On the other hand, the preferred time for consumers (without any incentives to change their preference) is likely to be soon after they complete a journey and are within an easy access of a plug. This is both most convenient since they are at the vehicle already, and also improves their options since they may need the vehicle soon and would prefer a more fully charged battery.

We have investigated the impact of different EV charging schemes on the overall system demand. The average daily journey profile and the evening peak generation period for a GB equivalent system (projected for year 2030) are closely aligned as shown earlier in Figure 2 and Figure 6. In an uncontrolled EV charging regime this could potentially lead to a significant increase in peak load of the system. Such co-incidence of EV charging with the peak demand period with 50% EV penetration in the system is depicted in Figure 11.

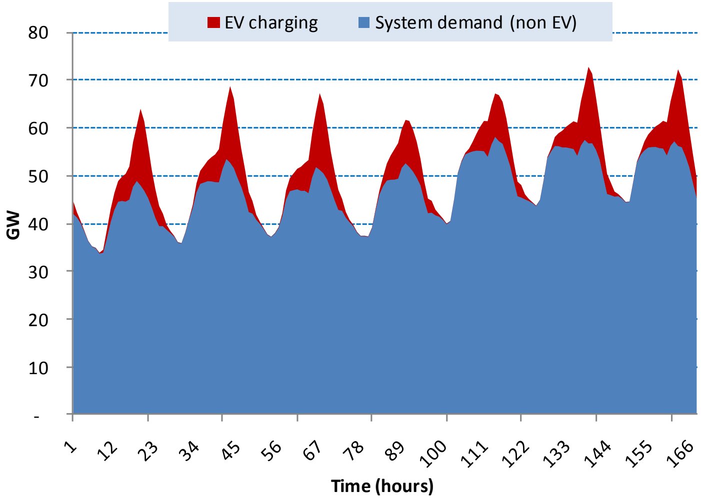


Figure 11. Co-incidence of EV charging with the peak demand period in case of uncontrolled EV charging

Controlled EV charging strategies, on the other hand, will try to spread the charging process across periods of low demand thus filling the demand valleys. This leads to relatively reduced effect on the peak demand of the system. Our EV model, while optimising this charging process under controlled charging strategies also considers the availability of intermittent (renewable) generation and tries to maximise the utilisation of this energy. Hence in this case the more favourable option would be to shift the charging process towards periods of low net demand (which is equal to system demand minus intermittent wind generation). This would result in not only reducing the impact on peak demand but also maximises the utilisation of low marginal cost conventional plant. Figure 12 below shows the impact of controlled (unidirectional) charging on overall system demand where it can be clearly observed that most of the charging takes place out during period of low net demand. The assumptions in terms of EV penetration, charging power and locations applied here are the same as for Figure 3.

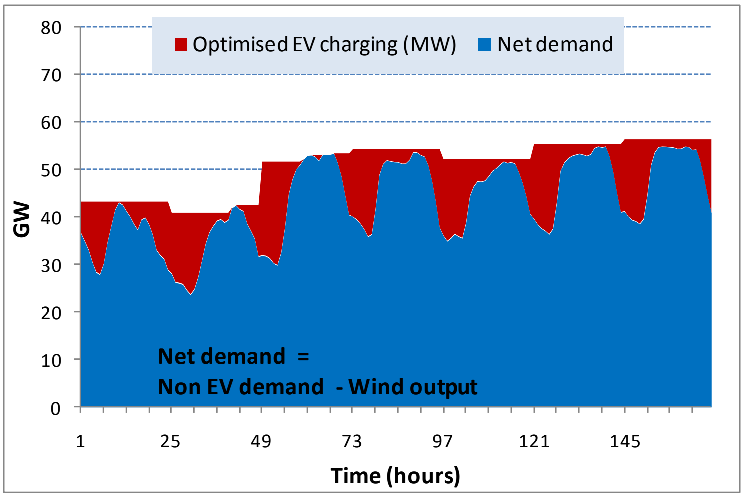


Figure 12. Effect of EV charging on overall demand under controlled (unidirectional) EV charging

In case of bidirectional optimised charging of EV, including discharging following the Vehicle-to-Grid concept, a further impact on peak demand is observed. The simulation of bidirectional charging strategy is shown in Figure 13 that displays the impact on overall demand due to EV charging and discharging for each hour of one of the high demand weeks. Similar to the controlled unidirectional charging strategy, the charging process (indicated by thin dark red lines) is primarily done during the off-peak (low demand) periods of the day while discharging (indicated by thin green lines) takes place during the peak hours of the day. This results in further shaving of the peak load seen by the generators as some part of the peak load is served by EV in the discharging mode.

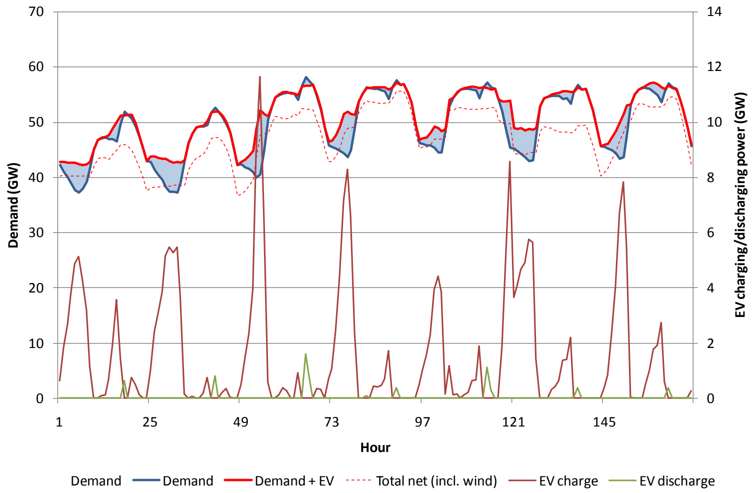
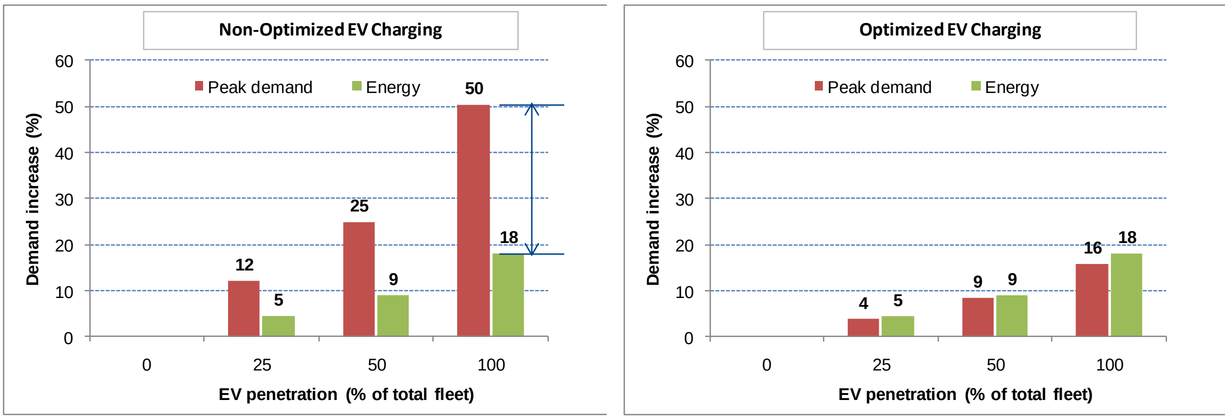


Figure 13. Effect of optimised (bidirectional) EV charging and discharging on overall demand

The above results and discussion demonstrates that peak demand levels of the system are strongly linked to the type of charging strategy that is applied. On the other hand the additional energy requirements to serve EV load may not be influenced by the charging strategy by the same extent. A comparison between the percentage increase in peak demand and additional energy required for different levels of EV penetration is provided in Figure 14 below.

It is important to observe the disproportion between the additional power and the additional energy requirements for a given level of EV penetration between the uncontrolled and controlled EV charging strategies. In case of uncontrolled charging of EV the increase in the system peak demand is from 12% to 50% and increase in system's energy requirement is 5% to 18% for 25% to 100% EV penetration respectively. On the other hand in case of controlled EV charging this disproportion between the peak and energy demand is significantly low.

In case of bidirectional controlled charging strategy when compared with unidirectional charging, a further modest decrease in the peak demand and a slight increase in the additional energy demand are observed. The small reduction in peak demand is linked to a small part of peak load being served by EV discharge while the slight increase in energy demand is linked to the additional energy to serve that non-EV load during peak periods and the associated energy losses in storage.

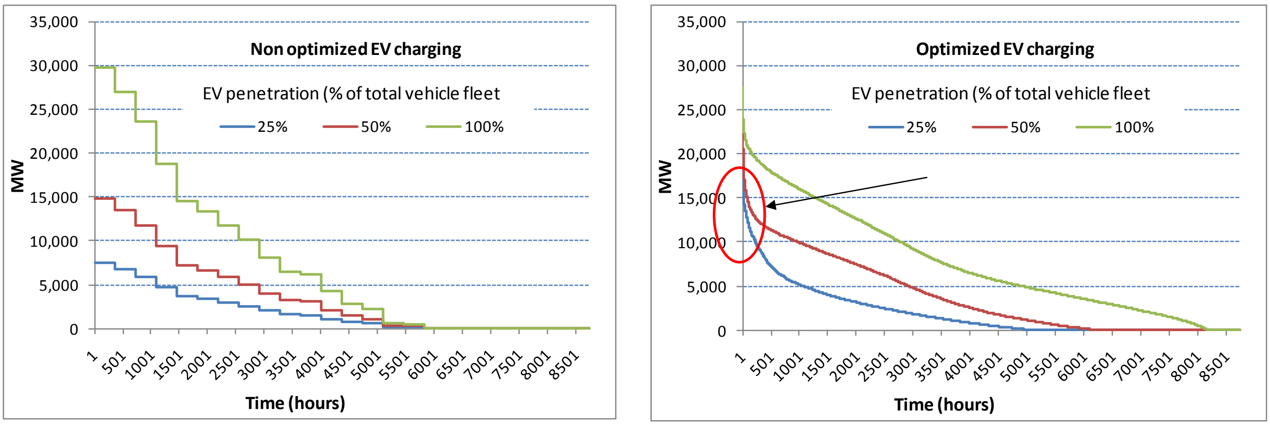


Uncontrolled EV charging. Controlled EV charging.

Figure 14. Differential impact on additional energy and peak demand

It is relevant however, to note that system energy provision requirements from different sources could be affected if uncontrolled charging of EV leads to the curtailment of intermittent (wind) energy, thus requiring increased production from conventional plant in the system. This is further explained in Section 4.4 on the integration of intermittent wind output.

Figure 15 shows the charging duration curves for the controlled and uncontrolled charging strategies. It is clear that at 100% penetration of EV, the EV related load peaks at a level of 30,000 MW for uncontrolled charging compared to about 23,000 MW for the controlled EV charging. However, at lower EV penetration (up to 50%) occasional high charging (lasting for very few hours across the entire year) in the controlled EV charging case helps to avoid wind curtailment during high wind output periods coinciding with low demand.



Uncontrolled charging

Controlled charging

Figure 15. Charging duration curves

Two main conclusions can be drawn from this analysis:

- Controlled charging of EV, both the unidirectional and bidirectional, would result in significantly low peak demand compared to the case when vehicle charging is uncontrolled.
- No significant impact is expected on the additional energy requirements for EV load, due to controlled charging of EV.
- In comparison of bidirectional controlled charging strategy with unidirectional charging, a further modest decrease in the peak demand and a slight increase in the additional energy demand are observed.

This differential impact on system peak demand and additional energy requirements affects the infrastructure capacity (generation, transmission and distribution) that would be necessary to maintain reliability of the system. This will be explained in Section 4.3 which discusses generation capacity requirements.

4.2 Impact on risk of supply

Same penetration level of EV could lead to different effects on the reliability of the overall system under different charging strategies due to differential impacts on the magnitude of demand during peak demand periods as explained in the last section.

In our modelling framework, the overall reliability of an incumbent system with various levels of EV is evaluated by computing the Loss of Load Probability (LOLP[8]) during each hour across the entire year. LOLP is a function of overall hourly load, output available from intermittent sources and the availability characteristics of the conventional generators in the system. Yearly distribution of LOLP for the analysed GB equivalent system (without EV) is shown in Figure 16 which is based on the chronological demand pattern extrapolated for the year 2030. It is seen that LOLP is higher during the winter season due to high demand periods.

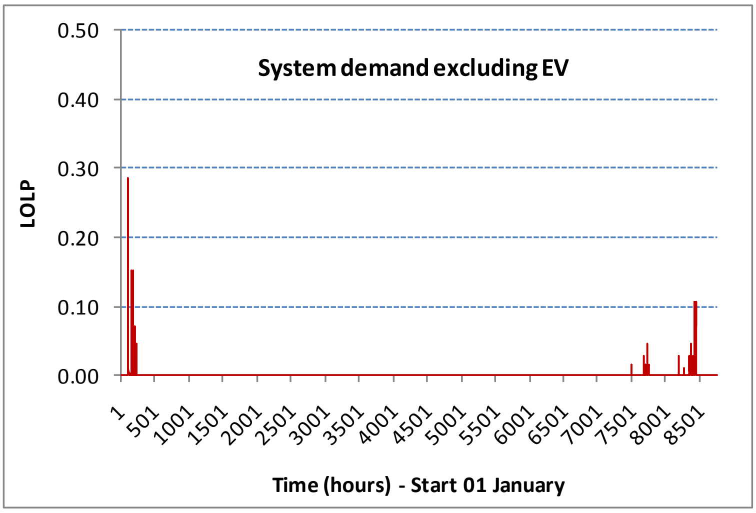


Figure 16. Risk of supply across the year (for GB system without EV)

The above shown LOLP values for each hour of the year are added to determine the annual LOLE (hours/year). Generation capacity is then added or removed from the system to achieve desired level of LOLE. Having determined the adequate amount of overall generation capacity in the system, EV load is included in the overall system demand through simulation of the system operation for the given charging strategy. LOLP is recalculated for each hour and generation capacity is iteratively added to the system unless the LOLE target is achieved. The hourly values of LOLP under the controlled as well as uncontrolled EV charging schemes for different penetrations of EV in the system with adequate generation capacity are shown in Figure 17 below. It is to be mentioned here that the sum of the annual LOLP values in each case (for a given EV level) will match the annual target of LOLE.

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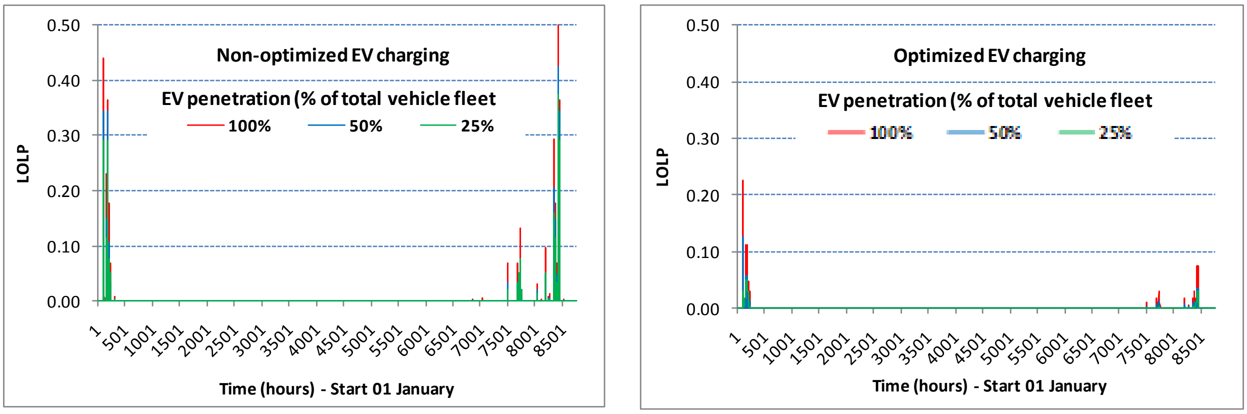
[8] LOLP represents the probability that the load will exceed available generation in the system, resulting in a loss of load (i.e. interruption of supply) situation.



Uncontrolled charging

Controlled charging

Figure 17. Risk of supply (LOLP) including EV demand

It is important to note that in both of the cases shown in Figure 17, the generation capacity in the system is adequate i.e. it provides the same level of annual loss of load expectation (LOLE), however, the distribution of the risk across the year will be different. Following two observations can be made:

- Under uncontrolled EV charging, the risk of loss of load increases during winter peak periods in particular at high penetrations of EV primarily due to coincidence of EV and non-EV loads.
- Controlled EV charging reduces the supply risk during winter periods and, the overall annual risk (LOLE) is more widely spread across the entire year. This is due to the shifting of EV load during off-peak hours of a day.

A comparison of the highest risk (among the 8760 simulation hours) across the entire year for the three charging strategies is drawn in Figure 18. It can be observed that the maximum risk level remains high for the uncontrolled EV charging strategies and it increases with the penetration of EV in the system. On the other hand this maximum risk value reduces with EV penetration for both of the controlled strategies. This is because of reason that there is minimal impact on peak demand on the one hand while additional generation capacity is being added to maintain annual reliability of the system.

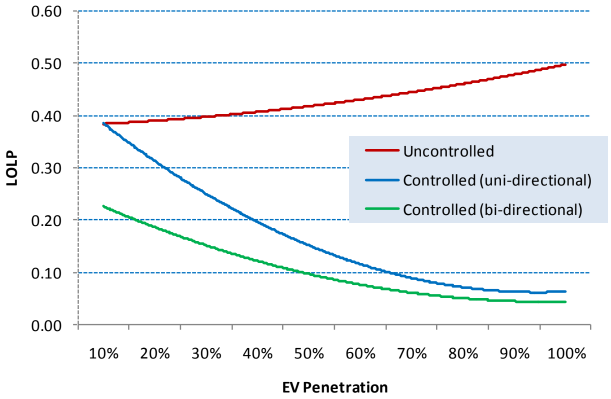


Figure 18. Loss of load probability (LOLP) during the maximum risk hour of the year

Although the distribution of risk of supply (LOLP) between the unidirectional and the bidirectional charging was observed to be insignificant, however, the highest risk level in a hour for bidirectional charging case is lower than the unidirectional charging for all penetration levels of EV. This is due to better management of peak demand in bidirectional (V2G) mode, resulting in relatively lower overall system peak load (due to EV discharge) to be served by the conventional generators.

4.3 *Additional generation capacity requirements*

Adequate amount of electricity generating capacity in the system is vital for maintaining reliability of the system in order to deal with uncertainties associated with both changes in demand and the availability of generation. Generation availability can be affected by forced outages of thermal generation plant, reduced water availability of hydro generation, and/or unavailability of intermittent generation. We have determined the generation capacity adequacy of the system that would deliver the required level of system reliability i.e. LOLE equal to 3 hours/year.

The generation capacity adequacy assessments were made for the three charging schemes. The additional generation capacities corresponding to different penetrations of EV were then computed as percentage of the capacity relative to no-EV case as shown in Figure 19 below for the GB equivalent system. Due to a significantly increased peak demand in case of uncontrolled EV charging (as explained in the last section), the corresponding levels of adequate generation capacity are high which rise significantly at higher levels of EV penetrations. On the other hand significantly less additional generation capacity is required with increase in EV penetration in case of controlled EV charging, thanks to only a modest increase in system peak demand. Another factor contributing to lower requirements of additional generation capacity by controlled EV charging is increased utilisation of wind energy due to enhanced ability of the system to absorb intermittent wind generation as explained in Section 4.4.

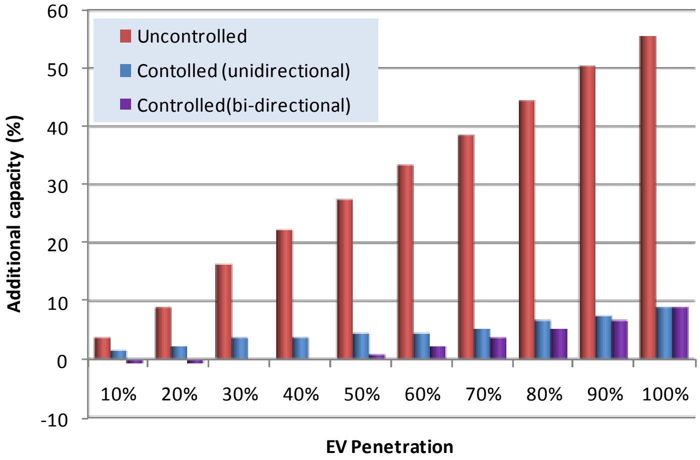


Figure 19. Additional generation capacity requirements for various levels of EV penetration in the system

The marginal difference in additional capacity requirements for a given level of EV penetration, between the unidirectional and bidirectional EV charging strategies, also reduces with increase in the EV penetration approaching zero at 100% EV penetration case. It can also be observed in case of bidirectional controlled EV charging that some capacity savings occur for below 20% EV penetration i.e., the overall generation capacity requirements would be lower compared at these EV penetration in this case compared to no-EV in the system. This is due to the substitution of some of the peaking plants by discharge of EV to serve part of peak demand.

The difference in the overall generation capacity requirements between the controlled and uncontrolled charging schemes increases with increase in EV penetration. Thus the impact of controlled charging in the form of generation capacity savings is provided in Table 7.

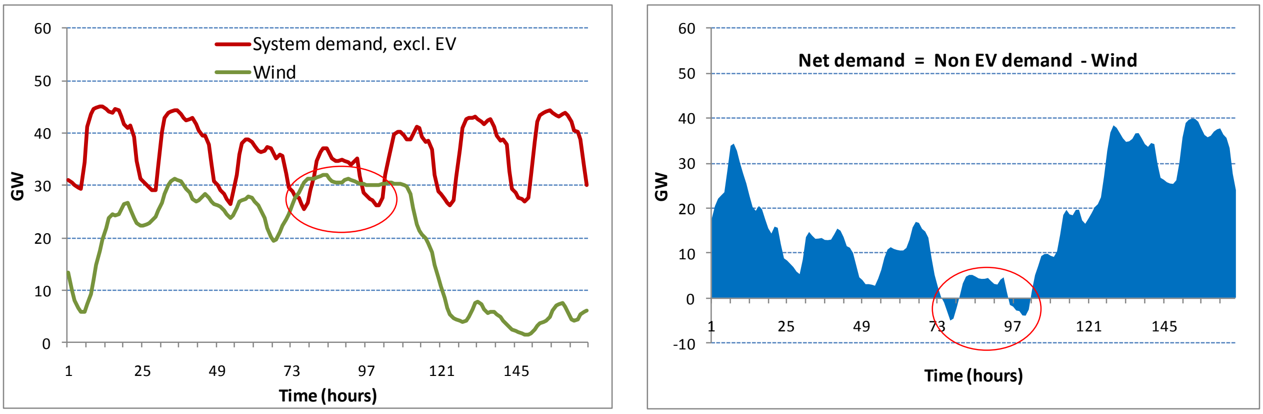
Table 7: Savings in generation capacity (GW) requirements due to controlled EV charging (compared to uncontrolled EV charging)

EV Penetration (%)	10	20	30	40	50	60	70	80	90	100
Controlled unidirectional charging	2	6	11	15	18	22	24	26	29	30
Controlled bidirectional charging	4	9	14	18	21	23	25	27	29	30

The above results demonstrate that if the flexibility feature of EV demand can be exploited through controlled charging of EV, the additional infrastructure (generation as well as transmission and distribution) requirements can be significantly reduced. Furthermore this would also result in increased utilisation of the generation assets leading to economically efficient operation of the system.

4.4 EV contribution to the integration of wind generation

Conventional electricity systems have been designed in such a way that generation follows demand where demand is mainly considered as passive i.e. non-responsive. With the rise in level of intermittent generation in the system there is increased uncertainty in the availability of generation when required as well as there is also a likelihood of surplus generation when system demand is low and the output from intermittent generators is high. Such a situation is depicted in Figure 20 where coincidence of high wind and low demand conditions leads to: a) available generation may exceed concurrent demand, resulting in: b) overall negative demand.



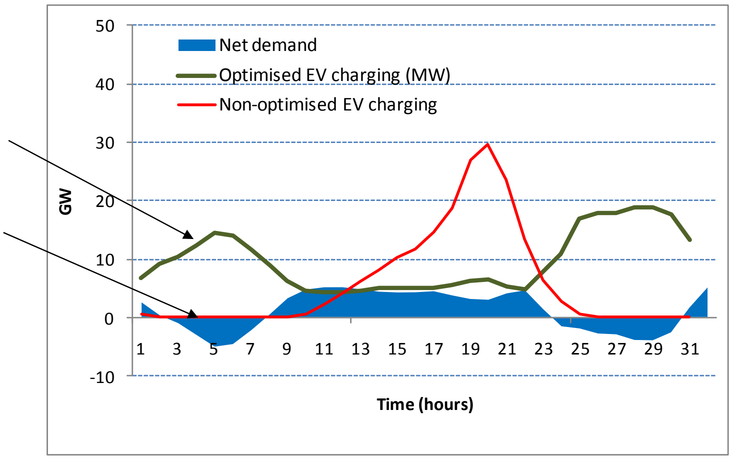
Available wind output exceeding system demand

Net demand is negative

Figure 20. Coincidence of high wind output and low demand conditions

The magnitude of the surplus (intermittent) power further increases due to must-run generation constraints in the system such as nuclear generation or operating reserve provision by conventional sources to maintain system security.

Electric vehicles with significant inherent storage capacity can absorb the surplus generation thus avoiding curtailment of this zero marginal cost energy if a controlled charging regime is applied. It can be seen that in this situation uncontrolled charging (that coincides with non-EV peak demand periods) will, on the one hand, lead to curtailment of energy during the off-peak hours while, on the other hand, significant increase in load during the peak periods would occur as shown in Figure 21 for a summer day. On the other hand controlled charging would utilise the surplus (wind) energy during off-peak periods thus avoiding wind curtailment besides significantly less impact on demand during peak periods.



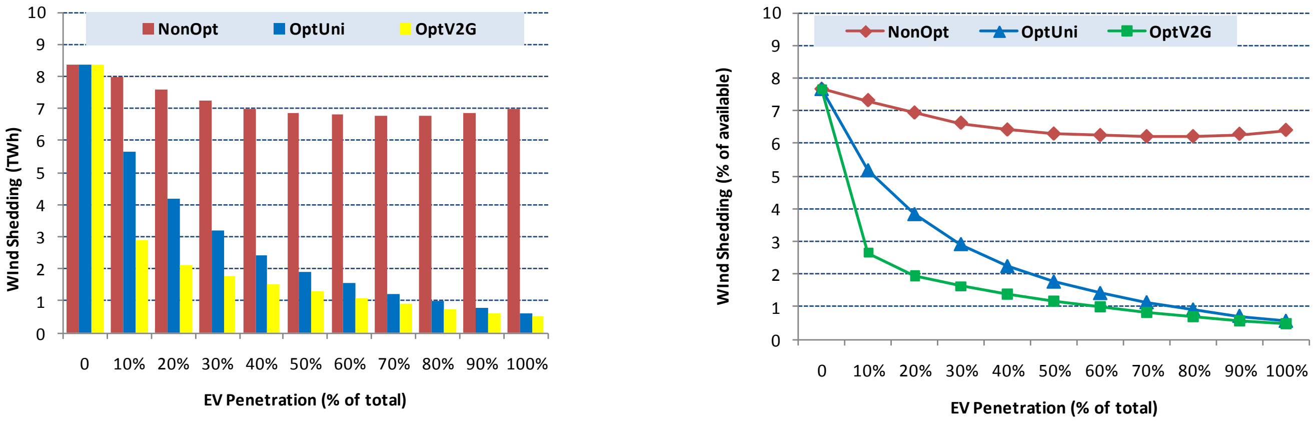
Optimal charging enhances demand during high wind to avoid curtailment

Non-optimized charging will lead to wind curtailment

Figure 21. Avoidance of intermittent energy curtailment by optimised charging

Therefore, the application of controlled EV charging can save significant amount of intermittent energy across the entire year. For the GB equivalent system with 30% wind penetration, the potential amount of wind energy curtailed was evaluated as given in Figure 22 for zero to 100% EV penetration in the system corresponding to the three charging strategies. It can be seen that initially with increase in EV penetration some reduction in the wind curtailment takes place for the uncontrolled EV charging. However, no further reduction is observed beyond 50% in EV penetration.

Under controlled EV charging a substantial decrease in wind curtailment was found. The gains due to bidirectional charging were significantly more than the unidirectional while they tend to converge with increase in EV penetration in the system. In case of unidirectional controlled charging one third of the curtailed wind energy was saved while the saving was two third for the bidirectional controlled charging at 10% EV penetration.

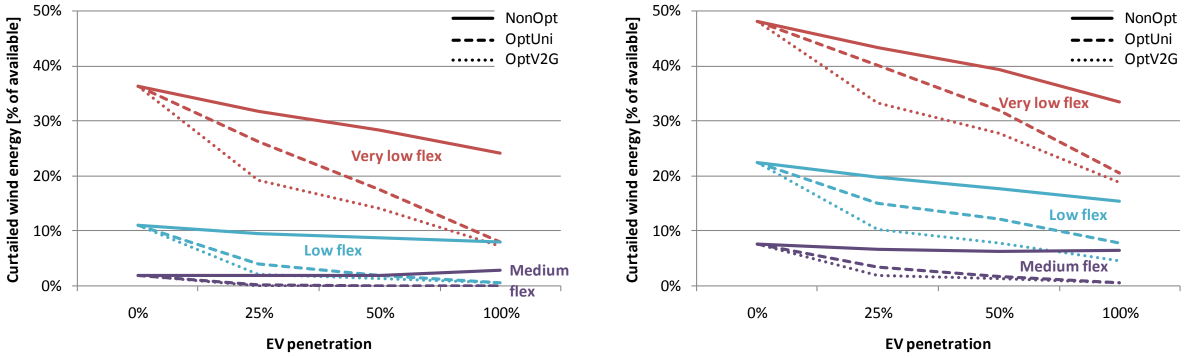


Energy curtailed (TWh)

Energy curtailed (% of available)

Figure 22. Impact of charging scheme on intermittent (wind) energy curtailment (Wind penetration – 30%)

The magnitude of wind energy curtailment and its avoidance by applying controlled charging strategies is also a function of the inherent (generation) flexibility of the system and the level of wind energy penetration in the system. Sensitivity studies were performed for systems with varying flexibility and for different shares of wind penetration for zero to 100% EV penetrations. Figure 23 illustrates that with increase in wind penetration the magnitude of wind energy curtailment increases.



Wind penetration = 20%

Wind penetration = 30%

Figure 23. Intermittent (wind) energy curtailment at two different wind penetrations in the system

A detailed impact of the flexibility of the system on wind energy curtailment for various levels of wind and EV penetrations under alternative charging strategies will be elaborated in Section 4.7.

A number of issues are associated with the curtailment of wind generation which include:

- De-loaded wind turbines can provide operating reserve which has a beneficial impact on production costs as reduced conventional reserve provision will be required.
- Reduced wind levels in the system may lead to reduced operating reserve requirements.
- Wastage of zero marginal cost energy directly increases the contribution from other generation, which could be avoided if this energy was absorbed by the system.

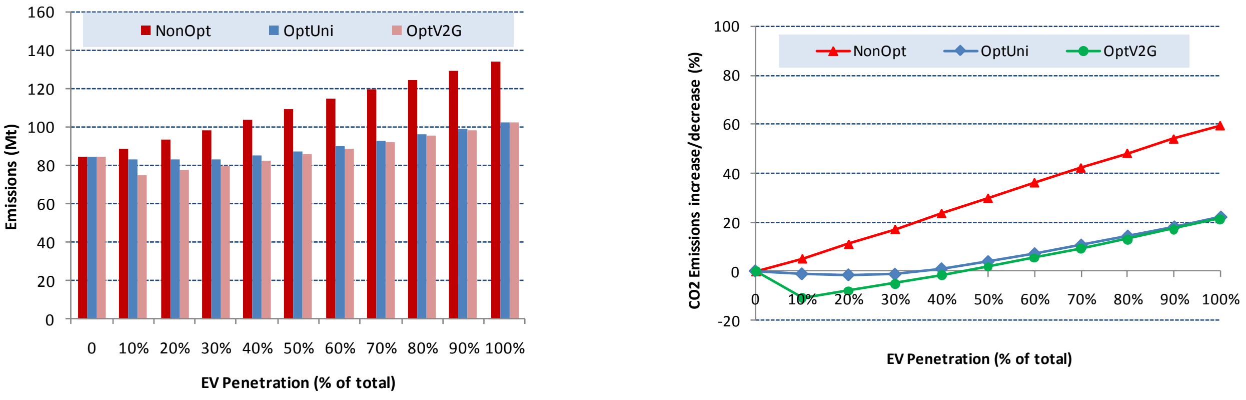
- Curtailment of wind energy will also requires the use of (expensive/peaking) fossil fuel plant to compensate the energy lost which is associated with increased production costs and emissions.

4.5 Environmental emissions

Transport sector is a major contributor to the environmental emissions resulting from energy system. For example; road based transport accounts for approximately 22% of the UK CO_2 emissions [DEFRA08], and therefore reducing the reliance on carbon based fuels in this sector is seen as a practical solution to reduce overall CO_2 emissions. EVs have the capability to deliver sustainable transport and lower CO_2 emissions. Inline with the objectives of this work we have conducted several studies to analyse the impact of various levels of EV penetration under alternative charging strategies on three types of emissions from the electricity system, namely CO_2, NO_x and CH_4.

In this section, we first focus on the impact of EVs on additional emissions from the electricity sector for different charging strategies, and then we proceed to put these additional emissions into perspective with emissions avoided by replacing the usage of fossil fuel in transport with electricity. This will provide a basis for an overall appraisal of EVs on emissions from the energy sector.

For the GB equivalent system the amount of overall CO_2 emissions from electricity generation at various levels of EV penetration is given in Figure 24a. It was found that overall CO_2 emissions in general for all charging strategies increase with the increase in EV penetration, however at lower EV levels (up to 40%) the CO_2 emissions have in fact reduced in the controlled charging cases. Figure 24b presents the CO_2 emissions from electricity generation as ‘percentage increase above no-EV level’. Here it can be seen that the CO_2 emissions for uncontrolled charging strategy linearly increase and approach to 60% additional emissions at 100% EV penetration. While, in case of controlled charging strategies the emissions initially reduce at 100% EV and reach to about 20% at 100% EV penetration.



a. Emissions (Mt)

b. Emissions increase/decrease (%)

Figure 24. Annual CO_2 emissions from the UK electricity system

The initial reduction in CO_2 emissions in case of controlled charging strategies e.g. about 2% and 10% reductions for unidirectional and bidirectional charging strategies respectively at 10% EV penetration, is due to a combination of two main factors; more utilisation of zero-carbon wind energy due to avoidance of wind energy curtailment in both of these cases and, increased utilisation of gas plant replacing coal (higher CO_2 emitter).

The results indicate significant savings in CO_2 emissions due to controlled charging of EV at various levels of EV penetration as given in Figure 25. The main reason for these emission savings is avoidance of wind energy curtailment and a shift in the generation mix where coal generation is replaced by less carbon intensive gas-based generation. This change in production mix is elaborated in Section 4.6.

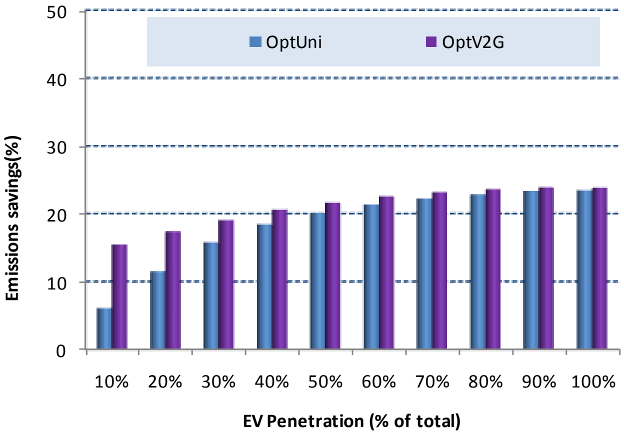
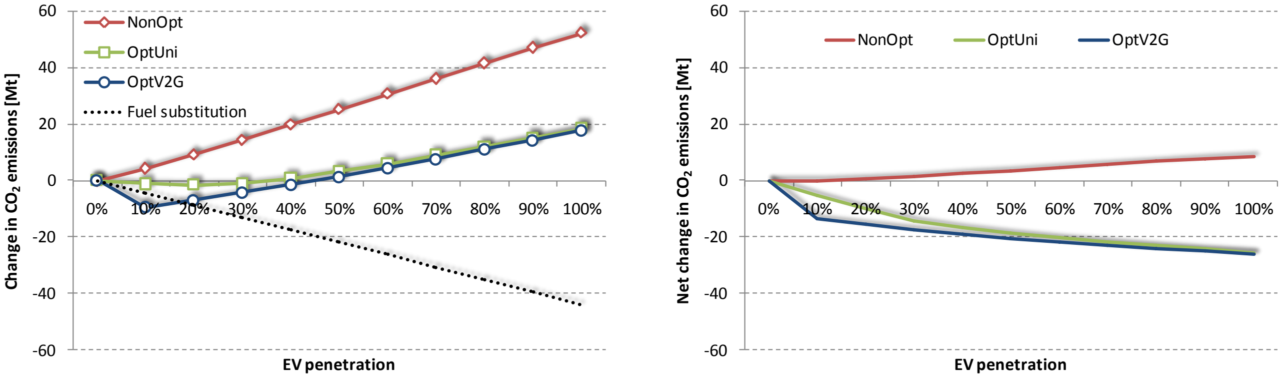


Figure 25. Savings in CO_2 emissions due to controlled EV charging

It is highly interesting to compare the changes in carbon emissions from electricity generation, which result from large-scale introduction of EVs into the system, with carbon emissions potentially avoided through substituting fossil fuels with electricity in the transport sector. To assess the emissions from vehicles powered by internal combustion engines (ICE), we assume the same annual national distance driven, and an average CO_2 emission factor for ICE-driven vehicles of 120 g/km.

Figure 26a compares the emission savings from the transport sector with absolute changes in the electricity sector emissions (for all three charging strategies), and Figure 26b provides the net change in carbon emissions, after offsetting for emissions avoided in the transport sector.



a. Gross emission impact (Mt)

b. Net change in emissions (Mt)

Figure 26. Comparison between the change in CO_2 emissions from the UK electricity system and the emissions avoided through substitution of fossil fuel in transport

Although the impact on emissions is likely to be system-specific, the above figures still allow for drawing a few general conclusions. The net impact of EVs on the emission in the overall energy sector will depend on the technology which is used to provide electricity for powering the transport demand that switched from fossil fuels to electric mobility. This technology will in turn depend on the implemented charging strategies, i.e. on the shape of the total national demand profile, obtained as the sum of the original system demand and the EV demand.

For the UK system in case of non-optimised charging, a large part of additional electricity required by EVs (which is likely to result in a very spiky total demand profile) is delivered by coal-fired generation, as it is the most expensive technology according to our assumptions for the UK system, and is therefore used to supply electricity during peak hours. Coal is a highly carbon-intensive technology, which results in additional emissions due to EV charging slightly outweighing the benefits of reduced emissions due to replacing fossil fuels in transport. For that reason, the overall emissions in this particular case rise with increasing EV penetration. On the other hand, when optimised charging strategies are employed, charging energy requirements are more evenly spread throughout the day, enabling that the majority of this additional demand is met by (in this case) cheaper gas-fired units, which are also much less carbon-intensive than coal. Also, a part of this energy is acquired by avoiding the curtailment of wind energy. The corresponding emission increases in the electricity system are therefore considerably lower (or even negative) compared to avoided transport emissions, which results in an overall environmental benefit i.e. reduced carbon emissions for the whole energy system.

This allows us to conclude that the overall emissions-related impact of shifting transport energy demand from fossil fuels towards electricity will greatly depend on the technology (or the mix of technologies) which is used to provide the additional electricity required by EVs. If we combine the average emissions from traditional ICE cars in the amount of 120 g/km, an assumed EV electricity consumption of 0.15 kWh/km, and an estimated efficiency of charging of 85%, it turns out that the borderline emission factor for electricity generation which will have a zero impact on the overall emissions from road transport is 680 g/kWh. This value is exactly between the typical emission factors for gas-fired CCGT units (around 400 g/kWh) and coal units (900-1000 g/kWh), and that is why if coal provides most of EV electricity requirements, the net impact on emissions will be positive, as opposed to when this additional electricity is provided by gas units. Certainly, in a system where additional electricity is provided by an even lower-emission or zero-emission technologies (such as hydro or nuclear), the net emission benefits would be even more significant.

Another indirect consequence of introducing transport-related energy demand into EU's electricity systems is that the transport energy would be captured by facilities covered by the EU Emission Trading Scheme[9]. At its current state, vehicles as carbon emitters are very difficult to monitor and control due to their large number and a high level of geographic dispersion. Its introduction into the ETS would greatly increase the scope of the scheme and its ability to influence the overall emissions from the energy sector.

The model developed for this analysis has also been capable of evaluating the emissions of other greenhouse gases, namely methane (CH_4) and nitrous oxide (N_2O). They have been estimated based on the output of thermal generators using fossil fuels, supported by emission factors from

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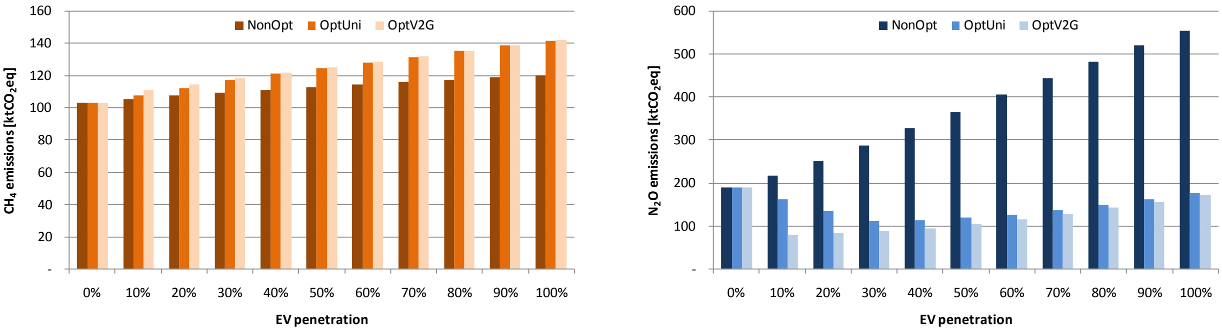
[9] The European Union Emissions Trading Scheme (EU ETS) is the largest multi-national emissions trading scheme in the world, launched in 2005. It currently covers more than 10,000 installations in the energy and industrial sectors. Under the scheme, large emitters of carbon dioxide within the EU must monitor and annually report their CO_2 emissions, and they are obliged every year to return an amount of emission allowances to the government that is equivalent to their CO_2 emissions in that year.

[IPCC11] and [DEFRA10]. The magnitudes of emissions of the two GHGs are presented in Figure 27 for a range of EV penetration levels and different charging strategies. The values provided are expressed as CO_2 equivalents applying the Global Warming Potential (GWP) values for the two gases.

Trends that can be observed for the two gases are mainly influenced by the contribution of two major thermal technologies – coal and gas. Gas-fired generators have higher CH_4 emission factors; on the other hand they are slightly less expensive than coal (after including the opportunity cost of carbon emission), which causes the output from gas units to increase when more efficient EV charging strategies are employed (uni- and bidirectional optimisation). For that reason, CH_4 emissions increase faster in optimised charging cases than with non-optimised EV load. Situation is quite the opposite with N_2O emissions, where coal-fired units are by far the largest emitters. This explains why when coal output is replaced with gas to increase efficiency in optimised charging cases, N_2O emissions decrease significantly compared to the non-optimised case.

Comparison with CO_2 emissions reveals that CH_4 and N_2O are not major contributors to aggregate GHG emissions. Their magnitude is some 2 to 3 orders of magnitude lower (expressed in CO_2 equivalent terms) than the emissions of CO_2 itself.



CH_4 emissions

N_2O emissions

Figure 27. Annual CH_4 and N_2O emissions for UK system (expressed as CO_2 equivalent)

It has to be noted that fuel costs, and hence merit order of different plants in the generation mix along with the CO_2 cost, would directly affect the comparative level of CO_2 emissions. The emissions evaluated are system-dependent and may vary significantly for generation systems with different capacity mixes.

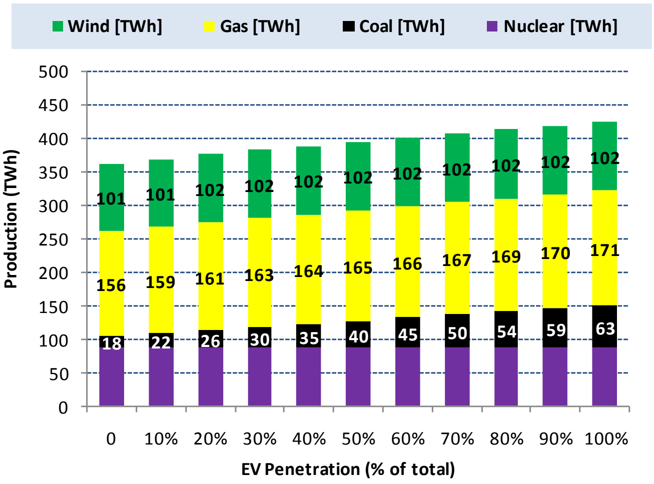
In a system where high-emitting generators operate as base-load units, cost-optimised charging of EVs might replace some of the low-carbon peaking generation with more carbon-intensive base-load generators, thus resulting in increased CO_2 emissions as the result of cost-optimal EV charging. For instance, in German electricity system (which is not analysed in detail in this report), base-load electricity is (among other technologies) provided by lignite-fired plants, as they are relatively cheap to operate (even after accounting for the opportunity cost of CO_2 emissions). In such a system it may be possible that charging EV batteries to reduce the overall system operation cost might result in increased carbon emission, despite the fact that the cost of CO_2 emission has been calculated into the operation cost in this analysis.

4.6 *Impact on generation mix and operational costs*

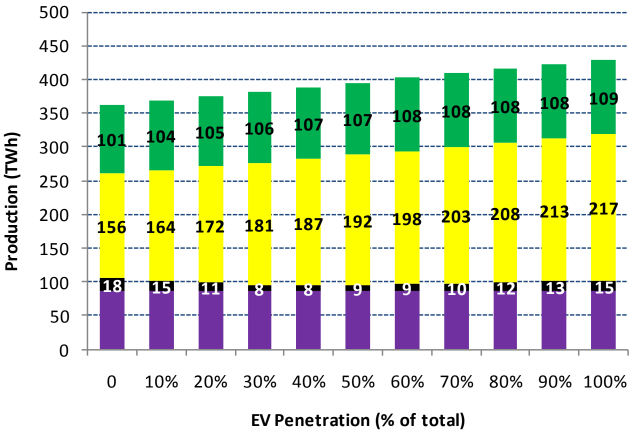
Increased penetration of EV in the system and the type of charging strategy applied, affects the production mix of the system i.e., it changes the utilisation of the different conventional technologies in the system. An uncontrolled charging strategy allows charging of the vehicles at times which coincides the EV load with rest of the system demand. During such a situation more peaking plants would be employed and their utilisation will increase. In the GB equivalent system analysed here, the coal plants serve would the peak demand due to their high marginal costs (as CO_2 costs augment the fuel costs). Therefore, in case of uncontrolled EV charging the utilisation of coal was observed to increase to meet the additional load foe EV charging as shown in Figure 28a.

The controlled EV charging, on the other hand, shifts the EV load to off-peak periods where less expensive plants (base load gas plants) are available. This leads to an increased utilisation of gas plants in the system. Furthermore, controlled charging in both modes i.e. unidirectional as well as bidirectional, significantly reduces the wind energy curtailment. This additional availing of wind energy also serves the demand that was earlier met by coal generation. The double effects the utilisation of coal plant and significantly increases the production from gas plant Figure 28 b and c. The production from nuclear generation remains unaffected with increase in the penetration of EV, being the least marginal cost base load plant.

a: Uncontrolled EV charging



b: Controlled (unidirectional) EV charging



c: Controlled (bidirectional) EV charging

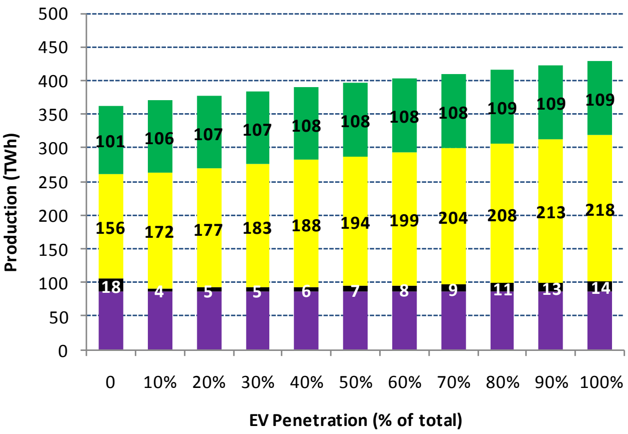


Figure 28. Impact of charging schemes on generation dispatch for the UK system

In case of bidirectional controlled charging a further reduction in the production from peaking plant is observed as some of peak load is being served by the EV discharge process when in V2G mode.

It has to be noted at this point that the impact of EV charging strategies on generation dispatch according to the above results is specific for the UK system that was analysed. The impact in other systems would depend on technical and cost characteristics of generators in that system. If for instance, there is a system where coal generators have lower marginal generation cost than CCGT units (opposite to the assumptions in the UK case study), it is likely that cost-optimal EV charging would replace the output of gas plants with that of coal-fired units, resulting in a different effect than what is observed in the UK case.

Changes in the production mix due to control of EV charging process affect the systems overall production costs. The additional (annual) operational costs attributed to various levels of EV penetration in the system under the three charging strategies are displayed in Figure 29. These costs are presented in terms of percentage cost increase (or decrease) above the costs when no EV was present in the system. In general the operational costs of the system would rise with increase in EV penetration. However, the rate and magnitude of cost increase significantly varies between the controlled and uncontrolled charging cases.

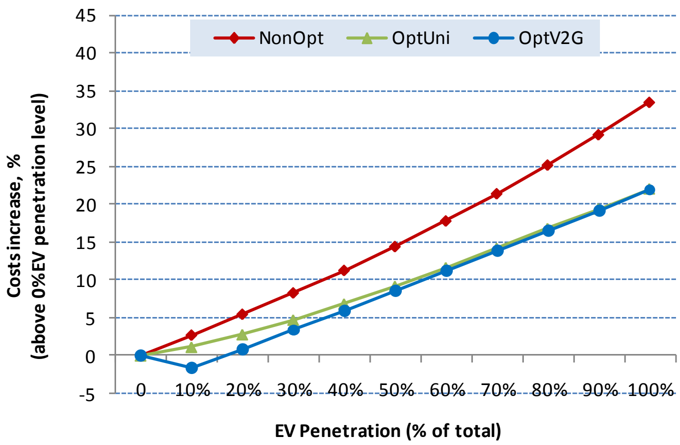


Figure 29. Changes in system operational costs (annual)

A small reduction in the overall annual operational costs can be observed at low penetration of EV (e.g. in 10% EV case). This is due to enhanced absorption of zero marginal cost wind energy that substitutes the generation from expensive plant. However, at higher EV penetrations no significant gain is found by bidirectional controlled charging strategy compared to unidirectional charging.

Various studies presented here indicate that significant cost savings can be made if EV charging is managed as shown in Figure 30. The magnitude of these production cost savings is more significant at very high penetrations of EV in the system.

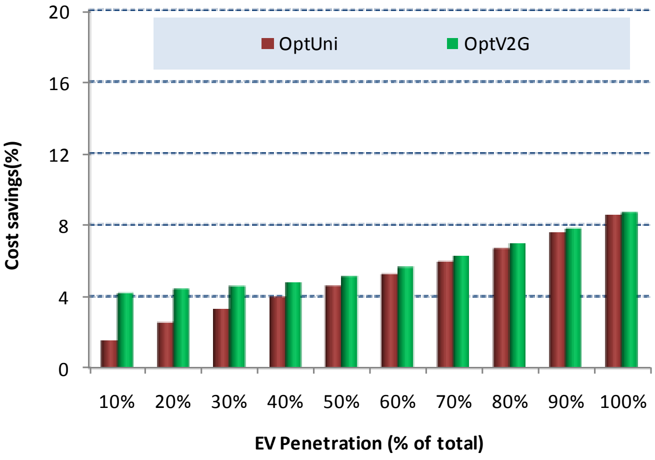


Figure 30. Operational cost savings due to controlled charging of EV (compared to uncontrolled EV charging)

The operating cost savings were found to significantly increase at high penetration of wind generation in the system. It is also visible that the benefit of V2G over unidirectional charging is significantly more at lower penetration of wind generation in the system and the difference tends to diminish at high EV penetrations. This is on account of relatively greater avoidance of curtailment of wind generation and secondly by injecting power into the grid during peak demand periods to displace some of the expensive generators. The influence of both of these factors reduces at higher EV penetrations. The cost savings due to controlled charging of EV are mainly attributed to:

- Avoidance of wind energy curtailment leading to reduced usage of expensive generators
- Enhanced use of less-expensive (lower fuel cost) base load plants
- Reduced provision of response by generators resulting in lower efficiency losses, fewer number of generators engaged, reduced start-up costs
- Reduced emission costs (system-dependent)

4.7 Impact of system flexibility

Flexibility of a generation plant is defined by its dynamic parameters i.e. minimum stable generation level (MSG), ramp rates, minimum up/down time, and associated cost characteristics which include start-up costs and part load efficiency losses. Combination of these flexibility characteristics of a generation plant will define the magnitude of flexibility that is available and the cost at which this would be available. The overall flexibility available in a system will depend upon the relative share of the different technologies present in the generation portfolio.

Different types of generation plant exhibit different levels of plant flexibility. Conventional nuclear plant are regarded as inflexible plant types due to their high MSG levels, very large up/down times and slow ramping characteristics. It is to be noted that flexibility is not only a question of the technical features of a technology but also related to the cost implications while serving as a flexible plant. For example, modern nuclear power plants are technically capable to offer flexibility; however, being low marginal cost, these are not ideally suited to be run part-loaded.

The flexibility characteristics of the incumbent system affect; the ability of the system to accommodate intermittent (wind) generation, environmental emissions, as well as the additional operational costs attributed to EV integration. Therefore, we have examined three different levels of systems flexibility to comprehend the influence of system flexibility on operational costs, wind curtailment and CO_2 emissions. As mentioned earlier in Section 3.3, three scenarios for generation system flexibility were investigated ranging from very low to medium level of flexibility as depicted in Figure 10. These scenarios differ in terms of the share of inflexible nuclear capacity in the system[10].

The variation in the amount of wind energy curtailment at various levels of EV penetration corresponding to systems having different overall level of flexibility was evaluated as presented in Table 8. Clearly low and very low flexible systems exhibit high levels of wind energy curtailment under all types of charging strategies. However, the magnitude of this curtailment is significantly avoided, for all penetrations of EV, if controlled (either unidirectional or bidirectional) management of the EV charging process is carried out. The magnitude of wind curtailment in medium flexibility systems is relatively low and this is further well reduced by controlled management. A general trend for all flexibility systems is a marked reduction in the amount of wind curtailment with increased penetration of EV, in particular for controlled charging strategies.

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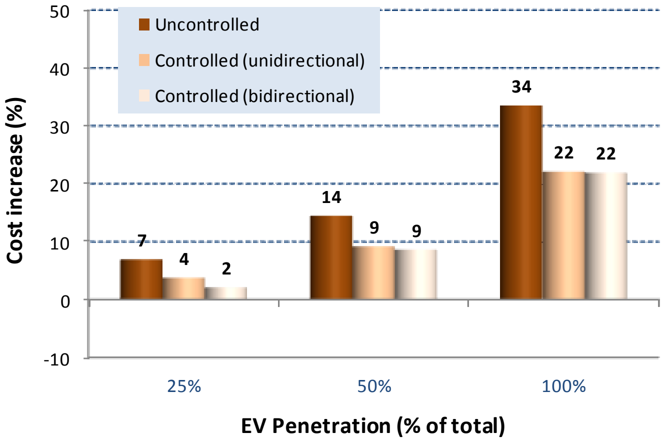
[10] For the purpose of flexibility impact analysis we have assumed nuclear plant as inflexible plant i.e. not performing any operating reserve provision duties.

Table 8: Amount of wind energy curtailed (% of available) in different flexibility systems

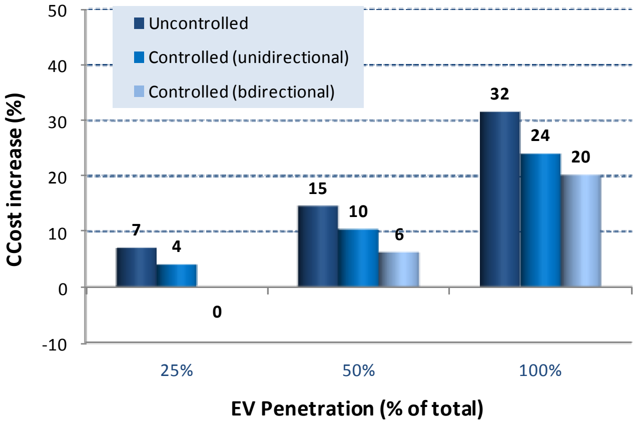
System Flexibility >>	Medium			Low			Very Low		
EV Penetration (%) >>	25	50	100	25	50	100	25	50	100
Uncontrolled charging	7	6	6	20	18	15	43	39	34
Controlled unidirectional charging	3	2	1	15	12	8	40	32	20
Controlled bidirectional charging	2	1	0	10	8	5	33	28	19

The impact of system flexibility on additional operational costs of the system (due to EV charging) was also evaluated for different charging strategies. The corresponding increase or decrease in the operational costs of the system is presented in Figure 31. The additional system costs for any given level of penetration decrease with the decrease in the flexibility of the system. This was mainly due to the capacity mix of the system as the additional EV load is served by less expensive (nuclear) plants in lower flexibility systems compared to higher flexibility systems where this additional load is served by more expensive coal plants.

a. Medium flexibility system



b. Low flexibility system



c. Very low flexibility system

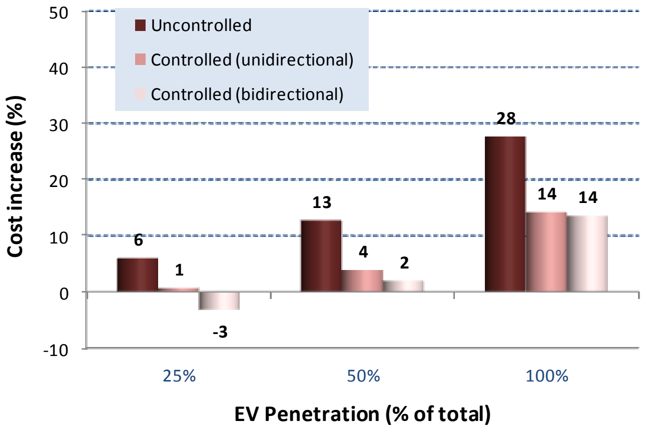


Figure 31. Additional production costs for various levels of EV penetration under different flexibility levels of the system

It can also be clearly seen that the advantage of both of the controlled charging schemes is significant for all systems. However, the relative gain due to controlled management of the charging process is more pronounced in lower flexibility systems. Furthermore, the cost reductions due to bidirectional (V2G) charging remain higher than the unidirectional controlled. Also this difference is more significant at lower EV penetrations in low and very low flexibility systems.

A comparison of the evaluated annual operational costs of the system was made for the three systems having different flexibility and the savings due to both of the controlled charging strategies compared to uncontrolled case was computed. These savings are provided in Table 9 for different levels of EV penetration in each system demonstrating that considerable savings are achievable if EV charging is controlled. For unidirectional control, the savings range from 3-11% corresponding to 25% EV in medium flexibility system to 100% penetration in very low flexibility systems and, 5-12% for the bidirectional controlled charging.

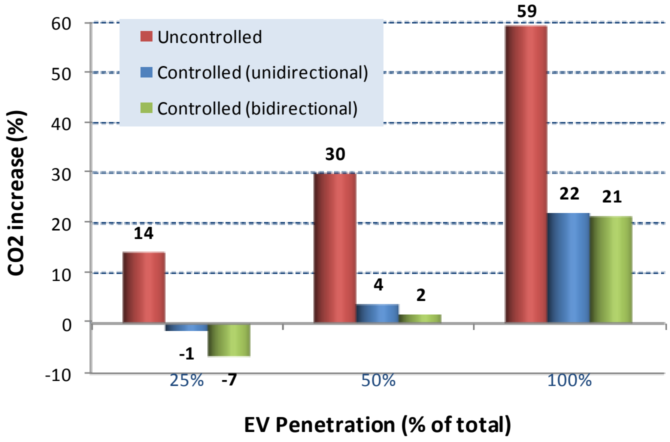
Table 9: Annual operational cost savings (%) due to controlled charging (in comparison to uncontrolled EV charging) for systems with different flexibility levels

System Flexibility >>	Medium			Low			Very Low		
EV Penetration (%) >>	**25**	**50**	**100**	**25**	**50**	**100**	**25**	**50**	**100**
Controlled unidirectional charging	2.9	4.6	8.6	2.8	3.6	5.7	5.1	7.8	10.6
Controlled bidirectional charging	4.6	5.4	9.5	7.0	7.5	9.1	9.1	10.4	12.3

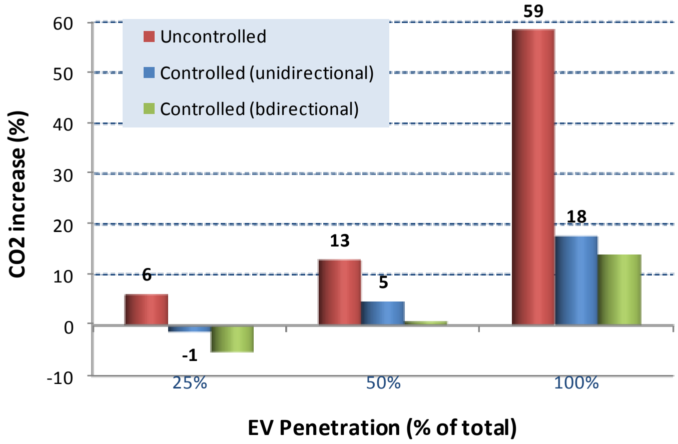
The relative gain due to controlled charging generally tends to increase as system flexibility reduces (with a slightly different trend when moving from medium to low flexibility systems in case of controlled unidirectional charging). This is mainly attributed to the additional degree of flexibility introduced by controlled charging, thus avoiding curtailment of zero marginal cost wind generation along with a higher utilisation of less expensive base-load plants.

As mentioned earlier environmental emissions from electricity production are linked to the combination of the various technologies in the system. The three different flexibility systems analysed differ widely in their capacity mix and comparing the absolute emissions among them is not a consistent choice, therefore, we have investigated the change in emissions that would result from various penetrations of EV in the system under alternative charging strategies as displayed in Figure 32. A common outcome in all systems was a high increase in the CO_2 emissions under uncontrolled charging strategy which were extensively reduced by adopting controlled charging strategies. Under uncontrolled charging strategy the largest increase in emissions would occur in the very low flexibility system due to use of peaking (most polluting coal) plant to serve the additional load due to EV charging.

a: Medium flexibility system



b: Low flexibility system



c: Very low flexibility system

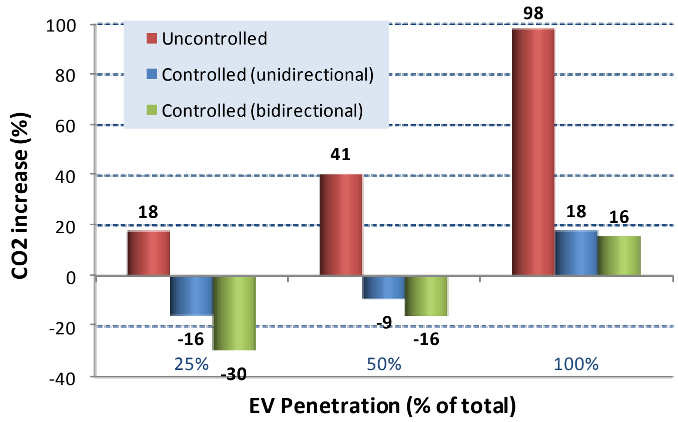


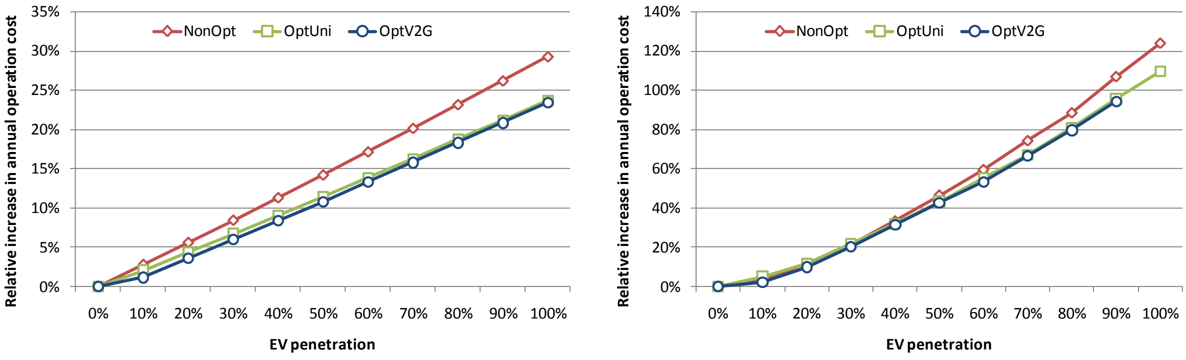
Figure 32. Change (%) in CO_2 emissions due to increase in EV penetration for systems with different flexibility characteristics

With controlled EV charging, at low EV penetrations i.e. up to 25%, the CO_2 emissions have been lower than the case when no EV was present in the system (please observe that CO_2 is negative at 25% under controlled charging in Figure 32, while in case of very low flexibility system this trend continues up to about 50% EV penetration.

4.8 *Impact of EV integration on other electricity systems*

In addition to the analysis of the impact of EV integration on the performance of the UK electricity system, further studies have been carried out to quantify this impact on two other European systems: Spain and Sweden. Input data for expected generation capacity and demand profiles for 2030 have already been discussed in Section 3. Each of the systems has its own specific features that will affect study results, as will be discussed in the following text.

We first look at how different EV charging strategies affect the annual system operation cost (mainly appearing in the form of thermal generator fuel cost). Changes in operation cost in the two systems, as compared to the case with no EVs, are presented in Figure 33. We can still observe a general trend of increasing operation costs as EV penetration grows, for any charging strategy. However, the rate and magnitude of cost increase can vary between the controlled and uncontrolled charging cases. Variations result from differences in cost parameters of generation portfolios.

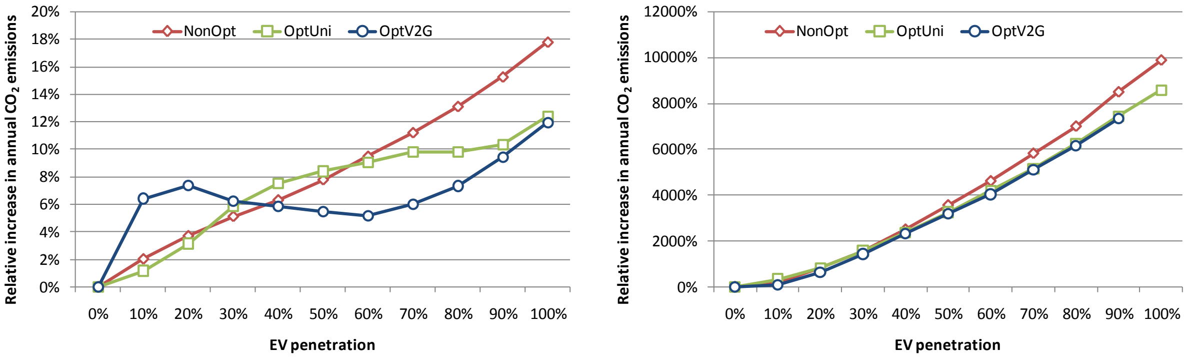


Spain Sweden

Figure 33. Changes in annual system operational costs for Spanish and Swedish systems

Cost performance charts suggest that in the Swedish case the operation cost increases more rapidly at higher EV penetrations in terms of relative growth than in the Spanish case. The explanation for this can be found in the composition of generation capacity used to simulate the operation of the two systems in 2030. Spanish system is still assumed to rely on a significant amount of coal and gas (i.e. fossil fuel) capacity, which incurs considerable fuel cost already in the no-EV case. Cost increases as a consequence of rising EV penetration are therefore in the order of several tens of percentage points. Swedish system on the other hand is assumed to be based on technologies with either zero marginal cost (such as hydro and wind), or very low marginal cost (nuclear energy), with some gas capacity (and to a lower extent oil) used as back-up. Its operating cost (i.e. fuel cost) is therefore very low in the no-EV case. However, as the total system demand grows due to additional electricity requirements from EV charging, this additional demand is mostly covered by thermal technologies with considerable marginal fuel cost. The relative increase in cost is therefore much more rapid than in the Spanish case. It has to be noted though that the absolute magnitudes of annual operation cost for the two systems differ greatly, again for the reasons explained above. For instance, in the no-EV case the operation cost of the Spanish system is $11bn while for the Swedish case this is only $0.12bn, although the projected annual electricity demand is about half that of Spain[11].

Annual carbon emissions resulting from electricity supply have also been evaluated for the two power systems. To illustrate the impact of EV penetration and charging strategies on changes in CO_2 emissions, relative increase in emissions above the no-EV case is shown in Figure 34.



Spain Sweden

Figure 34. Changes in annual carbon emissions for Spanish and Swedish systems[12]

Emission increase in the Swedish system reveals a similar pattern as the cost increase for the same system, albeit with significantly higher growth rates. Relative increases become very large for similar reasons as discussed for cost trends: baseline case (with no EVs) utilises almost exclusively zero-carbon technologies (hydro, wind and nuclear), which makes baseline emissions extremely small. Additional energy consumption caused by EV charging is then increasingly met by thermal generators (primarily gas), which results in massive increases in carbon emissions compared to the baseline case.

In the Spanish system, however, a different trend emerges. Although it might at first seem counterintuitive that optimised charging would increase carbon emissions higher than non-optimised charging, especially for lower EV penetrations, this is a consequence of the interaction between two major thermal technologies in the system: coal and gas. Coal is assumed to be marginally more expensive (after calculating in the opportunity cost of CO_2 emissions), but on the other hand gas units are assumed to have higher start-up costs. That is why for lower EV penetrations optimised charging is used to reduce the number of start-ups of gas units, and replace some of their output with coal units which are cheaper to switch on and off. This phenomenon diminishes with higher EV penetrations, where we observe that emissions in the optimised charging cases eventu-

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[11] The average (fuel) cost per unit of electricity supplied is 35.5 $/MWh for the Spanish system, and only 0.70 $/MWh for the Swedish. The low value in the Swedish case results from the majority of electricity being produced by either very low-cost generation (such as nuclear with an assumed fuel cost of only1.9 $/MWh), or zero-marginal cost technologies such as hydro or wind (fuel cost of other renewables with prioritised dispatch, such as biomass, has not been considered given that they are not subject to optimisation but rather assumed as fixed injection into the system).

[12] Specific CO_2 emissions in the baseline case (without EVs) also reveal a great difference between the assumed carbon footprint of Spanish and Swedish systems. The average emissions for Spain are 273 kg/MWh, while for Sweden this value is only 0.05 kg/MWh, due to virtually all electricity being produced by zero-emission technologies: nuclear, hydro, wind and other renewables.

ally fall below the ones for the non-optimised case. Unlike in the Swedish case with massive emission increases, Spanish emissions do not grow by more than 18% over the no-EV case even in the worst-case scenario in terms of EV charging.

To indicate the impact of EV charging on the ability of the system to integrate intermittent renewable output, in particular wind, Figure 35 shows how much of wind energy which is available annually would need to be curtailed to maintain the integrity of the system. As discussed earlier, it is a function of the flexibility of the system where wind generation is embedded, as well as the magnitude i.e. installed capacity and diversity of wind resources.

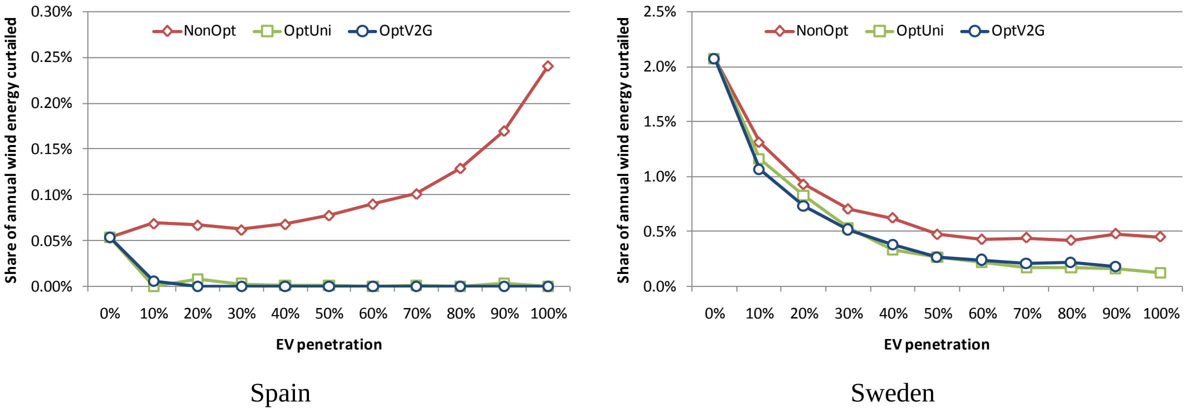

Figure 35. Wind curtailment as share of annual available wind energy for Spanish and Swedish systems

Wind curtailment in the Spanish case is rather small, and does not exceed 0.25% of annual wind output even in the worst-case scenario. This is a consequence of having considerable thermal capacity available in the system in the form of gas and coal units, which are flexible enough to modulate their output to follow variations in wind. Generators in the Swedish system on the other hand are not as flexible (given the large nuclear capacity), so the wind curtailment figures are an order of magnitude higher. In both cases optimised charging reduces the level of wind curtailment when measured against the no-EV case.

All of the results shown above – cost, emissions and wind curtailment – seem to suggest that there is only a limited benefit when moving from optimised unidirectional charging to bidirectional charging (V2G). There seems to be significant flexibility with respect to shifting EV charging load within the daily load diagram, even without considering the flow of electricity from EV batteries into the grid, so that most economic benefits can be achieved with unidirectional charging alone. It also needs to be noted that this analysis has not taken into account the aspects such as additional investment into ICT infrastructure to enable bidirectional charging, or battery life reduction occurring with more frequent charge/discharge cycles. These issues put additional constraints on the commercial case for the V2G concept, which need to be further explored.

4.9 Conclusions

The above considerations allow for drawing the following set of conclusions on the impact of EV charging on the operation and development of electricity systems.

Uncontrolled charging of EVs might have a significant impact on peak system demand; the total demand during peak periods may significantly rise for high penetrations of EV, due to synchronisation of EV demand and original system demand. This would require significant additional capacity of the system infrastructure (generation and networks) in order to maintain system security at an appropriate level. The increase in capacity requirements driven by higher peak demand could be disproportionately higher than the increase in energy requirements for EV charging.

EV charging strategies have a profound impact on the electricity supply mix and system operation costs. Controlled charging has the potential to reduce the cost of supplying additional EV demand due to:

- Lower usage of expensive (peaking) generators and higher usage of less expensive (base load) generators
- Avoidance of wind energy curtailment due to greater ability of the system to absorb intermittent generation. This leads to reduced usage of thermal generators.
- Reduced emissions and associated costs
- Reduced provision of response by thermal generators resulting in lower efficiency losses, fewer synchronised generators, and reduced start-up costs.

EV charging strategy (controlled or non-controlled) will have a considerable impact on economic and environmental performance of electricity systems. However, the exact extent of this impact is highly dependent on the characteristics of the incumbent system such as: generation technology mix, generator flexibility, fuel costs etc.

Controlled charging of EVs in systems which incorporate both inflexible conventional generation and an intermittent renewable resource such as wind may result in significant environmental benefits due to avoided curtailment of wind energy, which can be used to supply a part the additional electricity demand due to EV.

Economic and environmental gains due to bidirectional (V2G) control of EV charging/discharging process compared to a controlled unidirectional charging are found to be relatively marginal in electricity systems that have been studied. On the other hand, requirements on metering, control and communication infrastructure are likely to imply additional cost in case bidirectional energy flows are allowed. Further in-depth analysis is recommended that will involve all relevant factors (ICT requirements, impact of discharging on battery life etc.).

5 Regulatory Analysis for Efficient Integration of EV

Successful integration of large penetration of electric vehicles requires the establishment of a clear regulatory framework, appropriate market structures and complementary policy measures to support the efficient deployment of EVs. This will also be necessary to facilitate technological innovation and their applications with regard to both; vehicles and the electricity grid. Transparency of the regulatory regime will also ensure the market confidence of relevant stakeholders to avail the suite of opportunities brought by the transformation of the transport and electricity systems due to electric vehicles. The main opportunities include:

- Development of a new electrical demand base offering:
    - Significant carbon (emissions) savings potential,
    - Primary energy security-of-supply benefits
- Development (and/or management) of a large demand base with significant potential to support integration of intermittent renewables
- Availability of distributed demand, energy storage, ancillary services resource capable to offer a variety of non-network solutions (NNSs), including provision of distribution system balancing service
- Possibility to develop new businesses opportunities

Various work packages within the G4V project found that a large-scale roll-out of EVs also poses several challenges to the development and operation of future electricity systems.

Technical challenges

- Changes in conventional load patterns affecting:
    - Supply and demand balancing, and
    - Risk of localised loadings on distribution networks,
- Provision of adequate charging infrastructure and mitigating the distinct impacts of each type of charging infrastructure,
- Economic development and operation of future power system infrastructure,
- Development (or application) of modern technologies (hardware/software) for implementation of new business models, metering mechanisms, payment schemes etc.,
- Development of technical, security as well as health and safety standards for new equipment and procedures.

Market/regulatory challenges

- Derivation of tariff setting mechanisms, transparent payment as well as metering mechanisms,
- Development of new value chains and business models in mainly unbundled markets,
- Efficient operation of historically unconnected markets (auto industry/utilities/mobility providers),

- Definition of contracts among interlinked market players and settlement procedures,
- Security, control and access of a large volume of data,
- Transparency of (investment) cost allocation and recovery mechanisms (revenue flows),
- Appraisal of appropriate incentives/subsidies for large scale deployment of EV and an assessment of their magnitude, implementation area and the time to incorporate,
- Development of clarity and transparency on future tax regimes including potential of shift of taxes from conventional transport fuels to electricity.

In order to overcome the challenges outlined above, the work presented in this chapter focuses on formulating policy and regulatory recommendations in order to support the efficient system integration of electro-mobility in Europe. We have identified the following key areas within the scope of this work where conducive policy measures and regulatory regimes would be necessary:

- Provision and operation of charging infrastructure
- Development and operation of distribution grid
- Provision of ancillary services by electric vehicles
- Applications of information and communication technologies

In the subsequent sections we analyse the necessary requirements for cost-effective and secure operation of future electricity systems when integrated with large penetrations of electric vehicles.

5.1 Charging infrastructure and regulation needs

One of the key requirements in the wide spread implementation of electro mobility is the provision of charging infrastructure (CIS). The development of charging infrastructure will need to keep pace with the developing market to ensure consumer confidence in the ability to recharge their vehicles with minimal inconvenience. Generally three types of EV charging infrastructure can be distinguished:

- ***Private charging infrastructure*** (wall-boxes in private homes or in company garages)
  i.e. load points where the circle of users is limited
- ***Semi-public charging infrastructure*** (wall boxes/charging points in public garages, in front of super markets etc.)
  i.e. load points that have a more open circle of users albeit the exclusion of (single) users is possible for instance by economic means (e.g. parking fees)
- ***Public charging infrastructure*** (charging points on the curb of the street)
  i.e. load infrastructure that (in the absence of further assumptions) addresses any possible user

Providing the future EV customers with adequate CIS has technical, judicial and economic questions attached to it. Inter alia it is necessary to define what is “sufficient” in all market phases and for all prospective customers (amounts of CIS, technology etc.). In most markets at least the question of the necessary amount of CIS in the shorter term is answered by more or less complicated economic modelling (cf. the reports by the German National Electric Mobility Platform, NPE).

First experiences from some of EU member states show that the involvement of local public authorities might play a significant role in the deployment of CIS and PCIS. Municipalities control public space within their city limits/jurisdiction; they grant usage permissions for parking spaces (through whatever mechanism); they have traffic concepts of their own design for their downtown areas often involving a privilege for public transport etc. Here depending on national rules large bodies of public law are “touched” by electro mobility concepts in general and especially by the deployment of CIS in public spaces. The discussion on these national rules is beyond the scope of this analysis, however, it is suggested that these should nevertheless be kept in mind when designing an EU-wide or national strategy for the roll-out of electric mobility-related CIS. Provision of PCIS is emerging as a more complex problem due to their economics as well as due to more regulatory interventions for their roll-out. Therefore, PCIS are discussed in greater detail here in the following sections.

5.1.1 Need and provision of PCIS

There is a certain consensus that in the future a majority of customers will find it necessary from time to time to use public charging infrastructure (PCIS) to be able to charge their vehicles when away from their homes or during long journeys. The necessity to use PCIS will also be determined by the availability of alternative semi-public and private charging infrastructures to the customer.

Figure 36 shows different ways of providing PCIS as imagined today and/or observed in certain EU member states. The charging infrastructure could be operated by the network itself as assumed in Model 1 which leaves the retail/supply activity open to competition. Under this model the regulation of PCIS would probably be borne from the fact that the owner of the PCIS – the DSO – is a regulated entity today. Also this model at least implicitly makes the assumption that if different entities should be able to use single charging points, market process like for instances “change of supplier” would have to be followed whenever a new car uses the PCIS.

Alternatively all three parts of the value chain could operate independently from one another as in Model 2. However, this model does not imply that the provision of charging stations is a regulated activity or not.

Finally the provision of the PCIS could be merged with the retail business as in Model 3. Then the need for regulation as well as its possibility would be a rather open question as there is a certain consensus in the EU that retail is generally a business where competition is possible and should be upheld in the interest of the consumers.

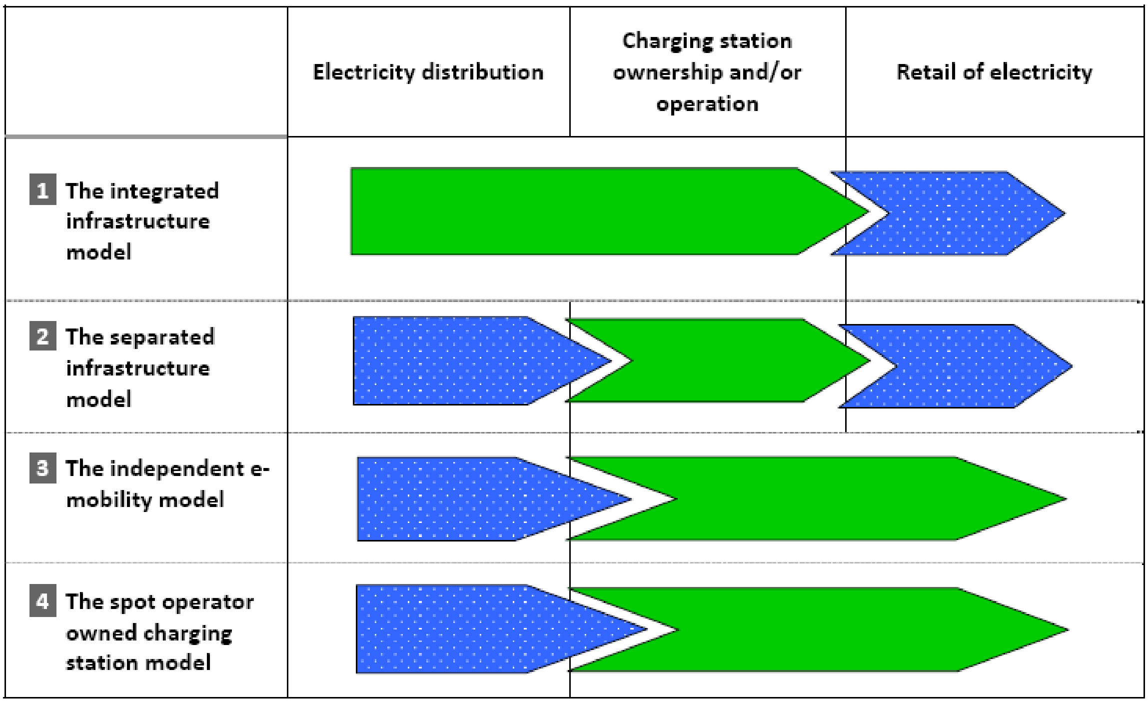

Figure 36. Alternative models for provision of Public Charging Infrastructure (PCIS)

(Source: Market Models for the Roll-Out of Electric Vehicle Public Charging Infrastructure, An EURELECTRIC Concept Paper, September 2010, p. 5)

The market models presented above constitute different business models and opportunities for different types of actors. But these models were not designed to answer the question whether any form of regulation was necessary. On the contrary: a regulated environment results rather automatically from organising the PCIS within the DSO. Here we will take a somewhat different approach and try to analyze the general necessity of regulation of PCIS i.e. at least implicitly we will focus on Models 2 and 3 and try to analyse a hypothetical competitive environment.

Furthermore we make the general assumption that the PCIS in question is an AC charging point with a maximum load of 22 kW or less. Whenever other technologies are considered they are explicitly named.

5.1.2 Business case for PCIS

With respect to the PCIS the relevant market might be relatively small areas when one considers a consumer that needs to charge her car immediately because its battery is almost empty. But considering the medium daily driving range per consumer and the size of the batteries such a distressed situation should be the exception and not the normal case. On the contrary one should expect that by and large consumers can;

a) Decide whether they want to charge now or later *and therefore*

b) Decide whether they want to charge at a certain point or at a different place.

It is improbable that a company supplying any area with PCIS can "ignore" the alternatives CIS that are available to most of her customers when setting the price for the PCIS i.e. for the electricity provided from the PCIS. Especially if one imagines a situation with more than one company providing PCIS in an competitive environment, a commonly used "Small but Significant and Non-transitory Increase in Price" (SSNIP) test would probably fail as large groups of consumers would seek and find alternative means of charging (in front of all other PCIS and semi-PCIS) when any company would raise its price in order to improve her earnings.[13] This would only worsen the economic performance of the PCIS on which the price was raised.

Therefore all different types of infrastructure should be recognised as constituting alternatives for the majority of users i.e. even somebody who has to park on the street at night may still charge at a semi-public point or at work regularly; thus limiting:

a) The overall usage of the PCIS, and
b) The market power of a hypothetical firm controlling a large part of only public load points due to the competition between different types of load infrastructure.

PCIS are therefore important, but they may play a rather limited role in supplying bulk of customers i.e. they may remain a "safety/back-up" especially at the early stages of the market. It is hard to imagine that PCIS would attract significant amounts of usage (i.e. distribute significant amounts of kWh) at low-medium penetrations of EV. There probably exists an economic problem (i.e. the cost gap) in roll-out of PCIS. However, this is not a "market failure" in the economic sense but rather a working market where firms do not enter a market where the probability of making losses is rather high. In effect the market power of companies supplying PCIS is rather limited due to competition from other sources of AC charging, reservation prices as recognised by consumers etc.[14]

As G4V generally focuses on a rather long-term market for electro-mobility, it should also be considered that fast charging (>22 kW, DC etc.) will probably play a significant role especially in populated areas and cities i.e. in charging concepts that look more like today's gas stations and less like the single CIS on the curb of the street as built today. A large deployment of faster CIS and/or PCIS would at least constitute another upper barrier on the prices one can charge at AC and 22 kW or at least worsen the capacity utilisation of the PCIS so far that they may not be able to operate economically even if infrastructure costs decrease and / or the number of cars and load cycles rises. It might also be easier to earn back the higher cost of the DC infrastructure as the speed of loading will probably lead to a higher maximum of chargeable cars per day and the speed will probably be considered a value added by the consumers.

Given the reasoning above, for adequate roll-out of PCIS it may need to be supported by other activities in the overall market for electro mobility or by public subsidies/support schemes, in particular at initial stages when penetration of EV is low.

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[13] There is a central assumption to this conjecture: electricity supply companies are unable to discriminate electricity delivered to cars with respect to prices at least if these cars can be charged at home.

[14] If of course a monopoly on the market for PCIS is not caused by a tendency towards a natural monopoly but by granting an exclusive operation right, the question of public control comes back into play. Also when cross-selling activities come into play the competition intensity e.g. in the retail market becomes important.

5.1.3 Policy and Regulatory Recommendations for charging infrastructure

In the light of above discussion and with relevant stakeholders we propose following policy and regulatory recommendation regarding CIS for Electric Vehicles:

- Emerging policies regarding electro mobility need to bring clarity on the responsibility for the development, ownership and operation of (public) charging infrastructure.
- Roll-out of public charging infrastructures may not be a profitable business case at initial stage of EV penetration in the system; however, it would be a prerequisite for large scale EV deployment. Therefore, public incentives or subsidies will potentially be required for adequate provision of PCIS, in particular at initial stages when penetration of EV is low.
- The case for standardisation is critical as most of the EV users should be technically able to benefit from most of the CIS. Keeping in view the long and successful tradition of inter- and intra-industry standard setting, we recommend that industry along with (semi)-public bodies should take lead on an international level with respect to developing standards for sockets, plugs, technical description of batteries (or battery packs) , communication protocols etc. Also the standardisation should cover all types of charging infrastructure i.e. public, semi-public and private charging infrastructure.

  Where standardisation will enable better planning and operate of the distribution networks, it will must also ensure health and safety protection of all those involved such as; EV users and CIS operators. However, we recommend that standardisation of charging infrastructure (and/or battery-packs) should not hinder their technological innovation and help to enlarge markets.

  Furthermore right momentum of standardisation would also be important as hasty decisions may lead to inefficient selection of pre-mature standards.
- Special electricity tariffs, if applied, should not risk market failures for any particular type of charging infrastructure, as all; private, public and semi-public charging infrastructure are deemed necessary to ensure confidence of vehicle users in terms of their ability to charge vehicles when required .
- Non discriminatory access to network and ensuring fair competition among CIS developers and operators will also be crucial for required roll-out of CIS.
- Monopoly in the charging business may pose a barrier to the development of the charging infrastructure in the long term. However, at initial stages in order to kick-start the deployment of PCIS and to ensure a profitable business case for early investors (risk takers), allowing operation of single firms within certain areas could serve as a more pragmatic approach.
- Good range of products should be offered by suppliers or CIS operators to suit wider customer base.
- In order to ensure transparency in the energy measurements, charging procedures and corresponding payments there is a need to bring clarity and standardisation on the location of metering devices.

- Fast charging stations and their application as storage facilities to support integration of intermittent generation (PV, wind etc) should be based on economic assessment which requires further research in this area.
- In order to provide system support services, there is a necessity for the standardisation of EV as well as CIS such as being (at least) prepared to accommodate the “intelligent” infrastructure (possibly in an upgradable fashion) that is enabler of these services.

5.2 Impact on distribution system and regulatory requirements

A substantial introduction of electric vehicles (EVs) is expected to require challenging improvements in the regulation of the distribution network to take into account the specific requirements of future mobile customers.

Nowadays European electricity markets are moving toward a clear distinction between regulated activities (such as transmission and distribution) and activities accessible in open market (such as energy retail). Depending upon the chosen market model, charging infrastructure operation may be managed in two major ways:

- There can be several charging infrastructure operators offering their services in an open market, or
- Charging infrastructure operators can be a regulated player (the DSO or another one) giving access to its assets to a multitude of service providers, that offer the charging service to final customers.

The regulatory requirements related to the DSO highly depend on the business model applicable to charging infrastructure ownership. If the charging infrastructure is within the DSO’s jurisdiction, the regulators will have to define how to extend the DSO role as the owner of the infrastructure, while guaranteeing non discriminatory third party access to all market players.

In other models, however, the DSO performs the activities related to grid operation in order to support electro-mobility while, the regulators would have to provide the necessary support.

In any case, the regulators will take into account the unbundling between network and supply functions to avoid obstacles to the development of network planning and operation activities. Hence, the regulatory evolution should clearly define the roles and the interactions among actors such as DSOs, retailers, municipalities etc. In particular, following main issues shall be clarified:

- *Non discriminatory access*: the grid-related activities, performed as a regulated business, shall be accessible at the same conditions to all the electro-mobility players. For example, clear rules shall be defined to regulate the request of new connections to the grid for charging stations.
- *Shared investment to be evaluated*: the additional demand for energy due to EVs may require investments to reinforce the distribution grid. The level of investment will depend on the penetration of EVs, as well as on potentially implemented advanced charging strategies. However, even with small penetrations, some problems could be expected at local level in low voltage grids, where the additional (EV) load could impact those parts of the grid, which already approach their maximum capacity. An assessment of sharing such investments among the beneficiaries should be made, followed by defining rules to share the required investment between the DSO and the other market actors.

- In order to promote the development of EV, the costs related to the reinforcement and upgrade of grid infrastructures (compared to BAU) in order to accommodate large penetration of EV have to be included in the RAB (Regulated Assets Base) and adequately remunerated (e.g. using a regulated investment remuneration rate).

Considering the various impacts of large scale penetration of EV on the distribution grid we have identified following main regulatory issues and relevant policy and regulatory recommendations are proposed.

5.2.1 The “Right to the Plug”

It is foreseen that a large proportion of electric vehicle users will preferably charge their vehicle in private parking place, such as the private garage at their home or at the workplace15. This implies the availability of charging points at these premises, which should be deployed in the next decade under different installation conditions. In many cases, the provision of such devices will pose problems related to the possibility to obtain the required authorisation in order to perform the installation. A clear example of these issues is in the installation in a co-owned parking area (such as a condominium garage) where it could be necessary to obtain the authorisation from the other owners. The same issue also arises for all the grid related works performed by the DSO in order to connect the charging station to the grid. Such situations can be a great obstacle to the development of the private charging infrastructure.

Therefore, it is expected that, all over Europe, specific regulation regarding the “right to the plug” would need to clarify all the installation aspects applicable to both; the customer and the DSO.

At present different initiatives are undertaken by some member states. For example:

- Dedicated regulation in France, presented in October 2009 by France’s Minister Jean-Louis Borloo in the scope of a ‘14-point Plan to Accelerate Development of Electric Cars and Plug-in Hybrids’
- AEEG Proceeding ARG/elt 56/10: possibility to require a second private connection to the grid dedicated to charging infrastructure (e.g. private garage)
- Italian legislative proposal A.C. 3553: right for final customer to have access to charging infrastructure (e.g. in shared environment like a garage)

Although such individual initiatives are welcome, there is still need for a harmonised regulation at European level.

5.2.2 Tax-related issues

A diversity of taxation regimes currently exists in different countries across Europe. Electric mobility clients may require adaptation of such region-specific taxation mechanisms.

An example can be found in the Italian legislation: In Italy electric energy is taxed to final customers who have to pay two basic taxation components, the VAT and excises. While the first is to be paid at national fiscal borough, excises are to be paid to the local municipality where the energy

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[15] A survey conducted in G4V project across eight European countries to identify potential EV user’s trends clearly indicate strong interest to charge EV at private parking places (mostly at home).

is used. This scheme is of course not compatible with mobile customers, because energy can be used in a different municipality from the one where it has been taken.

Mechanisms like the above one can constitute a serious barrier to the development of electric mobility and especially to the possibility to enable roaming services. Policy makers shall identify such incompatibility situations and provide updates to actual fiscal rules in order to remove them.

Another potential issue is some loss of government revenues presently arising from taxation of conventional transport fuels. Their compensation through shifting of such taxes to electricity (when used for EVs) may affect the business case of market players. An in-time policy and regulatory clarity on such issues is deemed necessary for smooth and large roll-out of electro mobility.

5.2.3 Public charging stations

A specific attention should be dedicated to Public Charging Stations, i.e. those charging station located in a public environment (such as streets and public parking areas) and accessible to all customers. As discussed earlier this kind of infrastructure is vital for large scale development of electric mobility. From distribution grid perspective, policy makers are encouraged to promote public infrastructure through specific actions such as:

- Establish facilitated procedures to obtain the right to install charging stations in public spaces.
- Introduce facilitated procedures to obtain authorisations to perform works in public spaces, when required for the installation of a public infrastructure (for example construction/ground works needed to place cables).
- Development or investments in public charging stations may require incentives..

5.2.4 Enhanced metering operations

Electric vehicles will require an enhancement of the current procedures and technologies used to provide metering service. For electric mobility being a new business, it is strongly suggested that smart metering technologies should be adopted from the very beginning in order to allow advanced services.

One of the important future goals is the enabling of dynamic energy prices in order to involve clients in energy efficiency programs. For example, it is possible to offer clients a reduced price when there is high availability of energy in the system (at night or in case of surplus of renewable energy) or increase the price when there are congestions in the distribution grid. This will require sufficiently detailed metering data to demonstrate the clients’ participation in such energy efficiency programs.

Regulators shall identify the minimal requirements and regulate these new metering services and also define the remuneration of entity responsible for the metering activity. In particular, the following aspects shall be addressed:

- Defining the rules for involved parties regarding ownership and access to the metering data and the quality of service that the metering point operator shall ensure for each of them.

- Envisaging the possibility to collect very detailed metering data (such as the full load profile) in order to enable advanced control strategies. In this case it is also possible to have a mixed remuneration mechanism, where a basic and standardised service is available for free or at regulated prices for all data users (DSOs, TSOs, retailers, consumers etc), while advanced metering data can be provided at a cost.
- Ensuring that privacy of the clients is always guaranteed: this topic is particularly important because metering data for mobile customers contain more information about the user compared to standard ones. For example they contain the locations where the client has charged his/her vehicle.
- Another possibility, related to metering service, is separating the energy consumptions for mobility from other consumptions. This service implies the need to have a dedicated measuring device for each connection point used to charge EVs. Regulators shall define roles and responsibility for the specific metering service. This would allow to enable opportunities, such as:
    - Offering to clients dedicated tariffs for electric mobility,
    - Accounting the overall amount of energy used for mobility in order to evaluate the impact of shift of energy demand from transport to electricity sector and plan future electricity grid.

5.2.5 Role of distribution system operator in charging control strategies

In the scope of G4V, a number of control strategies have been proposed (see e.g. Deliverable 6.2) in order to utilise EVs energy storage and load increase/decrease ability to offer various services to the electrical system and to mitigate possible congestion in the distribution grid. A family of these strategies has been allocated in the Pragmatic World, where solutions could be achieved without a radical modification of actual technological conditions. The DSO plays a central role in these strategies (with the support of an aggregator or an existing actor performing the aggregation function), because it has the possibility to actively control EVs charging behaviour in order to avoid critical conditions of the grid (e.g. congestion issues). The DSO would have to constantly monitor the state of the grid and, in case of congestion, send signals to the charging stations (or the aggregator) connected to the grid in order to modify the behaviour of the EVs (typically reducing their load).

Although this can be achieved by means of various technical solutions already available to the DSOs, however, regulatory implications has to be taken into account because the DSO (or the aggregator) would be playing a demand dispatching role, imposing certain limitations to final (EV) consumers. Therefore, the regulators should define transparent rules that DSO will have to follow in order to decide which consumers should be approached for dynamic power reduction and the level of such interventions. Furthermore, the regulation in this domain should facilitate the good coordination between the DSO and TSO for efficient operation of the overall system

5.3 Provision of ancillary services by EV

The scope of this section is to discuss the appropriate regulatory and market conditions for provision of ancillary services by electric vehicles (EVs). Here it is assumed that the charging infrastructure and the required ICT arrangements are in place. Also there are a critical (threshold) number of vehicles on the road that is using various kinds of charging places, at home, publicly available and at work. We further assume that the build-out of charging access points is market driven and open to all actors. The main question is thus under what condition the EVs could be used for providing services for the grid and under what market condition. It has been shown in the various work streams within G4V project that EVs can support a more efficient use of the electricity system. The battery capacity (energy storage) in the vehicles offers the possibility to even out demand curves and optimise the usage of volatile electricity generation, e.g. wind power, and also feed back electricity to the grid when needed, providing ancillary services.

The term ancillary services are here used to describe the different markets for balancing or regulating power, i.e., primary, secondary and tertiary reserves used to maintain grid stability due to either stochastic demand or supply.

5.3.1 Ancillary services and relevant market and regulatory issues

On the European continent, the primary reserve that should be ready within 30 seconds is usually provided by large thermal power plants that run below full output in order to provide flexibility by ramping up and down. The secondary reserve should be ready between 15s and up until five minutes and is also often provided by thermal units and hydro power plants. The tertiary reserve starts replacing the secondary reserve after 15 minutes and covers a time span of up to one or a few hours. Since the tertiary reserve is the only manual controlled reserve it contains a much broader range of applicable technologies, e.g., gas turbines, emergency generators and industrial electricity consumers.

Reserve power is traded somewhat differently than ordinary whole-sale power and the market mechanisms are different on the different power markets in Europe. For example, both the Nordic and the German TSOs are responsible for providing grid stability but the trading arrangement with power generators differs across markets. Due to the varying regulatory frameworks in place on the different markets, the following describes ancillary services and EVs in a generic fashion.

On the regulating markets (also known as balancing markets) in Europe, regulating power has to be available 100% of the time it is offered. Thus, theoretically, an EV battery that offers a month of primary reserve must be able to supply energy at all times across the month. The probability of having to deliver positive regulating at every hour throughout the month is in practically very limited. But whether the EVs should fulfil the same requirements as large-scale power plants must be further analyzed since the requirement will be a key-parameter for creating a positive business case for EVs as an ancillary service provider. One option is of course to pool several EVs and use the aggregated capacity as one resource.

In reality, balancing power is often provided through pooling of several power sources. Pooling lessens the need for 100% availability of individual participants and also the storage capacity constraint. In addition, the minimum capacities to bid on the market are then easily fulfilled. Thus a pool does not have a stringent availability constraint since another plant can replace the EV batteries once empty.

Unlike power plants, batteries in EVs can deliver much more energy over short time periods than they are rated for, often by a factor of two to three. Since primary reserve capacity is delivered only very shortly, this has to be taken into account. The lifetime of a battery depends on the depths of the charge-discharge cycle (deeper cycles deplete a battery quicker). The size of this effect varies across battery technologies. An optimal investment and operation strategy has to take this into account and hence affects the profitability for utilising the EVs in regulation purposes. One key question is whether the value of such a service is enough to cover for control and communication equipment needed to make this function possible as well as the cost for business contract with the battery car/owner.

One important component in the remuneration scheme is a market that includes both energy and capacity payments. Since the EV cost for keeping the capacity is close to zero (except the opportunity cost), the capacity payments become profitable. This means that EVs can compete against traditional actors since EVs can make lower capacity bids. However, remuneration in the form of energy payments is perhaps not as straight forward. If EVs are used for regulation down purposes, hence simply charging the battery when it is optimal for the system, and are paid for that the deal is beneficial. Regulating up is however more costly. Not only because there is a degradation cost when the battery is discharged, but also the cost of the electricity already stored has to be taken into account. An energy payment could thus cover this cost and make EVs compete on equal terms with traditional market actors. Therefore, expected revenues of EV from providing regulation up are low.

In addition, on many markets regulation bids are provided symmetrical for both up and down and this will worsen the business case for EVs if asymmetrical bids are not allowed.

In contrast to stationary power plants, it is not possible to guarantee that all EVs used in regulation purposes are plugged in at a given time. Therefore, the optimal market time frame for the regulation markets must be found. The contract time for different reserve markets in the EU stretches from months to hours. For EVs, due to the stochastic driving behaviour, a shorter market time such as one hour to a few minutes could make a more optimal market time.

In connection to the optimal market time frame for EVs, the size of regulation bids is another critical component. The amount of capacity and energy the EVs can provide is limited by the connection capacity and battery size and technologies. This implies that small bid sizes would strengthen the possibility of using EVs as regulation capacity since a small number of EVs than could enter the regulation market.

In conclusion, the possibility of using EVs as ancillary service providers will in the end be judged by how cost-efficient EVs are in comparison to traditional service providers. Therefore, the market and regulatory frameworks will have to be designed to allow non-discriminatory access to the market, lowering bid-sizes and allowing for pooling are few conditions that needs to be fulfilled.

5.3.2 Recommendations regarding provision of ancillary services by EV

- Developing a pan-European approach towards provision of ancillary services by EV should incorporate the existing differences and individual system requirements for different countries in terms of the development and operation of the system,
- Grid code amendments may be required to allow the use of load for managing demand–supply balance,
- There is a need to establish gains in the use of EV for reserve provision compared to conventional sources (hydro or thermal) and allocation of gains among relevant players,

- Pooling several EVs and using the aggregated capacity as one resource is a potential option for providing energy over short time periods. To make this possible the revenues should compensate the following costs in addition to some profit:
    - Impact on battery life/cost
    - Control and communication equipment needed
    - Administration/transaction costs (business contracts, etc)
- Individual systems may need to establish pre-conditions for effective utilisation of EV in the ancillary markets such as; presence of critical mass of EV at right place, right time, presence of ICT, pragmatic business models, etc
- Regulation must ensure a non-discriminatory access of EV/demand side to participate in ancillary services markets and removal of existing barriers.
- Remuneration schemes needs to be made clear and for various services offered by EV such as:
    - Capacity payments.
    - Regulation down - simply charging the battery when it is optimal for the system, and be paid.
    - Regulating up is however more costly. degradation costs, cost for electricity already stored, and the expected revenue from providing regulation up is low.
- Optimal market time frame for the regulation markets will have to be found. Due to the stochastic driving behaviour, a short market time such as one hour to a few minutes could make a more optimal market time frame,
- Size of balancing bids will need to be adjusted for EV. Smaller bid sizes would encourage the possibility of using EVs as regulation capacity. However, a pragmatic approach should be adopted here to avoid incorporation of unnecessary complications in the network operation.

5.4 Applications of information and communication technologies (ICT) and E-roaming

This section has been built on the work carried out in G4V Work Package 4 (Deliverable 4.2) where the applications of ICT and E-roaming is defined for facilitating the integration of electric vehicle in future electricity systems.

Roaming is a general term used in the mobile phone industry referring to the extension of connectivity services in a location that is different from the home location where the service was registered. E-Roaming process in the EV context is defined as follows:

- An EV user is a subscriber of a retailer (E-Mobility operator) that provides charging services.
- The driver connects his electric vehicle to an EV charging station (or pole) which is not owned/operated by his own retailer.

- After the validation and charging processes, the driver pays for charging services to his retailer (E-Mobility operator) instead of paying to the EV charging station operator from where he charged his car.

Certain assumptions were made in deriving the above definition. An important one is that if the retailer or the aggregator is not the one installing a public charging pole, then this is open without discrimination to all other retailers /aggregators to supply to their customers through that pole. This is regardless of being the DSO or some other independent entity installing and managing the pole. If the aggregator/retailer is the one installing the charging pole, or supplying a wall-box to a customer's house, then he is the only one supplying through that socket. In such a case the E-roaming concept arises when an aggregator/retailer cannot serve its own customer directly through his own infrastructure.

Roaming could be at a regional level, using infrastructure from another charging station operator or from another mobility operator, or could be international roaming if the car is from another country and the user's own retailer is not present in that market. It is plausible EV users will have to connect to charging poles in many different locations and most likely they will have to connect to charging poles owned by different companies. However, we assume that every user of an EV will only want to have a contract with one retailer who bills all the energy that the user consumes for his EV – regardless of the place where it is connected to the grid. Therefore, roaming in the electricity sector occurs when a retailer contract is used in a market where that retailer is not present. For that reason, a partnership with a retailer operating in that market needs to be established to allow the customer to have coverage and use his contract in that market.

In both cases of roaming, the communication flow is equivalent. In one case, the partnership within Retailers is between companies of different countries that operate in different markets, while in the other case, the companies are from the same country and may operate in the same market. The same applies when considering the different Clearing House actors involved in this process.[16]

The application of E-roaming concept demonstrates the need for cooperation of different stakeholders in order to offer their customers unrestricted (charging) service independent of their location.

One of the key actors in E-roaming process is the Clearing House (CH), although their functionalities are not only linked to E-roaming. The CH definition in the electro-mobility sector is wider than the current one used in the financial market, and it will further include technical aspects regarding agreements, contract relations, and security certificates.

CH could have different functionalities depending on the regulation and the market structures present in the different countries. For example, in one case it may be more related to provision of services in terms of billing, and contracts and not directly related to energy. In other markets, the CH may need to establish communications with traditional energy stakeholders like DSO, MPO, etc.

The following suggestions are made regarding the role of the CH in the E-roaming context:

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[16] For further examples regarding roaming and the communication flows associated with the process please refer to G4V-WP4 deliverable D4.2.

- CH can serve as one possible option to operate the infrastructure. However, it is also possible that the users have direct agreements with retailers (E-mobility operators) without using a CH especially at the low EV penetration.
- CH should be managed as a neutral entity mediating between two partners to provide validation services for exchange of technical information, contract relations or security certificates.
- CH offers functionality such as checking for roaming agreements and routing, aggregation and retrieval of mobility services. General routing of messages (for example for billing) will be supported to deal with charges for the service, additional roaming fees, information about the transferred units, the parties participating in the agreement, etc.

The European Parliament and the European Council have announced several directives and rules that affect the general framework for E-roaming and Clearing House within European Community. On one hand, the Directive 98/34/EC22 establishes procedures for the reporting standards and technical regulations and rules governing services of the information society. In this sense, the European Commission announced to mandate the European standardisation bodies in 2010 to develop by 2011 a standardised charging interface to ensure interoperability and connectivity between the electricity supply point and the charger of the electric vehicle, to address safety risks and electromagnetic compatibility and to consider smart charging.

One the other hand, the Rule nº 765/2008 lays down the requirements for accreditation and market observation relating to the marketing of products. This designs the framework at Community level within which to develop the performance of accreditation in the Member States and establish their obligations, as for example the need that no more than one national accreditation body is of general interest.

State involvement to facilitate roaming will probably be necessary, even in those Member States that have only one utility. This involvement could facilitate the development of vehicle roaming although it represents an extra cost for EV user. Nevertheless, a harmonised European approach would be able to speed up the market preparation for infrastructures and lower the risk of investments as customers should have:

- Free choice between different energy suppliers (from which utility they get their electricity),
- Free access to all charging stations independent of the charging station provider or energy provider (e.g. under national/international roaming),
- User-friendly operation and billing systems which as harmonised across EU.

5.4.1 Policy and regulatory recommendations regarding ICT

In the light of above discussion, following recommendations are proposed:

- An upgradeable Information and Communication infrastructure is deemed more appropriate and economic option that could keep pace with the penetration levels of EV,
- ICT interface harmonisation and compatibility within national boundaries as well as across EU will greatly facilitate EV users,

- Adoption of business models should be analysed more thoroughly including the relevant ICT infrastructure requirements as complicated models may need more intelligence and high ICT costs. In other words a cost/benefit assessment is required to decide the optimal level of complexity of the ICT infrastructure that is to be adopted.
- Assuring security of the (metering) data including; ownership, storage, transmission, retrieval and the privacy of the customer is essential element regarding application of ICT for electro-mobility.
- Intelligent ICT should be applied to ensure (where required) distinct metering of electricity consumptions for mobility or for other purposes.
- Procedural automation and simplification is recommended through smart metering systems such as for; Data exchange, process for switching suppliers, etc
- For E-roaming to become effective for large scale EV penetrations there is a need to clearly define the terms and conditions of the roaming related agreements among involved market players
- Regulation needs to establish transparency in the flow of information and settlement of bills among retailers, as well as between the retailers and EV customers
- Provision of free consumer choice of energy suppliers and access to all charging stations independent of the charging station provider or energy provider (e.g. national/international roaming).
- Customer-friendly operation of ICT infrastructure (e.g. automatic and remote software upgrading) and billing systems will also enhance the smooth integration of EV.

5.5 Conclusions

It is found that there are several challenges raised by the electrification of transport sector. This in fact leads to a significant transformation of the electricity systems in terms of its development and operation. The challenges are surmountable brings a suite of opportunities not only to develop new businesses or to develop and operate electricity system more efficiently but at the same time offers great potential to meet environmental and climate change obligations of the energy system as a whole. However, it is well understood that this transition will need evolution of pertinent policies and regulatory frameworks to materialise these opportunities.

Establishing a clear market, regulatory and policy landscape would be necessary to enable economic and secure deployment of EV at a large scale. This should encompass the key relevant elements of the system; charging infrastructure, distribution grid; ancillary services as well the information and communication infrastructure. It is also important that the future policies and regulation in the electro-mobility area should ensure appropriate standardisation of equipment, infrastructure and the various procedures involved to facilitate smooth uptake of EVs.

A number of recommendations are proposed regarding development of future policy and regulatory frameworks in key relevant areas. Incentives will also be required to act in different timeframes and on different issues to ensure that the market is developed in a coherent manner. Any incentives aimed to reduce barriers to large scale penetration of EV should be phased in to match the market uptake. A timeline of incentives could be developed and modelled to gauge impact upon the market.

6 Summary of Conclusions

Electric vehicles are widely seen as one of the key policy instruments to facilitate decarbonisation of transport energy demand, i.e. shift from fossil fuel to the electricity based transport sector that relies on renewable and other low-carbon electricity generation technologies.

Within the overall context of the work, this report focuses on possible contribution to power system management from flexible charging of electric vehicles or plug-in hybrid vehicles. An advanced economic and environmental evaluation model has been developed to enable simulation and assessment of alternative charging strategies. The model ensures that the energy stored in EV batteries does not compromise the ability of vehicles to carry out their intended journeys, while taking into account efficiency losses during battery charging, as well as other on-board consumption (e.g. air conditioning).

Some of the key findings from the studies performed include:

- Benefits of EV integration start to appear already at low EV penetrations.
- Optimised charging of EV enhances the system's ability to absorb intermittent renewable energy (wind).
- EV charging strategies have a profound impact on generation scheduling, system operation costs and additional infrastructure requirements.
- Additional cost and emissions in the power system due to the introduction of EVs are system-specific, i.e. strongly depend on the capacity mix of the system in question.
- Optimised charging leads to lower additional operational costs due to:
    - Greater ability of the system to absorb intermittent generation
    - Lower usage of expensive (thermal) generators
    - Provision of balancing services by EV
    - Reduced emissions and associated costs
- The additional gains due to battery discharging (V2G concept) are relatively small compared to unidirectional charging. Further in-depth analysis is recommended that will involve all relevant factors (ICT requirements, impact on battery life etc.).
- Changes in emissions from electricity sector as a result of additional demand from EVs will be offset by reduced emissions from using fossil fuels in road transport. The exact extent i.e. the actual net impact on the overall energy system will depend on the carbon intensity of technologies used to supply the additional electricity.

Successful integration of large penetration of electric vehicles will require a clear regulatory framework, appropriate market structures and complementary policy measures to support the efficient deployment of EVs. Transparency of the regulatory regime will also ensure the market confidence of relevant stake holders to take advantage of the range of opportunities brought about by the transformation of transport and electricity systems due to large-scale roll-out of EVs.

The following aspects are considered critical for creating a supportive and successful regulatory and policy environment:

- Transparency and clarity are required for the development of different types of standardised charging infrastructure and necessary network reinforcements.
- At initial stages with low EV penetration incentives may be required for developing the Public Charging Infrastructure.
- Adaptation of existing network planning and operation rules is required to embrace smart charging control strategies and promote non-network solutions.
- Exploitation of EV resource for provision of system support services will require fair access to relevant markets (capacity, energy and balancing), as well as clarity on the remuneration schemes.
- Regulation must ensure a secure, standardised and cost-effective application of ICT infrastructure for a large-scale roll-out of EVs and their efficient integration into electricity systems.

Establishing a clear market, regulatory and policy landscape will be necessary to enable an efficient and secure deployment of EV at a large scale. This should encompass the key relevant elements of the system: charging infrastructure, distribution grid; ancillary services as well the information and communication infrastructure. It is also important that the future policies and regulation in the electro-mobility area should ensure appropriate standardisation of equipment, infrastructure and the various procedures involved to facilitate a smooth uptake of EVs.

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