Project:
Development of an Evaluation Framework for the Introduction of Electromobility (DEFINE)

Combined Deliverable: D2.1, D2.2, D7.1 and D7.2

Simulation of the economic and technical impacts of different electric vehicle charging strategies on the power market and the power grid

20th January, 2015

Authors:

Gerhard Totschnig, Dr.

Author of chapters: 1, 2, 4, 5, 6, 8, 9

totschnig@eeg.tuwien.ac.at

Markus Litzlbauer, MSc.

Author of chapters: chapters 1, 3, 7, 8, 9

e-mail: litzlbauer@ea.tuwien.ac.at

Vienna University of Technology, Institute of Energy Systems and Electrical Drives,
Gusshausstr. 25 / E370 – 1, 1040 Vienna – Austria

Table of Contens:

1. Introduction

In this report the key questions relating to the interdependencies between e-mobility roll-out and European electricity markets and grids are analyzed. The work consists of adapting the power plant unit commitment model HiREPS to simulate different electric vehicle charging strategies. As input to the electricity market model and to the grid simulation typical passenger car driving patterns are developed based on survey data Austria and Germany. Different scenarios are simulated using the HiRPES model and economic and technical benefits of controlled charging are analyzed fpr 2030 and 2050. Based on the HiREPS results on controlled market based charging, the grid impact of different charging strategies were analyzed for a representative grid for 2030 and 2050.

The two models are developed in co-ordination with DIW and TU Wien in order to create a common and comparable model framework for Germany, Austria.

2. HiREPS Energy System Model

The dynamic energy system simulation model HiREPS is used by TUWIEN to simulate the interaction of the electric vehicle charging with the power system in Austria and Germany. The HiREPS model is a unit commitment and investment optimization model auf Austria and Germany with hourly temporal resolution and simulates the power generation, the heating sector including district heating and combined heat and power units and industrial load management. In this project HiREPS was extended to simulate also electric passenger car charging. Controlled charging of electric vehicles is only one of the demand flexibility options in the future power system. In order to evaluate the economic benefits of controlled charging correctly, it is important to simulate also other competing technologies offering power system flexibility. Therefore the HiREPS model simulates also the economically optimal expansion of pumped hydro power units in Austria and Germany, the possible use of future flexibility options like power to gas and adiabatic compressed air power storage, the interaction between power system and the heat sector and industrial load management.

For the electricity sector the HiREPS model simulates the electricity generation by hydro power plants and the possible future increase of pumped hydro units, fossil and renewable thermal power plants (gas, lignite, hard coal, nuclear, biomass, waste, biogas) including startup costs, minimal load requirement and efficiency reduction at part loaded operation, wind and solar power generation. All hydro power plants with an installed capacity of more than 10MW are included in the model with high detail (see Figure 1).

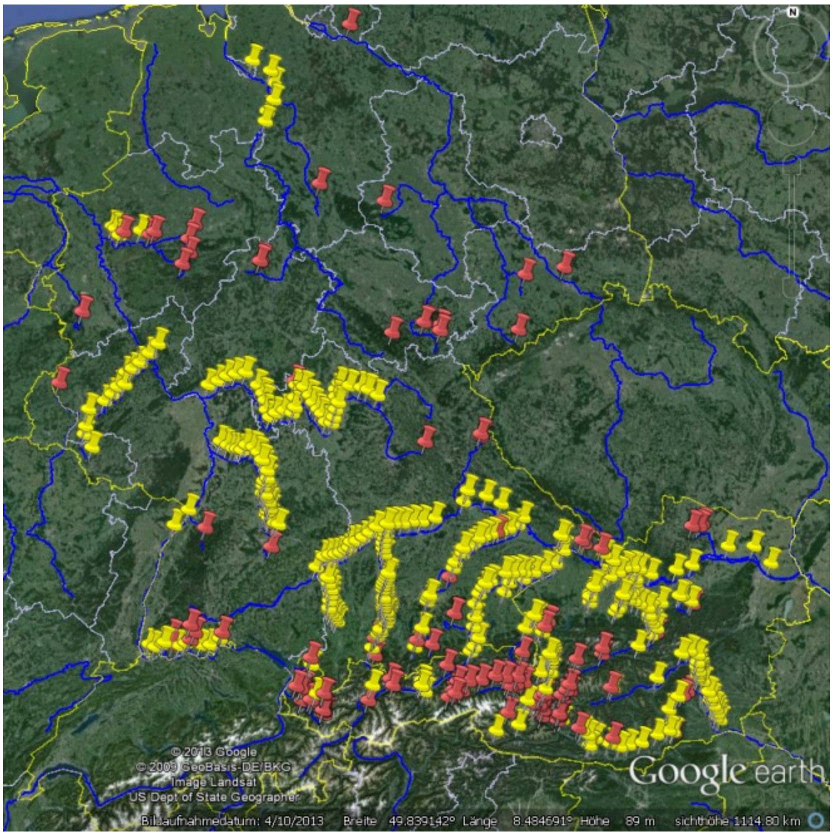

Figure 1: Hydro power plants of Austria and Germany in the HiREPS model. Yellow points indicate run of river power plant and red points reservoir power plants.

For the heating sector both district heating and decentral space heating and hot water generation are modelled. In district heating combined heat and power generation units are modeled in competition with power to heat appliances and other heat generation technologies and heat storages. In decentralized heating electric heat pumps, direct electric heater, gas, biomass and solar thermal heat generation and storage are modelled. A detailed description of the model can be found in the AutRES100 final Report (http://www.eeg.tuwien.ac.at/AutRES100/).

3. Development of typical passenger car drive patterns

Description of work:

This section discusses the preparation of typical usage patterns of passenger cars, which are required for the operation of EV as a switchable load in the HiREPS electricity market model of the Vienna University of Technology (TUW). The usage patterns are based on the survey “Mobilität in Deutschland 2008” and consider different weekdays, seasons and residential areas. The results are hourly profiles in table form for the dwell times, the driven distances as well as the locations, where the cars are parked. In addition, the usage patterns are generated for a pool of 240 cars including six different EV types. The applied methodology and the detailed results are described in the following chapters.

Selection and preparation of the mobility data

To prepare typical usage patterns of (electrical) passenger cars the best possible data base is needed. For this purpose different national and international mobility surveys ([3] to [7]) were compared and the advantages and disadvantages were weighed against each other. The final choice was the mobility survey "Mobilität in Deutschland 2008" (MiD08) [7], because on the one hand it comprises the largest extent with the biggest number of participants and incorporates the most parameters (e.g. the population of the city or municipality where the participants are living) and on the other hand all weekdays (Monday to Sunday) and all seasons are considered.

The mobility behaviour varies only marginally between Austria and Germany (compare [1]). Beyond that the electricity market model of the Vienna University of Technology simulates Austria and Germany in one big model, consequently the use of the German survey in the project “DEFINE” is favoured. The permit of usage of the research project “DEFINE” was confirmed in writing by the “National aeronautics and space research center of the Federal Republic of Germany” (DLR).

The following subsections describe the methodology and results from the editing and classification of the mobility data “MiD08” over merging individual days to entire weeks up to the calculation of hourly profiles in table form for the dwell times, the driven distances as well as the parking locations.

The mobility survey “MiD08”

The study "Mobilität in Deutschland 2008" (MiD08) investigated the mobility behaviour of people living in Germany: How often are people travelling? What transport means do they use? For what purpose are they travelling? How far are the ways and how long are people travelling?

The MiD08 provides a comprehensive and broad data base and offers the following special features[1]:

- coverage of complete households, including children from 0 years

[1] The listed items are taken directly from the final report of the MiD08 [7].

- key date survey over a complete calendar year
- reliable method for detecting paths by combining written and telephone survey methods
- very large sample of 25,000 households – including regional increases even almost 50,000 interviewed households
- extrapolation of traffic and transport performance differentiated by transport means, trip purposes and populations
- illustration of many results in time series

Filtering and data cleaning

The study "MiD08" includes a variety of different means of transport (such as walking, cycling, public and private transport), but for "DEFINE" only the MPT (motorized private transport) is of interest. Therefore, the entire data set was first filtered by the transportation parameter "MPT driver" and a transformation of people-related into car-related data was performed. However, this is not unique despite plausibility considerations. More information about this "non-unique mapping problem" and the used approach can be found in [1].

Subsequently, a data reassessment was performed based on the following criteria and the erroneous data blocks were adjusted or deleted:

- an incomplete data block (missing values of individual variables)
- an inconsistent data block (e.g. departure time plus travel time does not equal the arrival time)
- the next journey begins before the current trip ends
- the average speed of a the trip is over 130 km/h

The resulting data set comprises the one-day mobility data (MiD08, MTP on key date) with all the significant parameters (e.g. arrival and departure time, driven distance, weekday, season, etc.) and offers a total amount of 19,521 individual vehicles in tabular form and a time resolution of a minute. Considering the mobility characteristics, the one-day data are assigned to various EV types (hybrid electric vehicles and battery-electric vehicles). It is assumed that e.g. the travel times and the parking locations of conventional cars and electric vehicles don't differ.

Classification and data merging

For the annual linear optimization of the electricity market model (TUW) it's relevant to provide usage patterns of electric vehicles, which trace the mobility behaviour over a certain period of time (e.g. a week) and for all seasons. This makes a systematic chaining of the one-day mobility data necessary. In addition to the temporal classification (weekday, season, etc.) of the MiD08 data set, also a distinction on urban and rural areas makes sense, because the average daily mileage rises with a decreasing population (see Figure 2). This relationship has a direct impact on the energy demand and further on the charging profiles of electric vehicles.

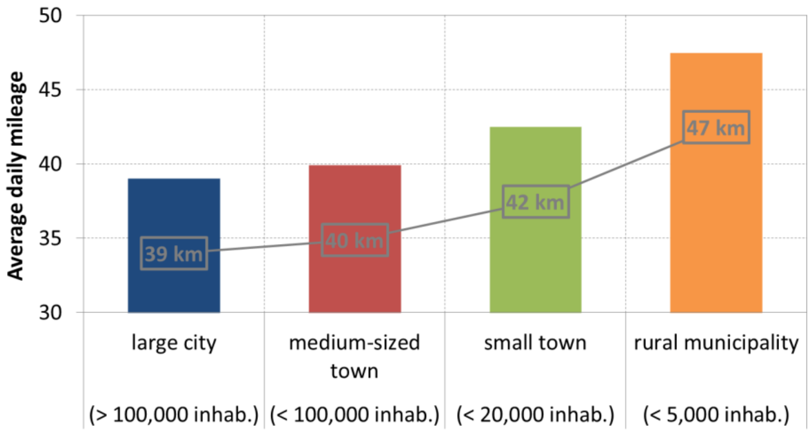

Figure 2: Average daily mileage of private passenger cars for different urban and rural areas (restricted MiD08 data set)

However, to reach a higher number of different profiles the categories “large city” and “midium-sized town” as well as “small town” and “rural municipality” were merged together. In this paper the new categories are referred to as “urban area” (> 20,000 inhabitants) and “rural area” (< 20,000 inhabitants).

For the preparation of driving profiles the following time and location relevant variables were additionally extracted from the MiD08 data set and assigned to the corresponding electric vehicle types (based on the electric driving range):

- weekday: Mo - So
- calendar week: 1 - 52
- month: 1 - 12
- season: spring - winter
- legal year: 2008 - 2009
- urban and rural area types: 10 - 40
  - 10: large cities (>= 100,000 inhabitants) plus
  - 20: medium-sized towns (20,000 to 100,000 inhabitants) and
  - 30: small towns (5,000 to 20,000 inhabitants) plus
  - 40: rural municipalities (< 5,000 inhabitants)

Figure 3 shows the average parking location distributions, which differ significantly between working days and weekends. In contrast, the distributions from Monday to Friday are similar. However, for the preparation of the usage patterns the weekdays are still implemented separately. In Figure 3 as well as for the usage patterns, the share of "non-driving days" has been adopted by one-sixth (16.67 % of all vehicles, see [9]) and assigned to the parking location "home". This portion represents those vehicles that are not used on any day. As mentioned, the MiD08 data set primarily contains only "mobile" days.

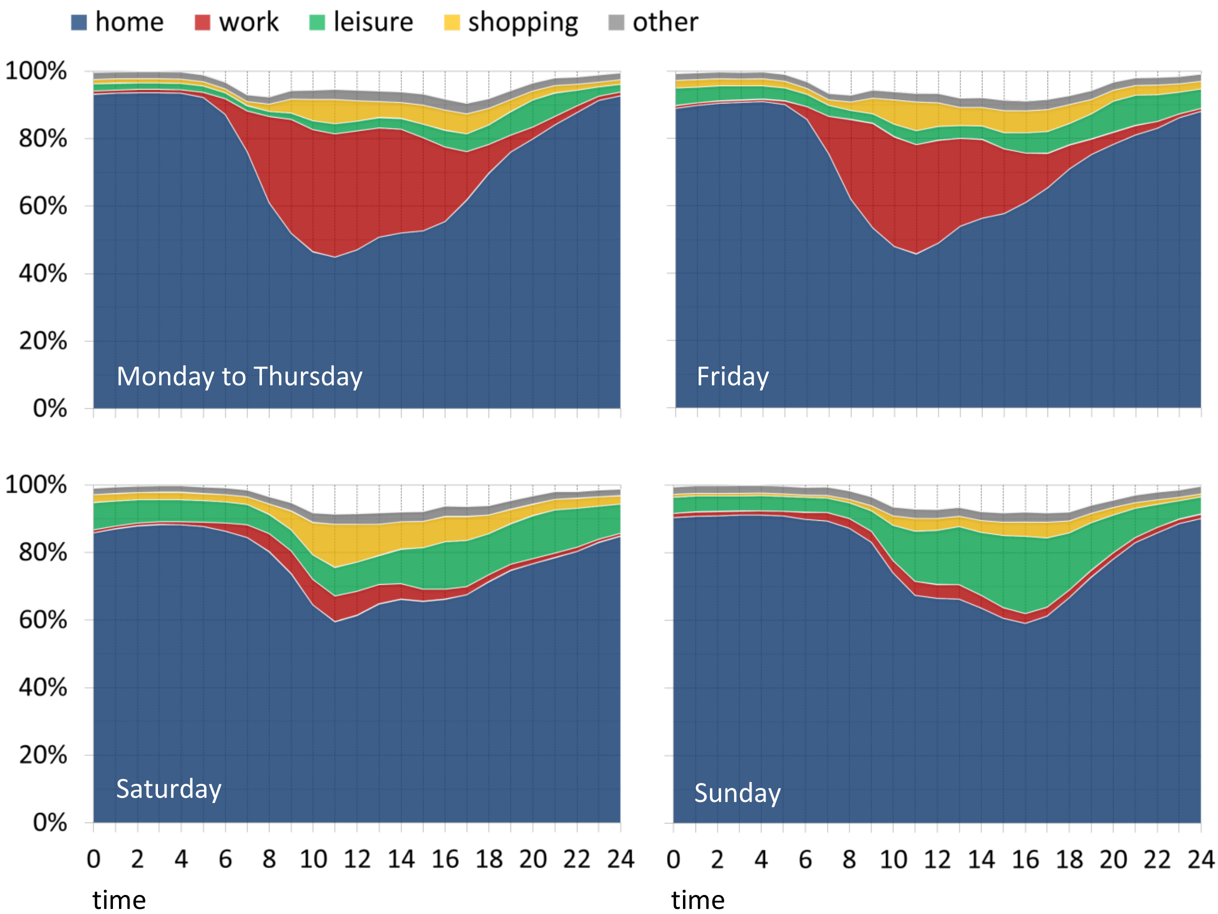

Figure 3: Average proportion of the individual parking locations

A problem in the chaining of the individual days to create e.g. a one week profile is that each day represents an individual vehicle or driver. Hence, a similarity analysis of the individual days of the week was performed. As a basis for comparison a GPS-based mobility data set – logged within the framework of the research project "Smart Electric Mobility" (SEM10) [1] – was used. This data set includes at least three-week continuous trajectories of over 30 private (conventional) vehicles. It was determined how strong the dwell times (per vehicle at the parking location "work") correlate with each other. The result shows that a random chaining of the weekdays (MiD08) – despite compliance with the order from Monday to Sunday – is not sufficient to achieve the same "similarity level" as the SEM10 data has. Therefore the MiD08 data set was divided in another two categories:

1) The dwell time at the parking location "work" (per working day) is higher or
2) equal to zero hours.

This means that a person, who goes to work by private car on a regular basis – is a commuter.

Finally the 19,521 one-day vehicles data (MiD08) were split up to 112 different data pools: A permutation of seven weekdays, four seasons and the four categories "urban area", "rural area", "car is used for commuting" and "car is not used for commuting".

Calculation of the usage patterns

As mentioned, for the annual linear optimization of the electricity market model (TUW) it's relevant to provide usage patterns of electric vehicles, which consider the mobility behaviour over a certain period of time.

Therefore, for all seasons (spring, summer, autumn and winter) and all EV types (BEV and PHEV in the categories "large", "mid-size" and "small") individual week profiles (time series for dwell time, distance and parking location) were created. To increase the calculation speed of the linear optimization the profiles were generated in a resolution of one hour instead of a minute.

The data basis for the needed EV usage patterns finally consists of the prepared MiD08 data set and the findings of work package 4 (WP 4).

Within the WP 4 the project partners UBA (Umweltbundesamt, Austria) and OEI (Öko-Institut, Germany) have defined different EV types (BEV and PHEV) in the categories "small", "mid-size" and "large" with all the necessary technical characteristics (e.g. battery capacity, electric driving range, yearly mileage, average energy consumption, depth of discharge and charging efficiency). UBA and OEI have also calculated the vehicle stocks (conventional cars and electric vehicles) for Austria and Germany up to the year 2030 for two different scenarios "BAU" and "EM+" [10].

The results of the studies ([2] and [8]) show that the specific energy consumption of electric vehicles is highly dependent on the ambient air temperature and on the use of devices like the air conditioning system. For the research project "DEFINE" the average energy consumption calculated by UBA and OEI was modified based on the average ambient air temperature and the measured specific energy consumption extreme values of the Austrian e-mobility model region "Electro Drive Salzburg" (winter: driving consumption + heating, transition time: only driving consumption, summer: driving consumption + cooling). Figure 4 illustrates the relationships graphically.

The following average factors for the specific energy consumption were assumed for the four seasons:

- spring: 0.88
- summer: 0.98
- autumn: 0.96
- winter: 1.18

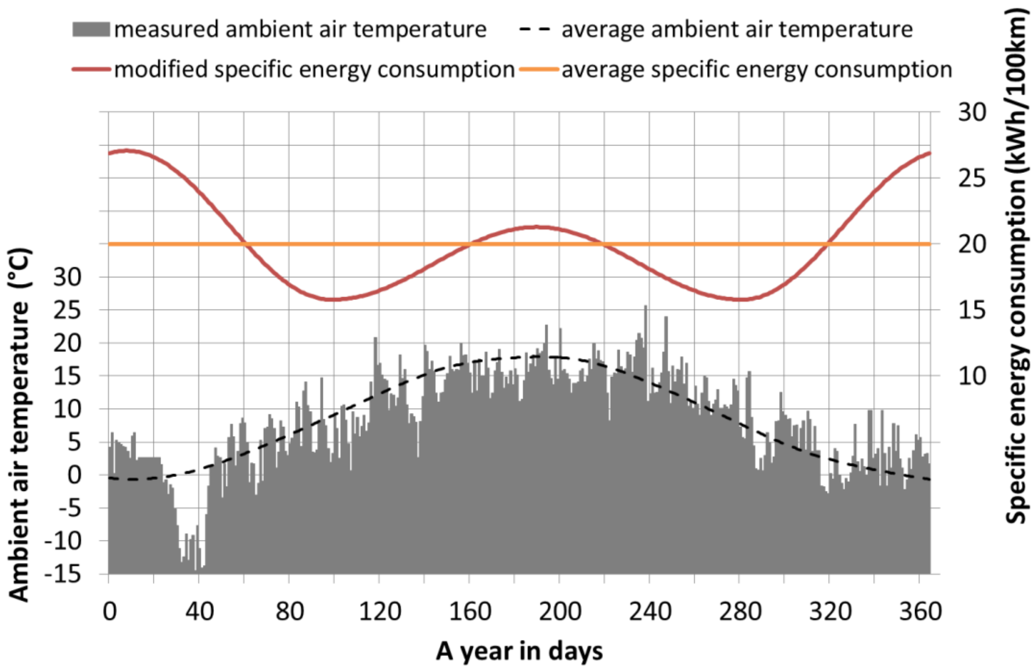

Figure 4: Modelling of the specific energy consumption of electric vehicles based on the ambient air temperature

For the four categories "urban area", "rural area", "car is used for commuting" and "car is not used for commuting" the one-day profiles of the survey MiD08 were chained together randomly to build a whole week (Monday to Sunday) for each season. It was ensured that the average annual mileage per EV type and EV category is met (according to Table 1) and that no profile is used twice. For this reason, the random chaining process was repeated many times. The resulting deviation of the values of Table compared to the values for the generated week profiles is at most 2 %.

Table 1: Yearly mileage of the considered EV types and EV categories (OEI, derived from MiD 2008)

small		mid-size		large	
BEV	PHEV	BEV	PHEV	BEV	PHEV
11,100 km/a	12,300 km/a	15,500 km/a	16,700 km/a	14,100 km/a	14,100 km/a

In a second step the usage patterns (week profiles) were assigned to the eight EV types in a way, that each battery electric vehicle (BEV) can handle all its trips electrically driven. For the rest of the week profiles with a higher mileage were allocated to the plug-in hybrid electric vehicles (PHEV). These cars have no range limit, because of the additional internal combustion engine. The Profiles of „dwell time", „charging power" and "state of charge" for an exemplary BEV and PHEV are shown in Figure 5 and Figure 6 (charging only at home and starting immediately after arrival with a max. power of 3.5 kW / 1-phase, 230 V, 16 A).

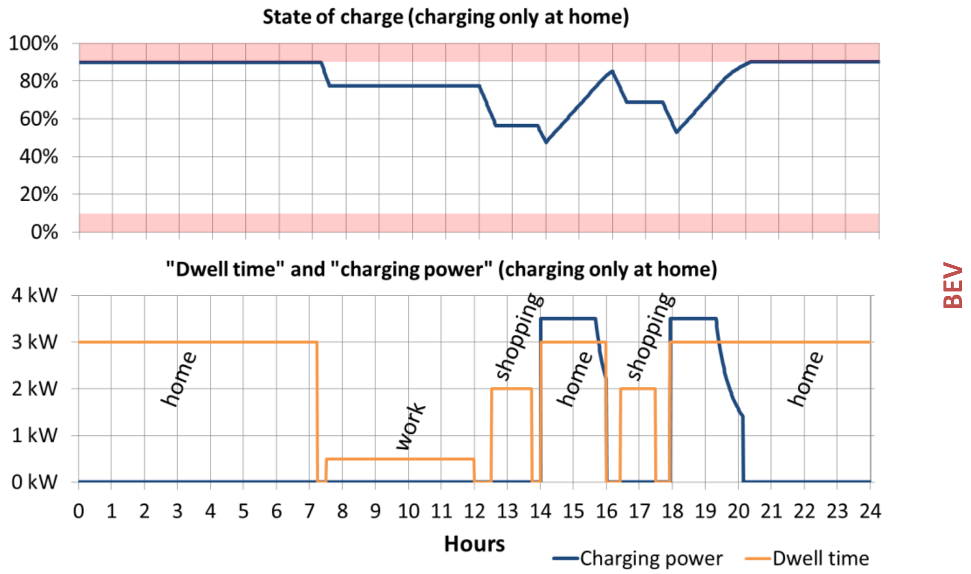

Figure 5: Profiles of „dwell time", „charging power" and "state of charge" for an exemplary BEV (charging only at home and starting immediately after arrival with a max. power of 3.5 kW / 1-phase, 230 V, 16 A)

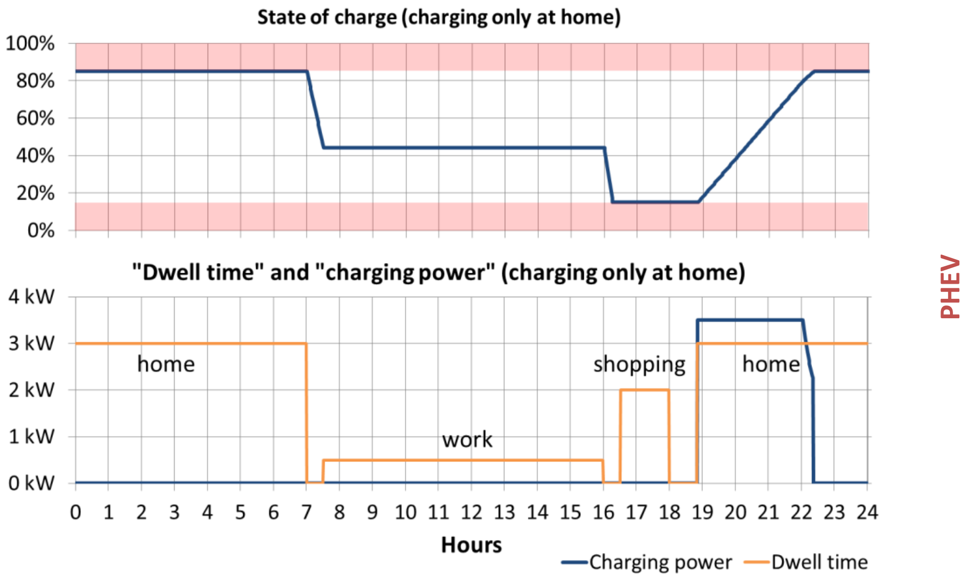

Figure 6: Profiles of „dwell time", „charging power" and "state of charge" for an exemplary PHEV (charging only at home and starting immediately after arrival with a max. power of 3.5 kW / 1-phase, 230 V, 16 A)

To validate that the energy consumption never exceeds the electric driving range of the battery electric vehicle (BEV) – depending on the charging scenarios "charging only at home and start without delay" – the following described tool was used:

With the help of the simulation software MATLAB a charging profile tool (developed at the Institute ESEA, Vienna University of Technology) has been extended and adapted to meet the needs of the project “DEFINE”. The mobility data (usage patterns), the vehicle parameters and the charging properties jointly form the pool of model input variables (see Figure 7).

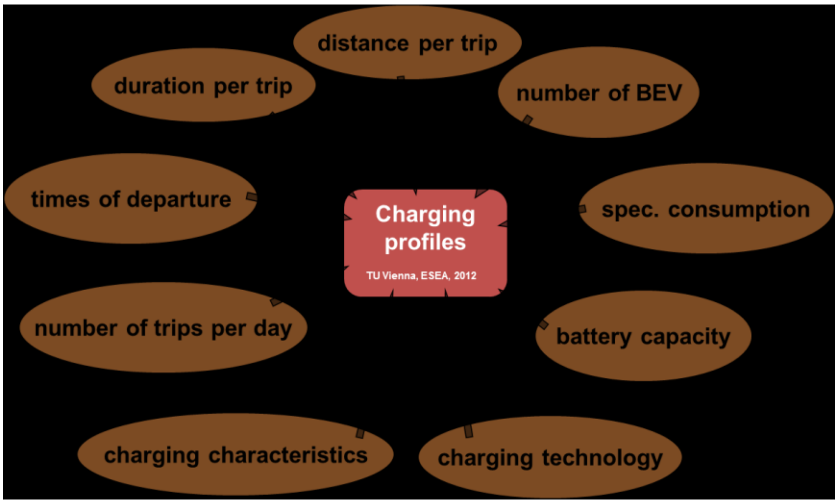

Figure 7: Input parameters of the MATLAB tool to create the charging profiles

The MATLAB tool enables an accurate calculation of the charging profiles and SOC-profiles for individual electric vehicles on a variety of selectable parameters. In the case of the project “DEFINE” the batteries of the pure electric vehicles (BEV) should never be empty.

To extrapolate the usage patterns (week profiles) of a resolution of minutes to a resolution of hours, the driven distances were accumulated. For the profiles “dwell times” and “parking locations” the most frequent parking location of each hour and the hourly proportion of this major parking location were used.

Output - passenger car drive patterns

The findings are represented by usage patterns for electric vehicles created in the form of seasonal week profiles (tables of hourly time series) for “dwell time”, “driven distance” and “parking location”. Ten individual usage patterns are calculated for each battery electric vehicles (BEV) and plug-in electric vehicles (PHEV) in the categories “large”, mid-size” and “small”. In terms of the vehicle drivers, the categories "commuter", "no commuters", “urban area" and “rural area” were distinguished. Finally, 240 individual usage patterns of 40 different electric vehicles (four EV types) – considering the seasons – were generated.

4. Implementation of electric passenger car charging into the HiREPS model

Charging Strategies

Two different charging strategies are analysed with the HiREPS model

- Cost based market-led (ML)
- Non-market-led (NL) immediate charging

In the non-marked-led immediate charging, the car is immediately charged at full speed till the car battery is full, whenever the user connects to the vehicle to the charging point.

In the cost based market led charging users of electric cars have a service contract with an aggregator company which optimizes the timing of the charging in order to get the lowest electricity prices. The charging of electric vehicles influences the electricity prices and the optimal low cost charging strategy is part of the HiREPS optimization. The cost saving of cost based marked-led charging are evaluated by comparing the cost with the non-marked-led immediate charging.

User charging behavior

The most obvious charging behaviour is termed frequent charging. The users will always connect to a charging point when possible. This allows the highest flexibility for cost based market led charging and also for vehicle to grid operation (see section below). This flexibility will result in the highest saving in electricity purchase costs.

In accompanying research conducted by TU Vienna for "ElectroDrive Salzburg" [5], however, an idle time of over 2 days was required before half of the vehicles were connected to charging points. So in this field test the electric car users connected very infrequent to available charging points. So for this research project also the impact of infrequent charging by EV owners was investigated (see scenario definitions below).

The investigated user behaviours are therefore:

- Frequent charging (FC): electric vehicle drivers will always connect to a charging point if there is an option to do so.
- Infrequent (IC) charging: electric car drivers connect their vehicles to charging points only if the battery is nearly drained and must be charged in order to use electric power for as many subsequent journeys as possible.

V2G Operation

The lifetime of modern batteries used in electric vehicles is currently limited to around 3000–5000 full cycles at a 100 percent depth of discharge of the nominal capacity or a service life totalling 12 calendar years [11]. The use of car batteries as electricity storage for the grid (vehicle to grid, V2G) was viewed as possible only in cases where 3000 full charging cycles had not been exhausted in normal driving within the 12-year period. In complying with this criterion, the simulated drive profiles permit V2G operation only for BEVs (see Figure 8). Plug in hybrid electric vehicles (PHEV) have both an electric motor and also an internal combustion engine. The battery is used only for the frequent short range commuting. The internal combustion engine allows to perform longer trips. In PHEV the battery size is small and therefore charged frequently. As a consequence during the normal driving operation typically there is not much room for additional charging cycles caused V2G (see Figure 8). Since pure battery electric vehicles (BEV) do not have a backup internal combustion engine, the electric battery hast to be large in order to allow a sufficient driving range.

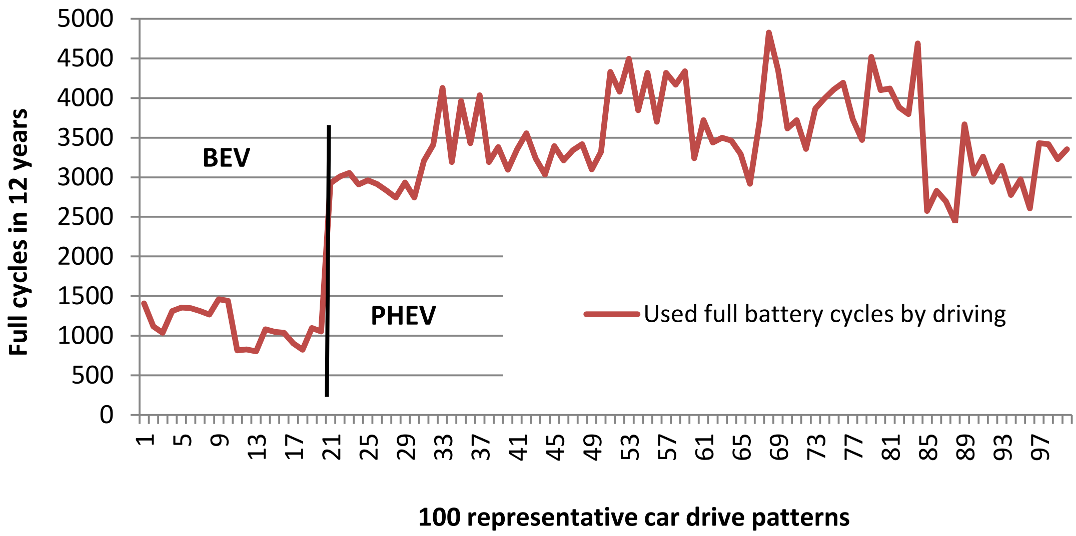

Figure 8: Full battery charging cycles by normal driving.

5. Scenario definitions

In the HiREPS simulations for Define, Austria and Germany are analysed together. Fuel costs and power plant capacities for Germany are taken from Scenario B of the scenario framework for the Electricity Grid Development Plan 2013 [13]. For Austria, maintenance of thermal capacities at 2012 levels has been assumed, plus an installed PV capacity double that of the 2020 target in the Green Electricity Act 2012 and a wind power rollout equalling 50% of the feasible potential for 2030 as simulated in the AuWiPot project[14]. Based on the 2011 PRIMES reference scenario, an increase in electricity demand of 10% has been assumed as regards 2010 [15].

In the EMOB+ 2030 scenario the impact of 6.4 million electric cars (13% of all cars) is analysed and in the 2050 scenarios the impact of 48 million electric cars (100% of all passenger cars). For 2030 and 2050 it is assumed that 20% of the electric cars are battery electric vehicles (BEVs) and 80% plug-in hybrid vehicles (PHEVs). For PHEVs, a simplification was made by assuming that these drive using only electricity until the battery is empty, and then use diesel or petrol. Further assumptions were made that all electric cars can charge at night, that 15% of all cars have a charging point at the workplace and that 30% of stops at public facilities offer a charging point.

GW Capacity 2030		AT	DE
Wind-OnShore		4.6	61.2
Wind-OffShore			21.9
PV		2.4	64.1
GasCC		5.1	38.6
Coal		1.2	21.9
Lignite			13.5
Costs 2030			
Coal	Euro/MWh		10.31
Lignite	Euro/MWh		1.50
Natural Gas	Euro/MWh		26.70
CO2 Price	Euro/tCO2		39.60

Table 2: 2030 scenario assumptions

EMOB+ Scenario: AT+DE			2020	2030	2050
small	BEV-small		59,695	634,340	4,778,412
	PHEV-small		96,317	979,269	7,376,719
mid-size	BEV-medium		53,686	547,301	4,122,758
	PHEV-medium		161,616	1,580,138	11,902,998
large	BEV-large		1,677	65,625	494,345
	PHEV-large		213,638	2,563,584	19,311,183
	Total EV		586,629	6,370,257	47,986,415
	Alle Autos	47,222,830	47,986,415	47,986,415	
		%	1%	13%	100%

Table 3: Vehicle fleet in the scenarios

To ensure that market-led charging does not infringe grid restrictions in the low-voltage grid, the figure of 3 kW is implemented in the HiREPS model as the scenarios' maximum total power per household (i.e. electrical load of household appliances, plus electric vehicles and power to heat plant).

6. Results of the electricity market simulation with HiREPS

2030 Results

Figure 9 provides an illustrative example of power generation and electricity consumption for the "market-led and frequent charging" (ML + FC) scenario in Austria and Germany during summer 2030. The area segments depict generation while the line segments depict demand components. The black line is the normal electricity demand in 2030. The dark blue line supplements the normal electricity demand with power consumption from pumped storage hydropower plants. The red line then also adds in the market-led demand from the use of electricity by the heating sector (P2H) and industrial load management. The bright blue line then also adds in the electricity consumed by the charging of 6.4 million EVs, led by the electricity market.

One can see that the electric vehicles contribute to the integration of the 66.5 GW of PV into the electricity system in summer, by creating an additional load at noon, while also contributing to increased demand at night. The diagram also illustrates how the simulated flexibility options – pumped storage, industrial load management, power to heat and 6.4 million EVs – enable the thermal power stations to enjoy relatively smooth operation, despite the major fluctuations in normal load and renewable energy generation. V2G grid feed-in is indicated by dark green areas. V2G exhibits similar application characteristics as pumped storage and an example area is marked with the red arrow.

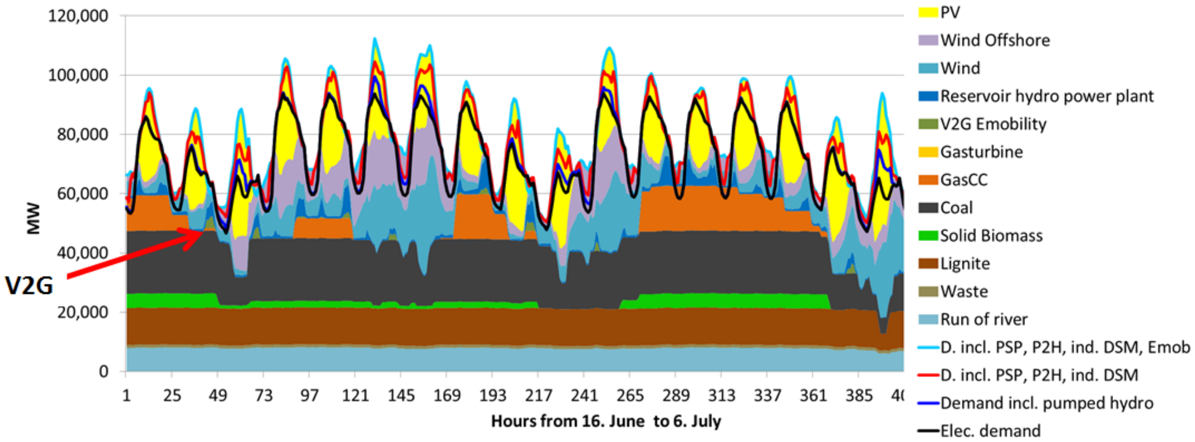

Figure 9: Power generation and consumption for Austria + Germany, summer 2030

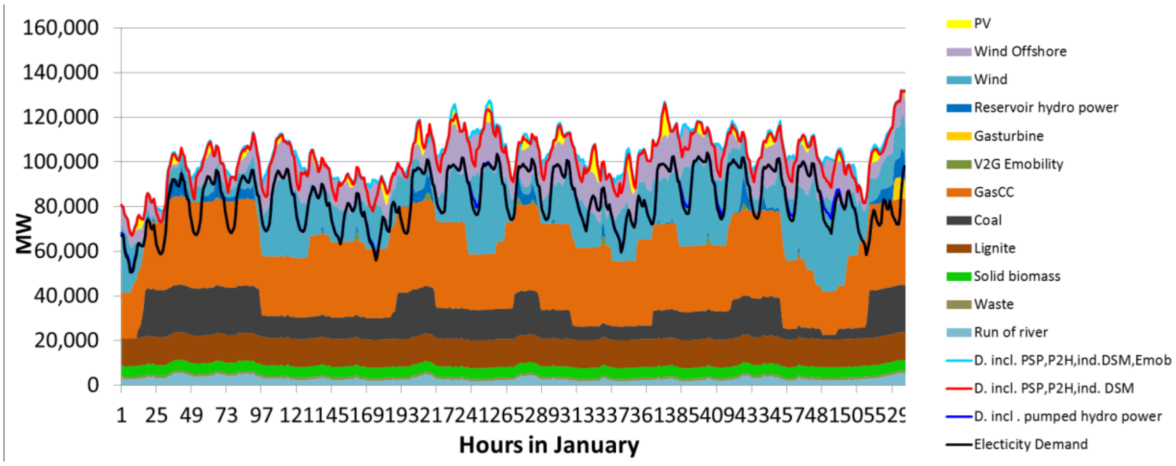

Figure 10: Power generation and consumption for Austria + Germany, winter 2030

The diagram for winter is similar (see Figure 10). Here, however, the market-led power draw from electric vehicle use is concentrated more on night-time hours, enabling smooth operation for thermal power plant. Demand from EV use for Austria and Germany with 6.4 million electric vehicles amounts to 17 TWh (without V2G power draw). The V2G power supply amounts to 1.6 TWh. As can be seen from Figure 11, the charging cycle limit of 3000 full cycles in 12 years is not exhausted even with V2G operation of BEVs. In Figure 11 one can see that with infrequent charging the battery cycles due to V2G are strongly reduced. With infrequent charging there is less time to optimize the charging and V2G opteration. This also is reflected by the cost reductions due to V2G operation (see below).

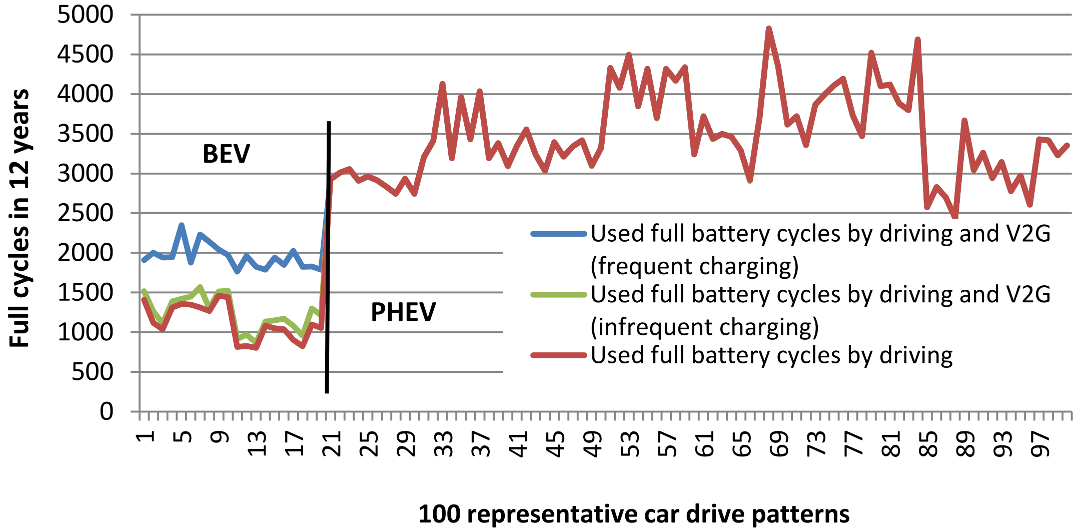

Figure 11: Full charging cycles for the 100 simulated drive profiles for EV use.

The maximum V2G power feed-in amounts to 5.4 GW (see Figure 11).

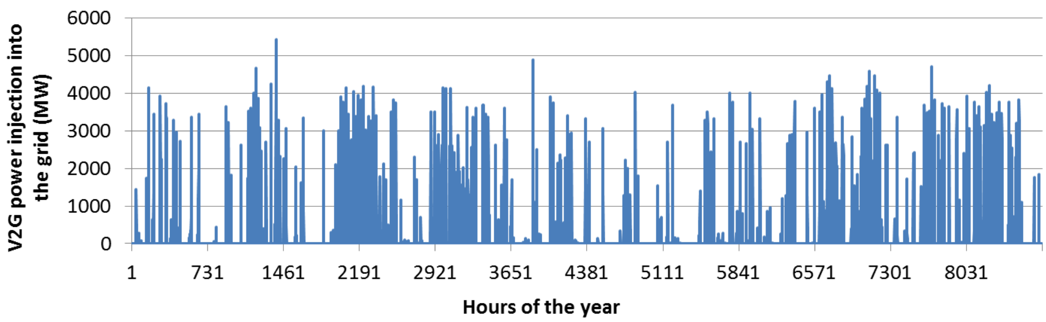

Figure 12: V2G usage during the 8760 hours of the simulated year 2030.

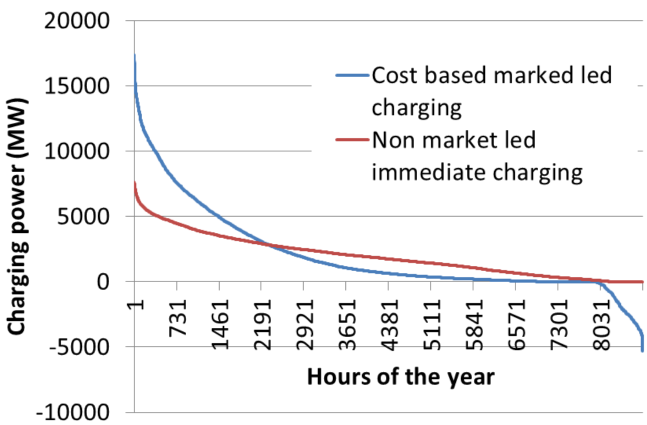

Figure 13: Duration curves for EV charging capacity in the scenarios "market-led, frequent charging with V2G" (MD+FC+V2G) and "non-market-led, frequent charging" (ND+FC) 2030.

Figure 13 shows the duration curves for the scenarios "market-led, frequent charging with V2G" (ML+FC+V2G) and "non-market-led, frequent charging without V2G" (NL+FC). The maximum charging power for market-led charging of 6.4 million cars amounts to 17.4 GW. At 7.6 GW, the maximum charging power for non-market-led charging is much lower. This is because vehicle usage and idle times are sufficiently well-distributed to avoid major cases of concurrency – even if charging takes place immediately on arriving at the charging point. In contrast, market-led charging creates significantly greater concurrency between charging events. This is desirable, however, since the market signal (cheap electricity) is sent only if generation surpluses exist in combination with low electricity demand. Accordingly, market-led charging does not work to increase the maximum electricity demand. Conversely, non-market-led charging causes the maximum electricity demand to rise by 7.1 GW. As explained above, a figure of 3 kW was used from the outset in the HiREPS model for the market-led charging scenario as the maximum total power per household (electrical load of household appliances, plus EVs and "power to heat" plant), to ensure that no infringements are made to grid restrictions in the low-voltage grid. See below chapter 7 “EV interactions with the power grid” for a detailed simulation on the power grid.

The electricity volume transferred by market-led charging versus non-market-led charging amounts to 12.6 TWh for Austria and Germany in 2030. The 6.4 million cars simulated thus surpass pumped storage (after optimum pumped storage rollout) in terms of the transferrable electricity volume: the power draw of pumped storage amounts to 8.3 TWh for the non-market-led charging scenario and 4.5 TWh for the market-led charging scenario.

The cost savings from market-led charging (ML+FC) amount to €179m/year or €28 per electric vehicle per year. For the 100 drive profiles simulated, the electricity cost savings from market-led charging (ML+FC) varied from €52 to €13 per EV per year. The additional cost savings from using the car battery as an electricity storage for the grid (vehicle to grid operation = V2G) amounts (ML+FC+V2G) amount to €9m/year or €10 per BEV per year. This V2G saving is in addition to the savings achieved by market-led charging. For the 20 battery electric vehicles simulated, electricity cost savings vary between €13 and €7 per BEV and year.

The figures stated above are based on the frequent-charging scenarios (see scenario definitions above). In accompanying research conducted by TU Vienna for "ElectroDrive Salzburg" [5], however, an idle time of over 2 days was required before half of the vehicles were connected to charging points. Further research was therefore conducted to study the impact of infrequent charging by EV owners (see scenario definitions above). This research revealed that market-led and infrequent charging (ML+IC) reduced the cost savings compared to market-led and frequent charging (ML+FC) by 17%, and amounted to €148m/year or €23 per electric vehicle and year. For the 100 separate drive profiles simulated, the electricity cost savings from market-led and infrequent charging (ML+IC) varied from €40 to €7 per EV per year.

For market-led and infrequent charging (ML+IC), the cost savings from V2G are reduced in comparison to ML+FC by 85% and thus amount to a mere €1.5m/year or €1.50 per BEV and year (contrasted with €9m per year in the ML+FC+V2G scenario). This V2G saving is in addition to the savings achieved by market-led charging.

The average number of hours that the electric vehicles spend connected to charging points is reduced for BEVs from 6553 h in the case of frequent charging to 1811 h (-72%) in the case of infrequent charging. For PHEVs, these hour totals change from 6822 h for frequent charging to 4702 h for infrequent charging (-31%).

Summary of 2050 results

The shifted electricity volume due to marked led charging in 2050 is 4.4 times larger than the effect of pumped hydro power units (after optimal capacity expansion) in Austria and Germany 2050. The average cost savings by market-led infrequent charging compared to immediate charging amounts to 51 Euro per electric vehicle and year for 2050. Immediate charging of 100% electric vehicles in the year 2050 increased the peak load, compared to the marked led charging, by 16 GW for Austria and Germany. The cost of 16 GW peak load generation capacity is about 16 Euro per electric vehicle and year for the 48 million electric vehicles 2050. The effects of electric vehicles on the CO2 Emissions, depends on the fact if additional renewable power generation is constructed for the additional electricity demand.

7. EV interactions with the power grid

Introduction

Towards a sustainable and environmentally friendly mobility in the motorized individual transport, it is necessary to increase the electrification of the power train. However, this change means that the charging of electric vehicles (EV) will take place not only at neuralgic points in the (semi-)public space, but to a large proportion decentralized in private garages and parking spaces [16]. This leads – depending on the connection power of the charging points and the EV penetration – to a significant additional grid load in the low voltage systems. Furthermore it leads to an increased utilization of the grid components (e.g. transformer and cables) and in addition to a reduced local voltage.

The completed research project "V2G-Strategies" [17] shows that cost-based controlled charging may increase the simultaneity of charging processes (same connecting powers assumed) and that the existing grid resources will possibly be more stressed than in the case of uncontrolled charging. Based on this knowledge the grid restrictions in the research project "DEFINE" were already considered in the very beginning of the modelling of the charging strategies. The Vienna University of Technology has analyzed the impact on the low voltage grid of various scenarios with the help of load flow calculations. The methodology and the results are discussed in this paper.

Description of work

Results from previous research projects (e.g. “V2G-Strategies”, FFG number: 825417) [18] show that in future the charging processes of electric vehicles cause significant additional grid loads mainly in low voltage grids. Therefore, this paper discusses the impact of electric vehicles on the low voltage grid. The basis for the analysis is a low voltage grid model of a residential area, which represents the Austrian building situation and housing conditions. Furthermore, different scenarios of EV penetrations (up to 100 %) and charging strategies are included in the investigations. Using load flow calculations the impact of these various scenarios on the considered low voltage gird are calculated for an entire year. The methodology and the results are discussed below.

Model Settlement

To estimate the impact of EV on the low voltage (LV) power grid a “typical” LV grid is needed as an research object. In this chapter the used model grid will be discussed in more detail. This model grid was created in the research project “aDSM” [19] and is now in use as data base for the grid analysis in the research project “DEFINE”.

The aim of the model settlement is to represent the overall Austrian residential structure. The synthetic low voltage grid consists of a rural and an urban area. The generation of a synthetic distribution grid offers the advantage that different grid situations can be represented in a single study area [20].

Based on the population survey [21], the number of buildings, the type of these buildings (bldg), the number of households per building and the number of people (ppl) per household (hh) are known.

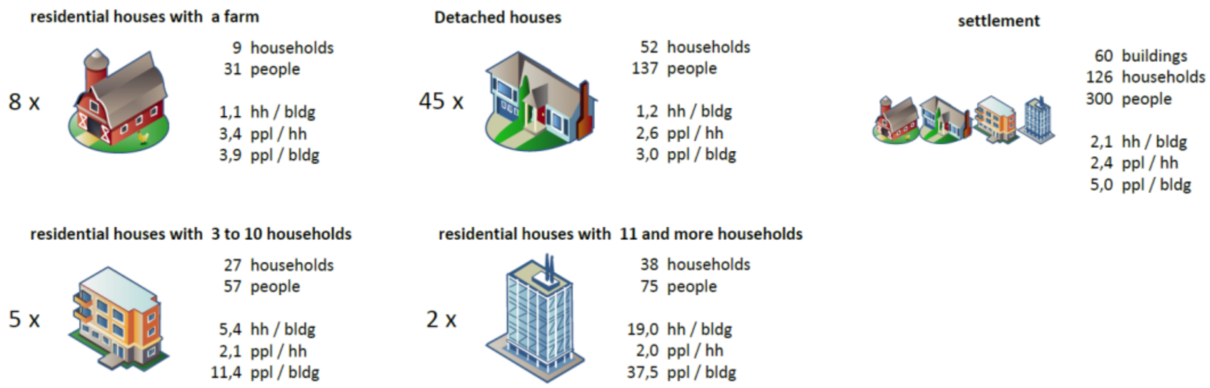

Figure 14: Austria mapped on a settlement with 300 inhabitants

The settlement involves a population of 300 people in 126 households and 60 residential buildings. Figure 14 shows the compilation of the model settlement.

Power Grid

The structure of the model grid is determined by the parameter "load density”. To simulate simultaneously single areas in the settlement with low and high load densities, a mixed approach of radial and open loop distribution systems was chosen. The open loop represents the urban area, while the radial grid segment – with partly very long feeders – represents the rural area. Figure 15 shows the basic structure of the model grid.

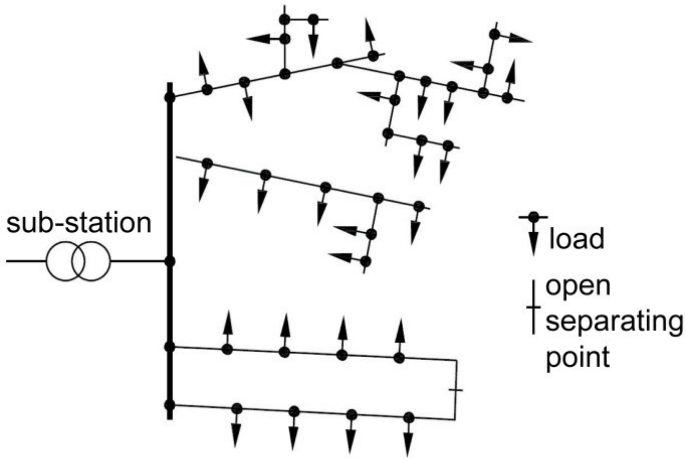

Figure 15: Grid topology - radial grid (upper feeder) and open ring (lower feeder) [2]

In practice, one grid station will be either in a more rural or in a more urban region. Consequently, there will be only one of the two shown grid types. However, in the model grid the two types are combined for one station as shown in Figure 15.

As the scale drawing of the model village shows (see Figure 16), a building configuration in the urban area was found, so that all requirements are met. Roads and buildings were drawn with the assumed size. The cable length of the nodes of the ring towards the land was sufficient for all the buildings and at the same time no unrealistic line lengths within the open loop grid were revealed.

In the rural area (lower right part of Figure 16) a "village arrangement" can be seen. Here a mixture of relatively densely populated one-and two-family houses and small farms occurs. In the left area, the case of a distant farm is covered.

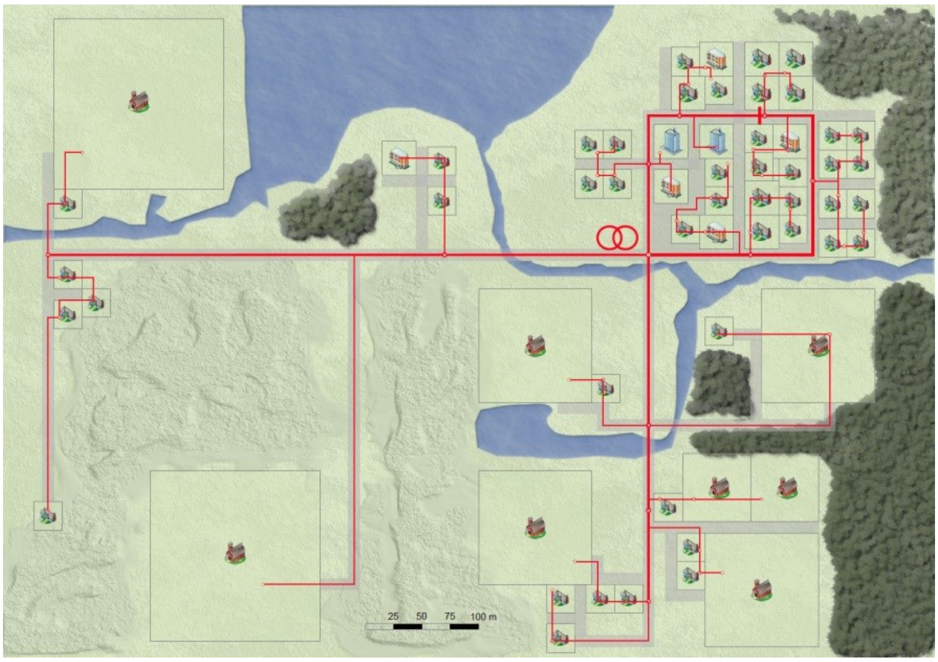

Figure 16: True-scale plan of the model settlement

EV Charging Profiles

In deliverable 2.1 the preparation of typical usage patterns of passenger cars is discussed. The findings are represented in usage patterns for electric vehicles created in the form of seasonal week profiles (tables of hourly time series) for “dwell time”, “driven distance” and “parking location”. Ten individual usage patterns are calculated for every battery electric vehicle (BEV) and plug-in electric vehicle (PHEV) in the categories “large”, “mid-size” and “small”. In terms of the vehicle drivers, the categories “commuter”, “no commuter”, “urban area” and “rural area” were distinguished. Finally, 240 individual usage patterns of 40 different electric vehicles (four EV types) – considering the seasons – were generated.

These patterns are required for the operation of EV as a switchable load in the subsequent electricity market model of the Vienna University of Technology (please see deliverables 2.1, 2.2, 7.1 and 7.2). The resulting EV charging profiles of the market model represent the additional grid load for the power grid analysis, which is described in the next chapter.

In the research project "DEFINE" different EV penetration scenarios for electric vehicles are expected by 2030. These result in a maximum share of electric vehicles (BEV and PHEV) in the total Austrian vehicle stock of up to 16 % (see deliverables 4.1 – 4.5 and 5.1). In addition, a scenario for the year 2050 was considered. For this scenario the Vienna University of Technology assumed that each car involved in the model settlement is electrically driven (100 % BEV + PHEV). Based on these EV penetrations various cost-based controlled and uncontrolled charging strategies were applied by the Vienna University of Technology.

Further, a frequent (FC) and infrequent (IC) charging was distinguished. Frequent charging is ground on the assumption that the electric vehicle users always plug in and charge their EV immediately when a charging station is available at a stop. Conversely, the electric car owners connect their vehicles to charging points only when the battery is so low that it must be charged in order to use electric power for as many subsequent trips as possible. This type of user behavior is termed infrequent charging. For the two cost-based controlled charging scenarios (frequent/infrequent charging) for 2030 also V2G (“vehicle to grid”) was considered – but only for pure electrically driven cars (BEV). For more detailed information about the different charging strategies and the used marked model please see deliverables 2.1, 2.2, 7.1 and 7.2.

In the already described model settlement with 300 people and an EV penetration of about 16 % (2030) the amount of electric vehicles was set at 33 cars (5 BEV and 28 PHEV). For 2050 (100 % electric vehicles) 195 EV (38 BEV and 157 PHEV) were adopted. For each considered electric vehicle a charging profile for an entire calendar year was determined based on the different scenarios. Figure 17 shows the averaged and normalized charging profiles (controlled and uncontrolled) at home for a workday in 2030. Compared to the uncontrolled charging profiles, the peak of the controlled charging profiles shift towards noon and night hours, where electricity is rather cheap. The difference between frequent (FC) and infrequent (IC) charging is relatively low. Only for controlled charging there is a significant deviation in times of high electricity prices. During these periods the BEV – which are connected to the grid and have a suitable state of cahrge (SOC) – operate in V2G mode (see purple line in Figure 17 at around 7 a.m. and 6 p.m.). In case of controlled plus infrequent charging the BEV are rarely connected to the grid and therefore their SOC is not sufficient to perform V2G. The charging profiles for 2050 can be found in the appendix.

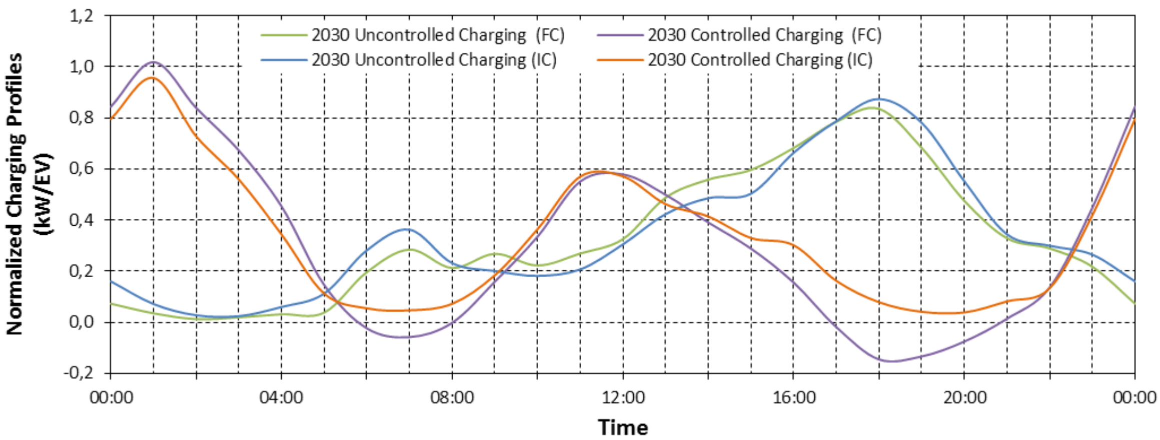

Figure 17: Different charging profiles at home for 2030 (16 % EV, V2G)

Power Grid Analysis

The basis for the analysis is the already explained model grid of a residential area, which represents the Austrian building situation and housing conditions. The settlement involves a population of 300 people in 126 households and 60 residential buildings.

To simulate simultaneously single areas in the settlement with low and high power densities, a mixed approach of radial and open loop distribution systems was chosen. The open loop distribution system represents the urban area, while the radial grid segment – with partly very long feeders up to 840 m – represents the rural area.

Based on practical experiences characteristic cable lengths for the different grid areas as well as typical building types were adopted. Taking into account the data for standard cable types (buried cable, aluminum conductors, 50 and 150 mm²) and a standard transformer (630 kVA) the whole electrical low voltage distribution grid was fully mapped in the load flow calculation programme NEPLAN®. For the electrical connection powers also typical values for households – corresponding to the respective building categories – were assumed and for the individual households synthetic, appliance-based load profiles for an entire calendar year were recorded [22]. Compared to standardized, normalized H0-household load profiles, the synthetic load profiles offer the advantage that they replicate the load peaks more exactly and provide more plausible results (e.g. maximum loads) for analysis in low voltage grids.

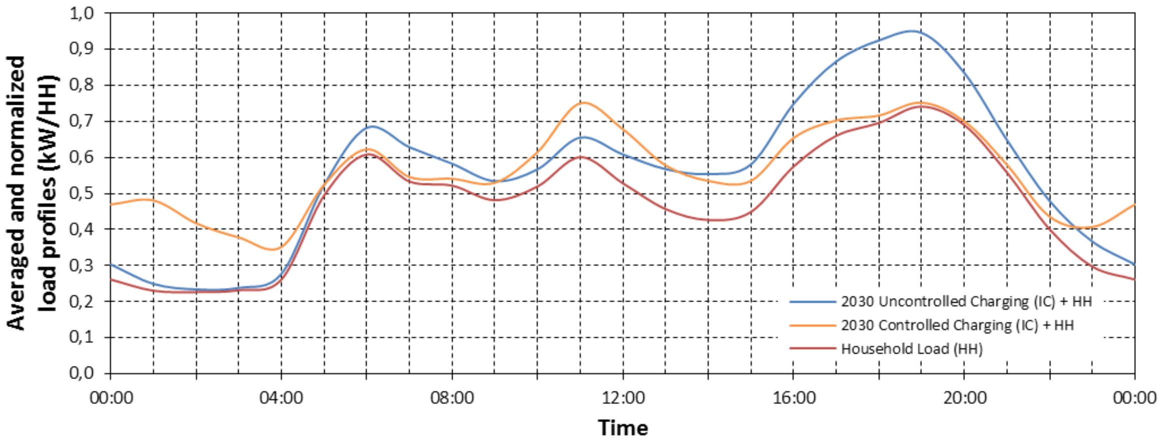

Figure 18: Household load profile plus different charging profiles at home for 2030 (16 % EV, infrequent charging, V2G)

In addition to the involved electrical loads of the household, the charging profile for each electric vehicle was assigned to different grid nodes in the settlement model. The number of EV per grid node depends on the number of occupants per household and households per node. In the course of this study only those charging events were taken into account, which took place at home. Charging events e.g. at work or other stops were not included because they do not stress the low voltage grid in question. Figure 18 shows the averaged and normalized charging profiles (controlled and uncontrolled, IC)[2] accumulated with the household load profiles for a workday in 2030. Above all, the

[2] The averaged and normalized charging profiles (controlled and uncontrolled, FC 2030 and IC +FC 2050) for a workday can be found in the appendix.

uncontrolled charging increases the evening peak load significantly. In case of controlled charging the additional grid load appears during noon and in the nigth. The peak load during noon can be reduced accordingly by expansion of photovoltaics. With a EV penetration of 100 %, the household load peak increases even more strongly (see **Error! Reference source not found.** in the appendix).

The annual electric demand of the settlement (without EV) is 538 MWh/a. The overall electrical consumption for controlled and uncontrolled charging occurs not at the same time but the amount of charging energy exchanged with the grid is similar. The annual charging demand (including V2G) for all 33 EV (year 2030) is 90 MWh/a and for all 195 EV (year 2050) is 518 MWh/a.

Using load flow calculations the impact of various scenarios on the low voltage gird were investigated. Figure 19 shows the box plot for the occurring loads of the grid components (e.g. cables) as a percentage of the thermal limit values (controlled and uncontrolled, IC, 2030 and 2050)[3]. In comparison, on the left side of Figure 19 the resulting grid loads without electric vehicles (BEV + PHEV) can be seen. In the scenarios 2030 (33 EV) no low voltage grid component (transformer or cables) is overloaded.

In the area of the model grid which is carried out as an open loop (see Figure 15) the load density and the grid impact is strongest. All the maximum values of Figure 19 occur at cables of this open loop structure. To ensure that the required grid coupling (closing the ring) can be done in case of failure, the relevant grid components will be strained with maximal 70 % (of the thermal limits) in normal operation. Because of this restriction, there are violations of load limits at some cables in the scenarios of 2050 (195 electric vehicles in the settlement).

[3] The results for “frequent charging” are illustrated as figures in the appendix.

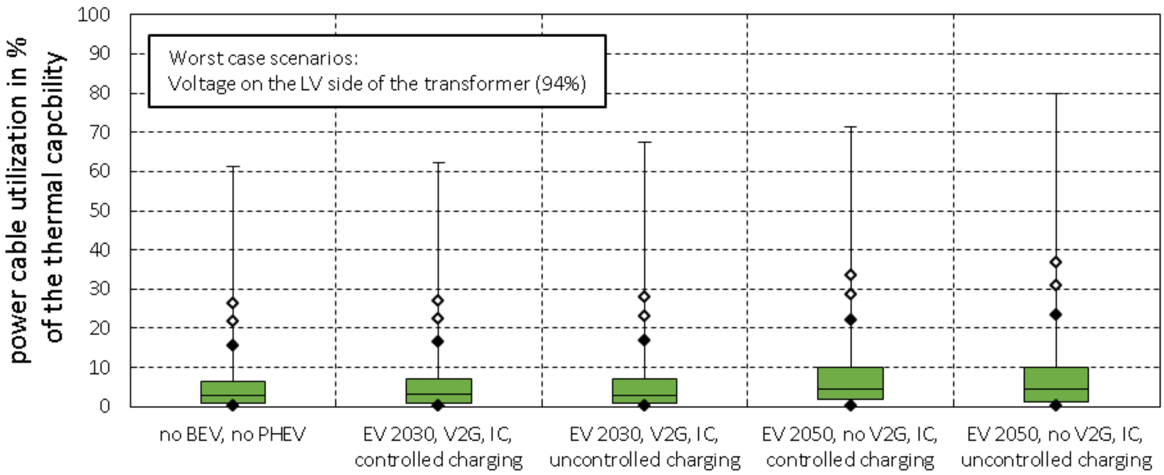

Figure 19: Box plots (minimum, 5 %, 25 %, 50 %, 75 %, 95 %, 98 %, 99 % quantiles and maximum) of all power cable utilizations in percentage of the thermal capacity; different scenarios (IC); minute values

With respect to the grid voltage, an extreme case has been adopted, in which the overlaying grid levels has already a high degree of capacity utilization ("peak-load"), caused through intensive electrical demand. Based thereupon the voltage on the LV side of the transformer is adopted with 94 % and the remaining voltage reserve for the observed low voltage grid is only 6 % [23]. Figure 20 shows the box plot of all grid node voltages (controlled and uncontrolled, IC, 2030 and 2050) and for comparison the values without EV. However, in this worst case scenario, no voltage limit at any grid node of the considered settlement was violated. The scenario "controlled charging, IC, 2030" shows a maximum voltage above 94 %. The reason for this effect is the included V2G mode with a load flow from the electric vehicle to the power grid (e.g. like a photovoltaics system). In the scenarios of 2050, the grid voltage drops at some nodes sharply and reaches values close to the limit. Consequently, in case of a failure and closing the open loop structure, it can possibly happen that a violation of voltage limits occurs. The same is true if the load further increases at that time.

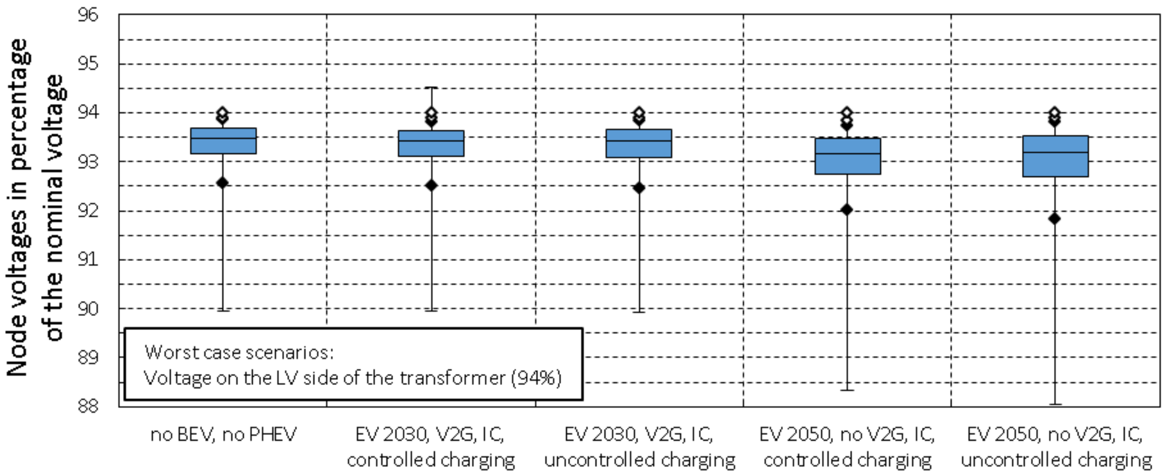

Figure 20: Box plots (minimum, 5 %, 25 %, 50 %, 75 %, 95 %, 98 %, 99 % quantiles and maximum) of all node voltages in percentage of the nominal voltage; different scenarios (IC); minute values

Results - EV interactions with the power grid

To estimate the impact of EV on the low voltage power grid a model of a "typical" Austrian settlement was developed. The goal of this model settlement is to represent the overall Austrian residential structure. The settlement involves a population of 300 people in 126 households and 60 residential buildings. The underlying synthetic low voltage grid consists of a rural and an urban area. This allows a simulation of various power grid topologies in one model. Based on practical experiences characteristic power cable lengths for the different grid areas and typical building types were adopted. For the individual households synthetic, appliance-based load profiles for an entire calendar year were recorded and different EV penetrations as well as various cost-based controlled and uncontrolled charging strategies were applied.

For a EV penetration of up to 16 % of the total Austrian vehicle stock (5 BEV and 28 PHEV in the whole model settlement) and connection powers per charging point of 3.7 kW (single-phase) and 11 kW (three-phase) no violations of grid constraints (thermal and voltage limits) on the low voltage level are expected. However, in the scenarios with 100 % of electric vehicles (38 BEV and 157 PHEV) there are violations of load limits at some power cables. Despite a worst case assumption, voltage problems have not been identified in any scenario of the model power grid.

In future the charging loads of electric vehicles, analogous to the degree of EV penetration, will inevitably lead to gird congestion problems on the low voltage level. Therefore, it is recommended to use low charging power levels and a symmetrical three-phase connection to preserve existing grid reserves. In addition, it should be noted that in grid sections with long feeders (with already high utilization) grid bottlenecks may already occur earlier.

8. Conclusions

A high-resolution power and heat system simulation model (HiREPS) for Austria and Germany was deployed to compare the relative impact and cost factors for cost based market-led and non-market-led immediate charging. Further investigations assessed how electric vehicle owners' charging behaviour impacted the benefits of market-led charging. In the analysed EM+ 2030 and 2050 szenarios, EVs make up 13 % (2030) and 100% (2050) of all passenger cars. Cost based market-led charging leads to more uniform, smoother operations for thermal power plant and reduces dependence on pumped storage. Market-led charging leads to a temporal shifting of electricity demand. This shifted electricity volume is comparable to the effect of pumped hydro power units (after optimal capacity expansion) in Austria and Germany in 2030 and 4.4 times larger in 2050. The average cost savings by market-led infrequent charging compared to immediate charging amounts to 23 Euro per electric vehicle and year for 2030 and 51 Euro per electric vehicle and year for 2050. Immediate charging of 100% electric vehicles in the year 2050 increased the peak load, compared to the marked led charging, by 16 GW for Austria and Germany. The cost of 16 GW peak load generation capacity is about 16 Euro per electric vehicle and year for the 48 million electric vehicles 2050. The effects of electric vehicles on the CO_2 Emissions, depends on the fact if additional renewable power generation is constructed for the additional electricity demand.

Charging the batteries of electric vehicles will take place to a large proportion decentralized in private space (at home or at work). This directly results in an additional grid load on the existing low voltage grids to which the necessary charging infrastructure is connected. Using load flow calculations the effects of uncontrolled and cost-based controlled charging were examined on the basis of a representative low voltage grid. The results of scenario 2030 show that under the chosen conditions neither grid components will be overloaded nor voltage limits are violated. However, in the scenarios with 100 % of electric vehicles (scenarios 2050) there are violations of the "n-1 criteria" at some power cables, but these grid problems seem to be solvable by using adequate load management systems. Despite a worst case assumption, voltage problems have not been identified in any scenario of the model power grid. Generally, to use the grid infrastructure efficient and as long as possible, the charging of electric vehicles in private space is recommended with a low power level. Furthermore, a three-phase charging is to prefer to achieve a balanced grid load.

9. References

[1] Leitinger, C., Litzlbauer, M., Schuster, A., et al. (2011): Smart Electric Mobility – Speichereinsatz für regenerative elektrische Mobilität und Netzstabilität, FFG-Forschungsprojekt, NE2020, 2. AS, Projektnummer: 821886, Endbericht, Wien 2011.

[2] ElectroDrive Salzburg (2012): Statusbericht der E-Mobilitätsmodellregion ElectroDrive Salzburg, http://www.e-connected.at, Juni 2012.

[3] Herry, M., Sedlacek, N., Steinacher, I. (2007): Verkehr in Zahlen – Österreich, Ausgabe 2007, Bundesministerium für Verkehr, Innovation und Technologie, Wien, November 2007.

[4] Herry, M., Steinacher, I., Tomschy, R. (2008): Mobilität in NÖ – Ergebnisse der landesweiten Mobilitätsbefragung 2008, Amt der NÖ Landesregierung, Abteilung für Gesamtverkehrsangelegenheiten, Wien, 2008.

[5] Herry, M., Russ, M., Schuster, M. Tomschy, R. (2004): Mobilitätsanalyse Stadt Salzburg und Umgebung 2004, Endbericht Version 1.0, Magistrat der Stadt Salzburg, Wien, Juli 2005.

[6] Herry M., Steinacher I., Tomschy R. (2009): Mobilität in Vorarlberg – Ergebnisse der Verkehrsverhaltensbefragung 2008, HERRY Consult GmbH im Auftrag des Amtes der Vorarlberger Landesregierung, Abt. VIa – Allgemeine Wirtschaftsangelegenheiten, Endbericht, Wien 2009.

[7] Infas, DLR (2010): Mobilität in Deutschland 2008, Ergebnisbericht, Bundesministeriums für Verkehr, Bau und Stadtentwicklung, Bonn und Berlin, Februar 2010

[8] Geringer, B., et al. (2012): Batterieelektrische Fahrzeuge in der Praxis, Institut für Fahrzeugantriebe und Automobiltechnik, TU-Wien, Endbericht, im Auftrag des ÖVK und des ÖAMTC, Wien 2012

[9] Litzlbauer, M. (2012): Grid integration of electric vehicles considering the mobility needs, Vortrag, 26th International Electric Vehicle Symposium, Los Angeles, USA, Mai 2012

[10] Kasten, P. (2014): Scenario building in DEFINE, interner Bericht, Forschungsprojekt DEFINE, transnationalen ERA-NET Plus Electromobility+ Ausschreibung, FFG-Projektnummer: 832408, Berlin 2014

[11] Personal communication from Benedikt Lunz, Energy Storage Systems Research Group, Prof. Dirk Sauer http://www.isea.rwth-aachen.de/de/energy_storage_systems_staff/

[12] Final report on accompanying research conducted by TU Vienna in "ElectroDrive Salzburg".

[13] Scenario framework for the Electricity Grid Development Plan 2013 – Draft (date: 17 July 2012),accessed on 24 Oct. 2014, link: http://www.netzentwicklungsplan.de/sites/default/files/pdf/Szenariorahmen_2013.pdf

[14] Andreas Krenn: Energy Workshop, Wind Atlas and Wind Potential Study, Austria, Feasibility Estimate of Existing Wind Power Potential,accessed on 24 Oct. 2014, link: https://www.klimafonds.gv.at/assets/Uploads/4-KrennEnergiewerkstatt.pdf

[15] Capros et al., PRIMES Reference Scenario 2011,accessed on 24 Oct. 2014, link: http://www.e3mlab.ntua.gr/e3mlab/index.php?option=com_content&view=category&id=35%3Aprimes

[16] Leitinger, C., et al. (2011): „Smart Electric Mobility - Speichereinsatz für regenerative elektrische Mobilität und Netz-stabilität“, FFG research project, NE2020, 2th call, FFG project number: 821886, final report, Vienna 2011

[17] Prüggler, W., et al. (2013): „V2G-Stratgies - Konzeption von Vehicle to Grid bezogenen Entwicklungsstrategien für österreichische Entscheidungsträger“, FFG research project, NE2020, 3rd call, FFG project number: 825417, final report, Vienna 2013

[18] Burnier de Castro, D., Rezania, R., Litzlbauer M. (2012): „V2G-Strategies – Auswirkung verschiedener Elektromobilitätsszenarien auf die Spannungsqualität von Niederspannungsnetzen unter Betrachtung der Phasenunsymmetrie“; oral presentaion: 12. Symposium Energieinnovation, Graz, 2012

[19] Gawlik, W., et al. (2014): „aDSM - Aktives Demand-Side-Management durch Einspeiseprognose“, FFG research project, NE2020, 5th Call, project number: 834612, final report, Vienna 2014

[20] Groiß, Ch., Maier, Ch., Gawlik, W. (2013): "Active and anticipatory Demand-Side-Management in Households"; Oral presentation: CIRED, Stockholm, Sweden; 10.06.2013 - 13.06.2013; in: "22nd Internat. Conference and Exhibition on Electricity Distribution", Paper No. 1277 (2013), ISBN: 978-1-84919-738-0; S. 1 - 4.

[21] Statistik Austria, 2004, "Gebäude- und Wohnungszählung 2001", Verlag Österreich GmbH, 1070 Vienna

[22] Zeilinger, F., Groiß, Ch., Schuster, A., (2014): „Detaillierte Modellierung des Haushaltsstromverbrauchs zur Untersuchung von Demand Side Management“; oral presentation: 13. Symposium Energieinnovation, 12. - 14. 02. 2014 Graz.

[23] Maier, Ch., Groiß, Ch., Litzlbauer, M., Schuster, A., Zeilinger, F. (2014): „Eigenverbrauchssteigerung in Haushalten durch Demand-Side-Management“; oral presentation: 13. Symposium Energieinnovation, 12. - 14. 02. 2014 Graz

Appendix

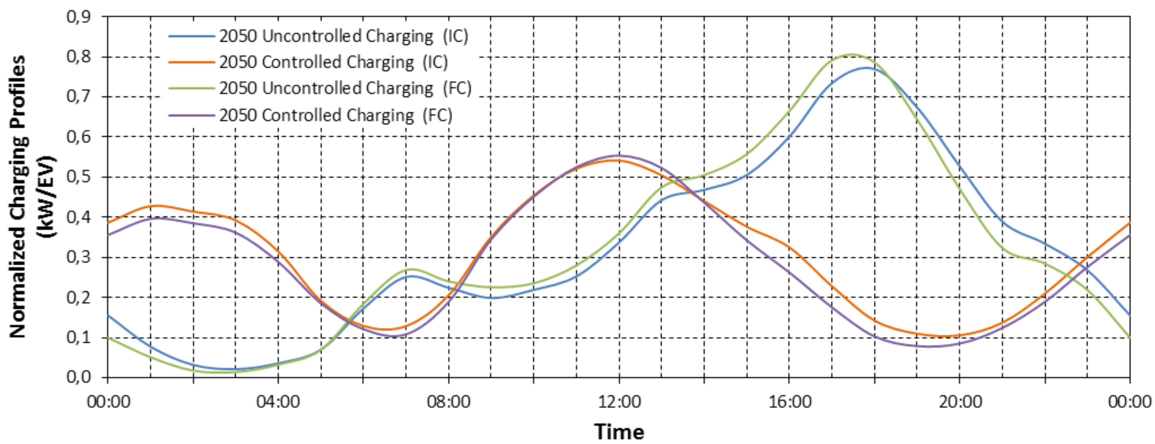

Figure 21: Different charging profiles at home for 2050 (100 % EV, frequent + infrequent charging, no V2G)

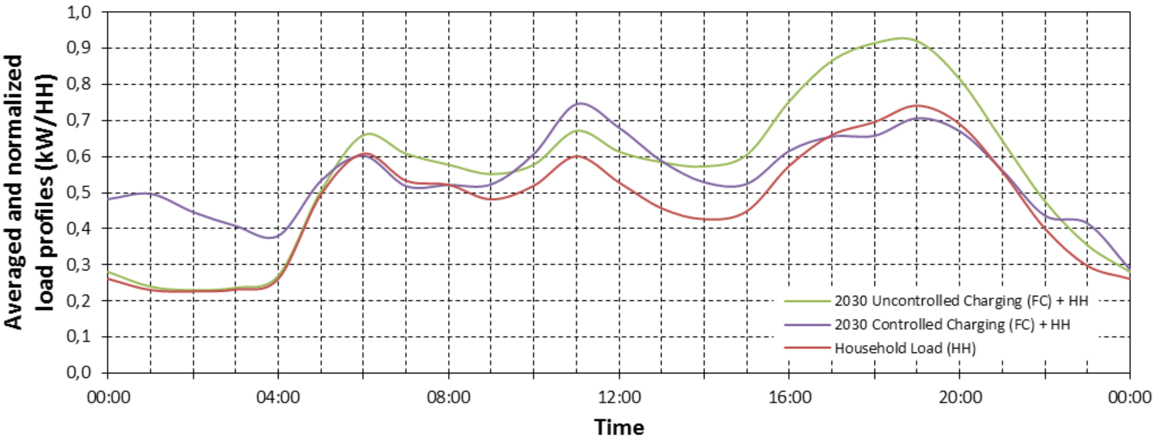

Figure 22: Household load profile plus different charging profiles at home for 2030 (16 % EV, frequent charging, V2G)

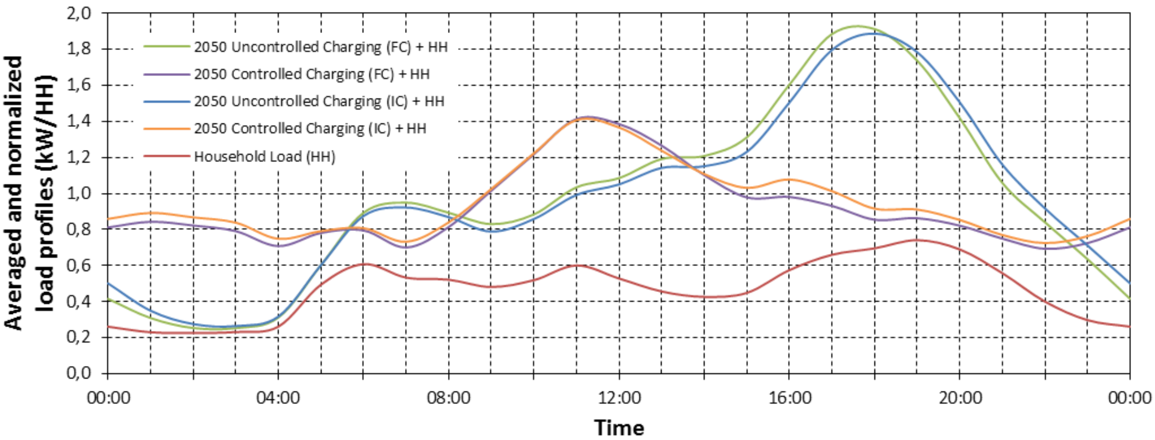

Figure 23: Household load profile plus different charging profiles at home for 2050 (100 % EV, frequent + infrequent charging, no V2G)

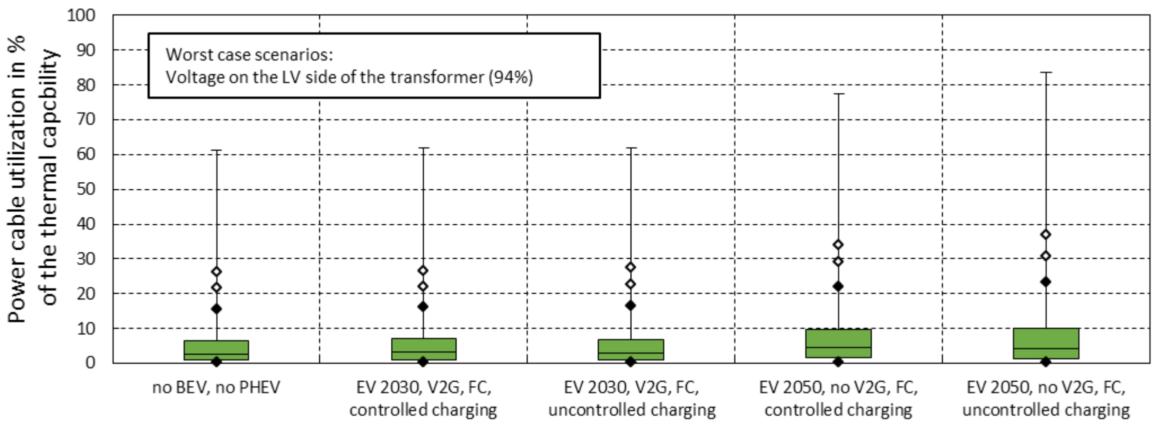

Figure 24: Box plots (minimum, 5%, 25%, 50%, 75%, 95%, 98%, 99% quantiles and maximum) of all power cable utilizations in percentage of the thermal capacity; different scenarios (FC); minute values

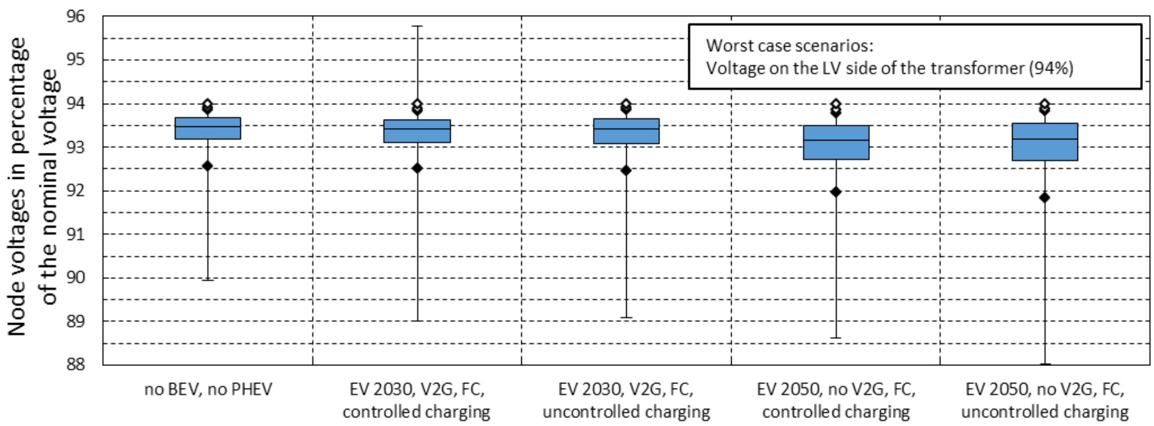

Figure 25: Box plots (minimum, 5 %, 25 %, 50 %, 75 %, 95 %, 98 %, 99 % quantiles and maximum) of all node voltages in percentage of the nominal voltage; different scenarios (FC); minute values