Work Package (WP) No: **5**

WP title:

Modeling of the energy demand related to the mass introduction of EV/PHEV

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Claas Matrose (RWTH) Paolo Scuro (Enel)	29/07/2011	1.1	Added Table of Content, introduction and conclusion	
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Paolo Scuro (Enel)	31/08/11	1.4	Fixed charging strategies names according to G4V	

1 Introduction

This deliverable has been produced in the scope of Grid4Vehicle (G4V) project and has the purpose to provide requirements for the recharging infrastructure that shall be deployed in order to charge electric vehicles.

The purpose of the deliverable is to describe the process adopted in order to simulate the effect of electric vehicle charge over the distribution grid. A number of different distribution grids (medium and low voltage level) have been collected from the DSOs involved in the project. The analysis of these data sets is described in this deliverable as well as the algorithms used for an analysis of the impacts of electric vehicles in these distribution grids. Furthermore, the different input data sets and assumptions are described – the represented behaviour of the batteries of EV, loads of households, number of cars per household etc.

The first chapter describes the set of grid data used as a reference for European distribution grids; the second chapter describes the algorithm itself, while third one provides an overview of the effect on the simulation obtained modifying the most important parameters. A further chapter has been dedicated to illustrate different possible behaviour of electric vehicles and especially the effect of charging strategies. Finally, the last chapter describes the format of results. Due to the large number of simulated grids and all the combinations of parameters, it is not possible to include in a single deliverable the overall set of results. Instead, the results have been used in WP7 in order to derive the roadmap.

The Grid4Vehicle project focuses on the effects of a large-scale rollout of electric vehicles on the electricity grid. It was therefore chosen not to focus on all aspects influencing the acceptance of electric vehicles, but to focus on those that would have a direct impact on the grid. This includes the factors related to the vehicle use, but especially those related to the charging process of electric vehicles. Factors more related to the general acceptance or purchase of electric vehicles are thus not taken into account. Within this category of charging related factors another focus is put on those factors that are user dependent. This means that vehicle or infrastructure dependent factors (like battery lifetime and duration of charging) are less focussed on. Between the categories use and purchase related factors and technical and user related factors, some grey areas exist.

Table of Content

2 Distribution Grid Database

In this project grid data from 5 different European countries has been analysed. The data has been separated by the voltage level (medium and low voltage level) and the type of area (urban, suburban and rural). The Figure 1 and Figure 2 show the structure of a medium and a low voltage grid. Geographical information was not included in every grid, so that this information could not be evaluated. The figures therefore represent only a schematic structure of the grids.

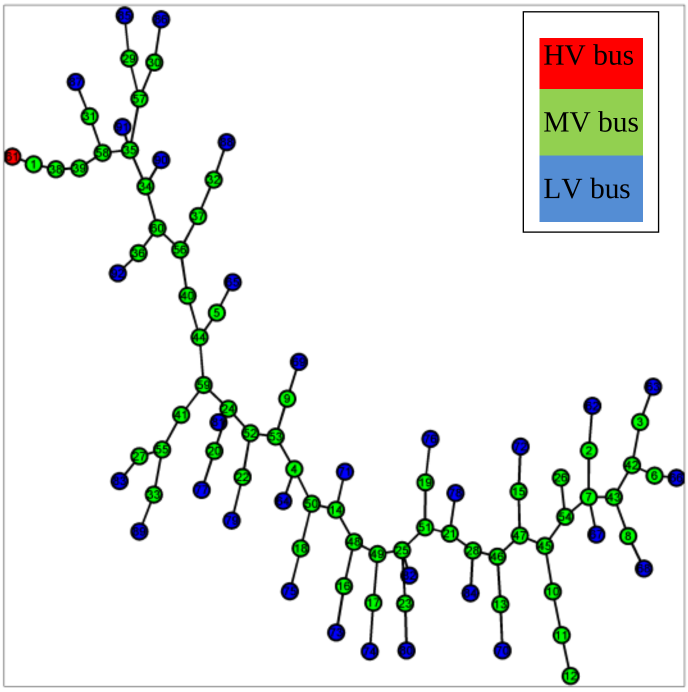

Figure 1: Exemplary schematic representation of a medium voltage grid

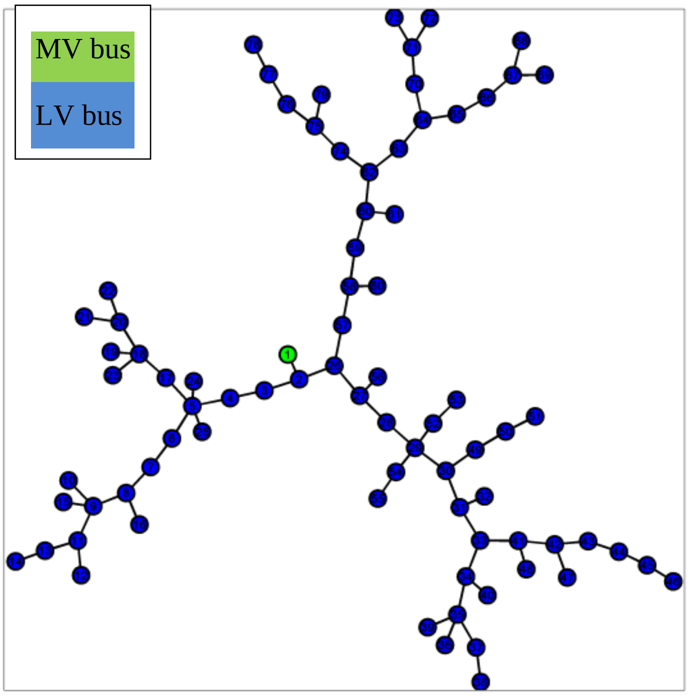

Figure 2: Exemplary schematic representation of a low voltage grid

Basically a rural network should be less densely populated as an urban network. This fact could be found in most of the collected grid data. The tables below list the average number of supplied customers at each network node. The empty fields indicate that for the respective network structure in that country no data was available for the calculation.

Note that average values result from the given exemplary grid data. No general statement possible

MV	Rural	Suburban	Urban
Sweden	5,87		143,77
Germany	135,2		115,57
Italy	71,37	48,58	124,9
Spain	48,61	54,88	193,53
Portugal	26,95	51,77	56,99

Table 1: Costumers per node in MV grids

LV	Rural	Suburban	Urban
Sweden	1		1,26
Italy	1,39	1,30	1,22
Spain	1,50		94,96
Portugal	0,81	0,53	1,11

Table 2: customers per node in LV grids

Following, the differences between the respective networks are considered. Thereby, both the differences in the grid structures, divided into rural, suburban and urban areas and the differences between the countries are investigated. Therefore, the size of the grids is considered. Representative for the size, the total lines lengths of the grids is analysed. Next, the electrical characteristics of the networks are considered in detail. Here especially the rated power of transformers and the thermal limit of the investigated in lines.

An increase in the length of lines from urban to rural areas is expected. This is due to the fact that rural networks need to cover large and less populated areas. The Figure 3and Figure 4 show an increase in line length from urban to rural networks for most of the countries.

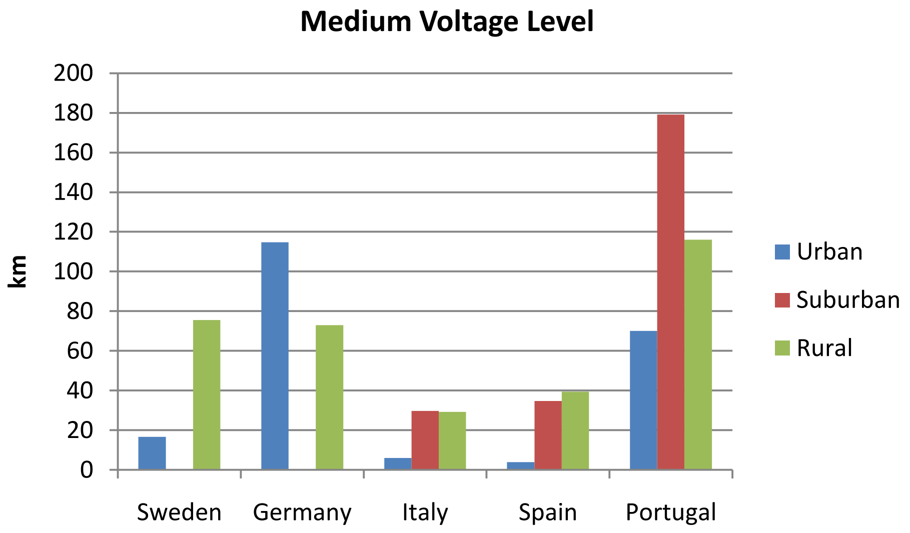

Figure 3: Line length in MV networks

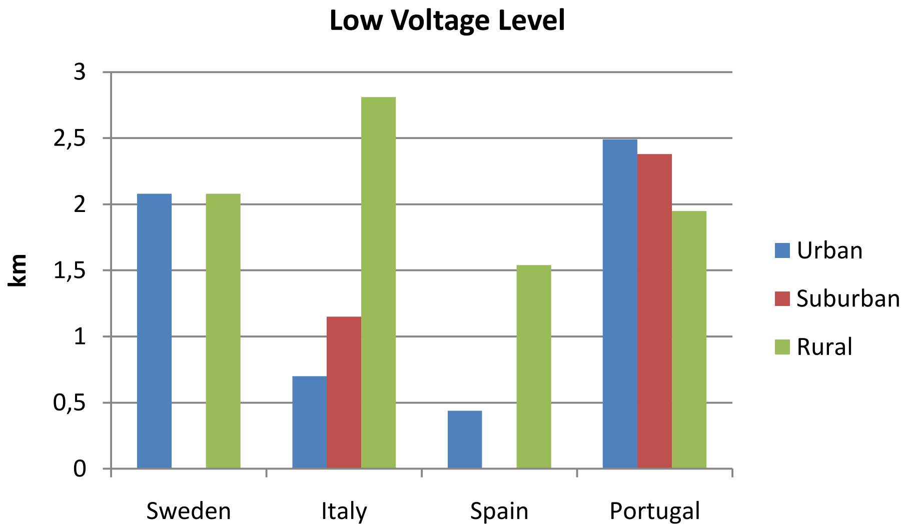

Figure 4: Line Length in LV networks

Further the average rated power of the transformers in the secondary substations reflects the grid structures. In urban grids transformers will have a larger rated power than in rural networks. The number of customers and thus the amount of load increases with the population density. Therefore, transformers must be installed with higher rated powers. The

Figure 5 shows the average values for the MV/LV transformers.

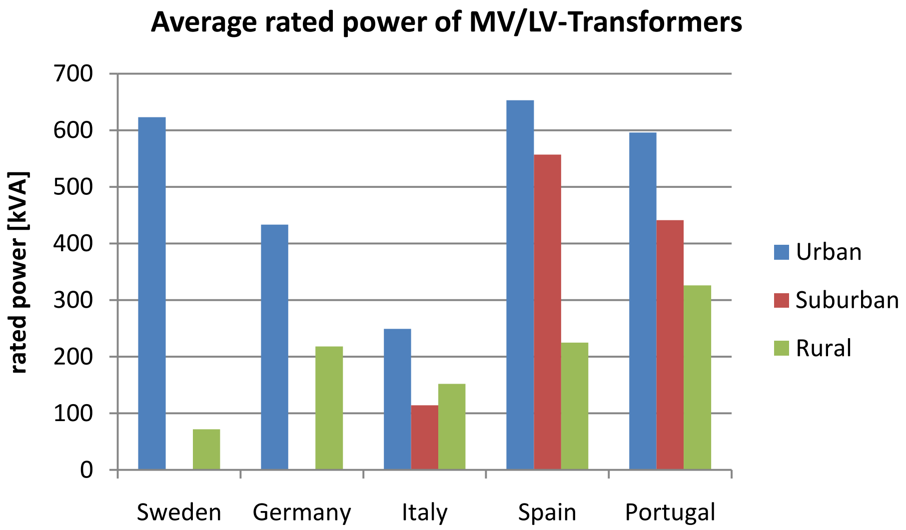

Figure 5: rated power of secondary substations

The next technical parameter that is investigated is the thermal current limits of the lines. This has been done separately for medium and low voltage lines. The Figure 6 shows the average values for the maximum current of medium voltage lines. These values again show major differences between the different grid structures. The limit on the lines in urban areas is roughly twice as large as for the lines to rural areas (Figure 7).

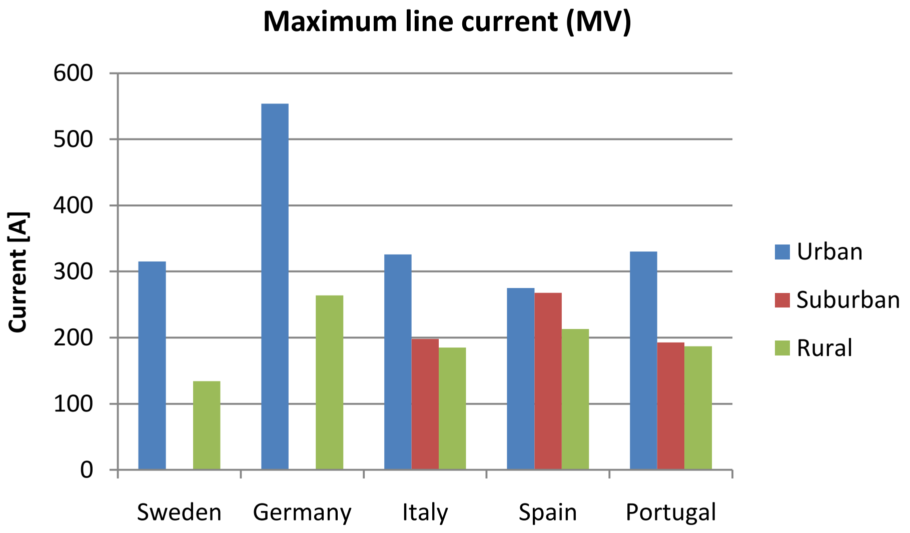

Figure 6: MV maximum line current

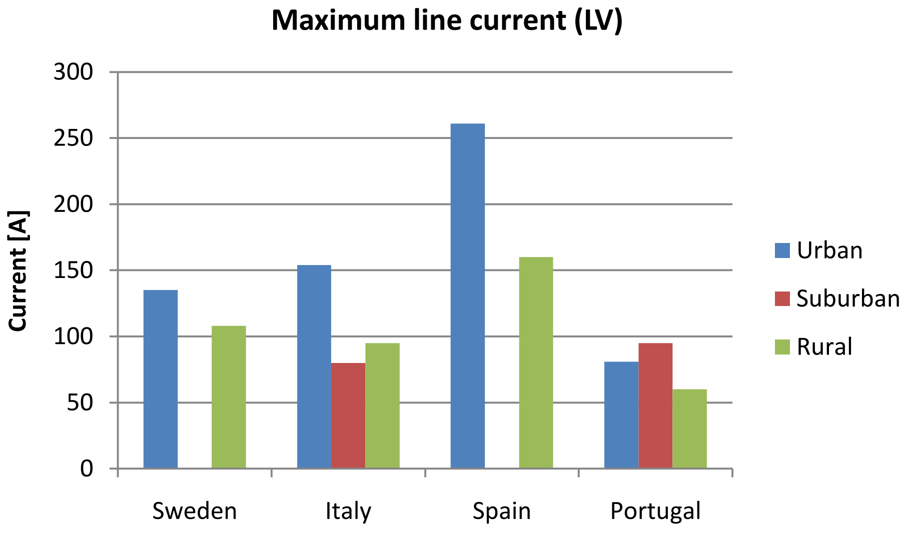

Figure 7: LV maximum line current

3 Load flow calculation algorithm

Based on the distribution grids collected and described in the precedent section, this chapter describes the methodology of the load flow calculation and the implemented algorithm. A general description of the load flow calculation tool is described in chapter 2.1, followed by a description of the probabilistic approach in chapter 2.2 and the allocation of the electric vehicles to the busses of the grid, which is described in chapter 2.3.

3.1 Overall functionality of the load flow calculation algorithm

The overall functionality of the load flow calculation algorithm consists of three parts:

- Allocation of loads to the busses of the grid
- Performing the load flow calculations for different scenarios
- Probabilistic interpretation of the obtained results

The allocation of the loads to the busses is performed according to the information provided with the grid: For each of the distribution grids and for each bus it is known or a method was given how to calculate, either how many households are connected to the bus or what the peak load at the bus is. Then the adequate number of smart meter profiles is allocated to the bus as a load (this is the case for Italian and Spanish grids) or standard load profiles are allocated to the bus in dependence of the peak load (this is the case for German, Portuguese and Swedish grids). Table 3 shows, which approach has been used for which country.

Country	Germany	Italy	Portugal	Spain	Sweden
Pool of Smart Metering Data		X			
Standard Load Profiles	X		X	X	X

Table 3: Overview of allocation of loads in dependence of grid origin

The pool of Smart Metering Data contains a lot of load profiles measured for domestic clients. In contrast to the standard load profiles the pool of smart metering data also contributes to the stochastical results of the load flow simulation (see also chapter 2.3).

For some grids not the number of households for each bus is known, but only the maximum load. In these cases, standard load profiles are used. The following figure shows the used load curves for the five described countries, standardized to the maximum load. For most countries, the peak load is between 7pm and 9pm, for Portugal the maximum load occurs around noon. The data was provided by the grid operators of the different countries together with the grid data.

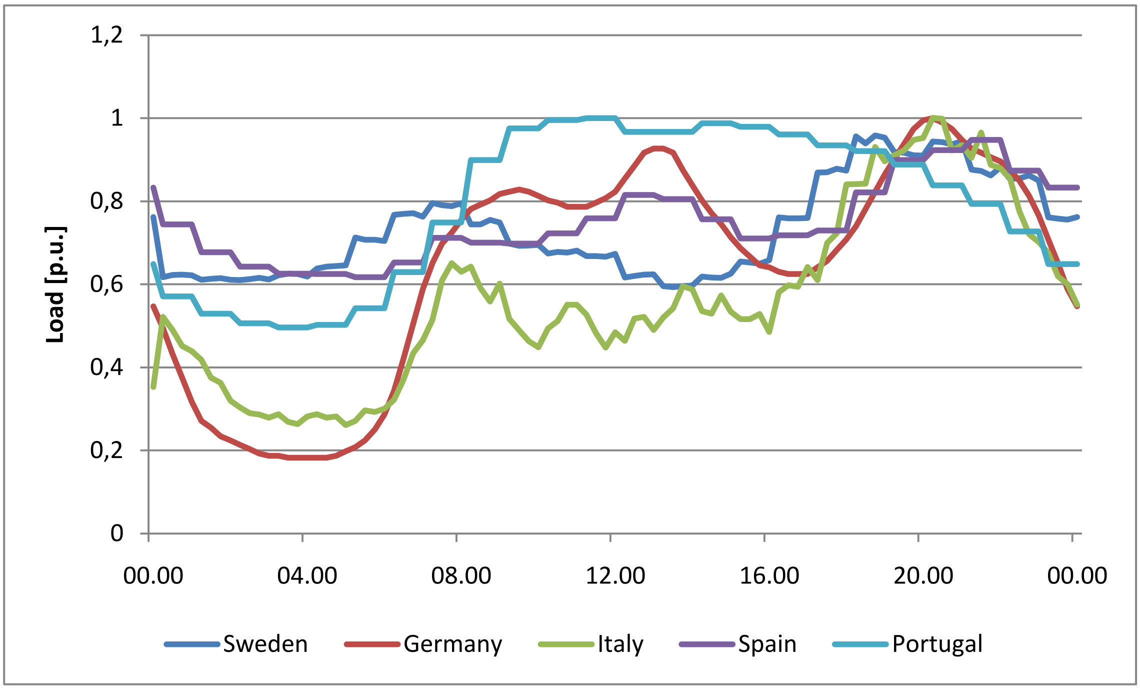

Figure 8: Standard load profiles

After allocating the loads to the distinct busses, the actual load flow calculation is performed. Core of the load flow calculation algorithm is MATPOWER©, a package of MATLAB® M-files for solving power flow and optimal power flow problems [MAT11]. Based on the structure of the grid and the allocated loads the load flow calculation uses numerical methods to come to loadings of the grid assets.

3.2 Allocation of the vehicles to the grids

For each bus it is either known, how many households are connected to the bus or the grid data contains the information of the peak load at each bus. For each country, the number of households, the number of vehicles and the peak load of the country are summarized in the Table 4 (information given by grid operators of different countries): Given this information, one can obtain the number of vehicles per peak load [Vehicles/MW] or the number of vehicles per household. Given the number of households at each bus or the peakload at each bus, one can thus calculate the number of vehicles for each bus. If information about the number of households and the peak load are available, the number of households will be used as a basis for the calculation of the number of vehicles.

	Households	Vehicles	Peak Load [MW]	Vehicles/ MW	Vehicles/Household
Sweden	4.000.000	4.279.000	27.3	156,9	1,07
Germany	40.034.000	41.737.000	76.8	543,3	1,04
Italy	23.646.000	35.680.000	52.1	684,4	1,51
Spain	19.031.000	22.145.000	43.9	504,0	1,16
Portugal	4.977.000	5.757.000	9.4	612,7	1,16

Table 4: Summary of assumptions regarding the load situations

Once the number of vehicles at a bus is known, the load profiles of the vehicles are derived from a pool of driving patterns. For each scenario (a combination of charging power and charging infrastructure) a pool of driving patterns of about 20.000 vehicles has been derived, which are allocated to the busses in a probabilistic way.

3.3 Description of the probabilistic Approach

There are two main reasons to perform the load flow calculations in a probabilistic way, which result from uncertainties concerning the allocation of the loads to the grid busses:

- If smart meter data load profiles are used to model the load of residential customers, it is not known, which smart meter profile is allocated to which bus in the grid. Thus, the smart meter profiles are allocated to the bus in a probabilistic way with a certain number of iterations for each time step.
- The number of vehicles at each bus is known, but the allocation of the load profiles to the busses is not known. Thus, the load profiles have to be allocated to the busses in a probabilistic manner.

To draw conclusions concerning the probabilistic allocation of smart meter load profiles and load profiles of vehicles to the busses with regard to the load of assets, a certain number of iterations has to be calculated in order to be able to analyse the load of the assets. An example is shown in Figure 9: It shows the loading of one line of the grid at one instant of time: The load profiles of the smart meter data and the load profiles of the vehicles have been allocated to the busses 10 times at one instant of time. In 5 cases, the loading of the line has been between 0.83 and 0.84 p.u., in 2 cases it has been between 0.82 and 0.83 p.u. (blue columns). The red line shows the estimated normal distribution of load distribution with a mean value of μ=0.84 and a standard deviation σ.

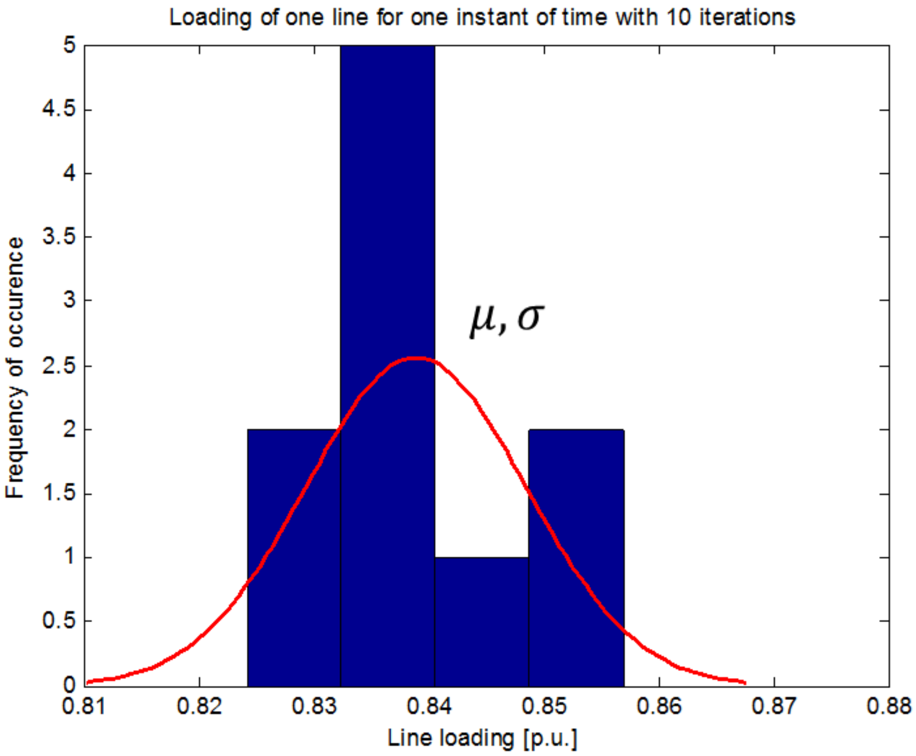

Figure 9: example for probabilistic results

The fit of the frequency distribution and the estimated normal distribution enhances with the number of iterations. The more iterations are simulated, the better is the frequency distribution described by the estimated normal distribution, which is demonstrated in Figure 10, where the results are shown for 50, 250 and 1000 iterations.

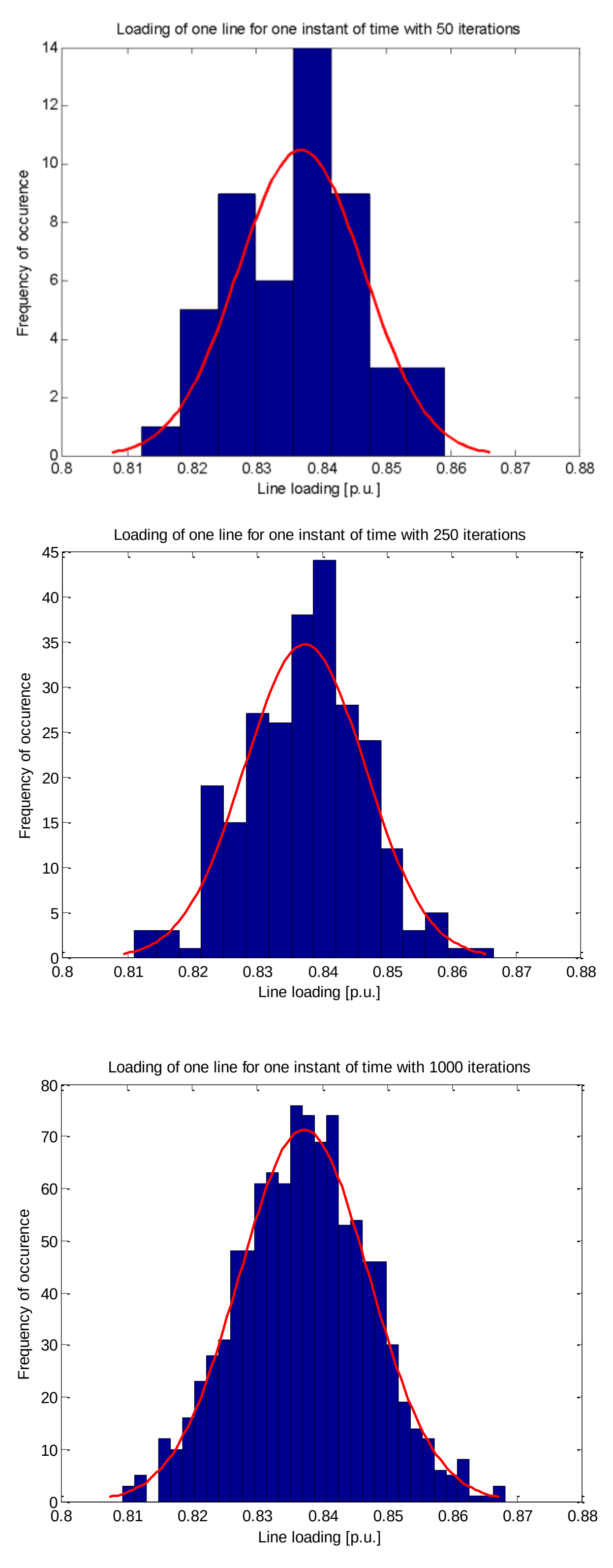
Loading of one line for one instant of time with 50 iterations
Frequency of occurence
0
2
4
6
8
10
12
14
0.8
0.81
0.82
0.83
0.84
0.85
0.86
0.87
0.88
Line loading [p.u.]
Loading of one line for one instant of time with 250 iterations
Frequency of occurence
0
5
10
15
20
25
30
35
40
45
0.8
0.81
0.82
0.83
0.84
0.85
0.86
0.87
0.88
Line loading [p.u.]
Loading of one line for one instant of time with 1000 iterations
Frequency of occurence
0
10
20
30
40
50
60
70
80
0.8
0.81
0.82
0.83
0.84
0.85
0.86
0.87
0.88
Line loading [p.u.]

Figure 10: load distributions with 50 (top left), 250 (top right) and 10000 (bottom) iterations

In order to decide, how many iterations have to be performed to come to reliable results, it is necessary to analyse how the values of the normal distribution (namely mean value μ and standard deviation σ) develop with an increasing number of iterations. The results are shown in Figure 11 and Figure 12: Depicted are mean value and standard deviation of the loads in each iteration about 30 medium voltage lines as a function of the number of iterations. For the mean value μ less than 50 iterations are needed to come to the same result as after 1000 iterations. On the other hand for the standard deviation σ around 200 iterations are needed before the value stabilizes around the value at 1000 iterations.

In the simulations it has also been shown that the frequency distribution of the simulations can be described with normal distributions. This has been proven with the Lilliefors-test [LIL11]. The Lilliefors-test analyses, if a frequency distribution follows a normal distribution at a certain confidence interval[1]. At this confidence interval the test is either successful (that means, the frequency distribution follows a normal distribution) or it is unsuccessful (that means the frequency distribution does not follow a normal distribution). In some cases the test cannot be applied, because input load data is too close to zero (marked with “not applicable”).

For 30 assets the Lilliefors-Test has been applied for different numbers of iterations. Already with a few iterations the Lilliefors-Test confirms, that the frequency distribution follows a normal distribution for almost all the assets. Only for one asset the Lilliefors-Test is not applicable: The Lilliefors-Test cannot determine a mean value and a standard deviation taking into consideration the given confidence interval, because the loadings of the asset are close to 0 p.u.. These cases are uncritical with regard to the grid enhancement, since no overload will occur at these assets. Also a slight tendency can be seen that the Lilliefors-Test is the more successful the more iterations are performed.

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[1] The following results have been performed with a confidence interval of 95%.

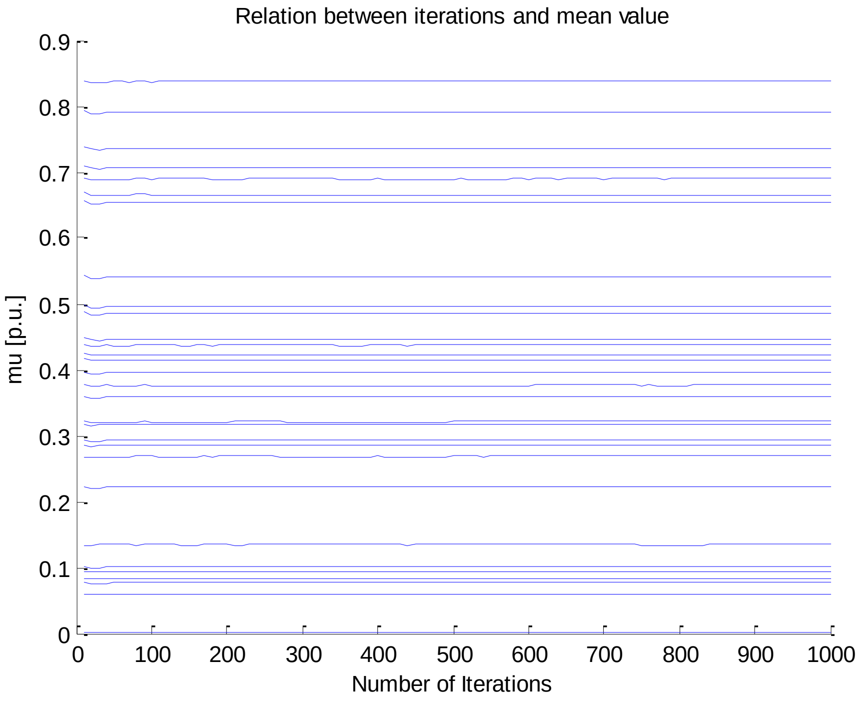


Figure 11: Relation between iterations and standard deviation value

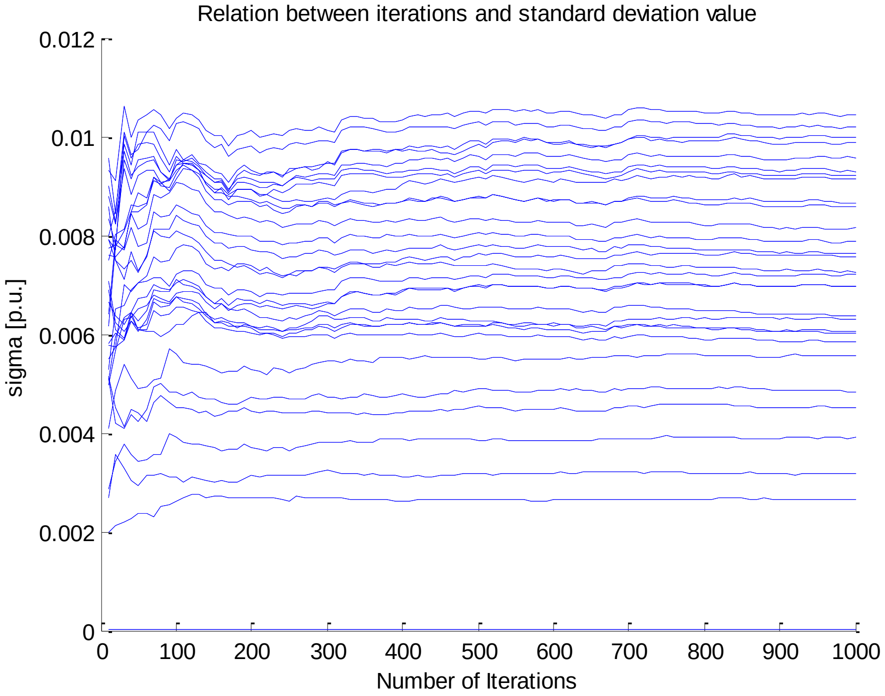


Figure 12: Relation between iterations and standard deviation value

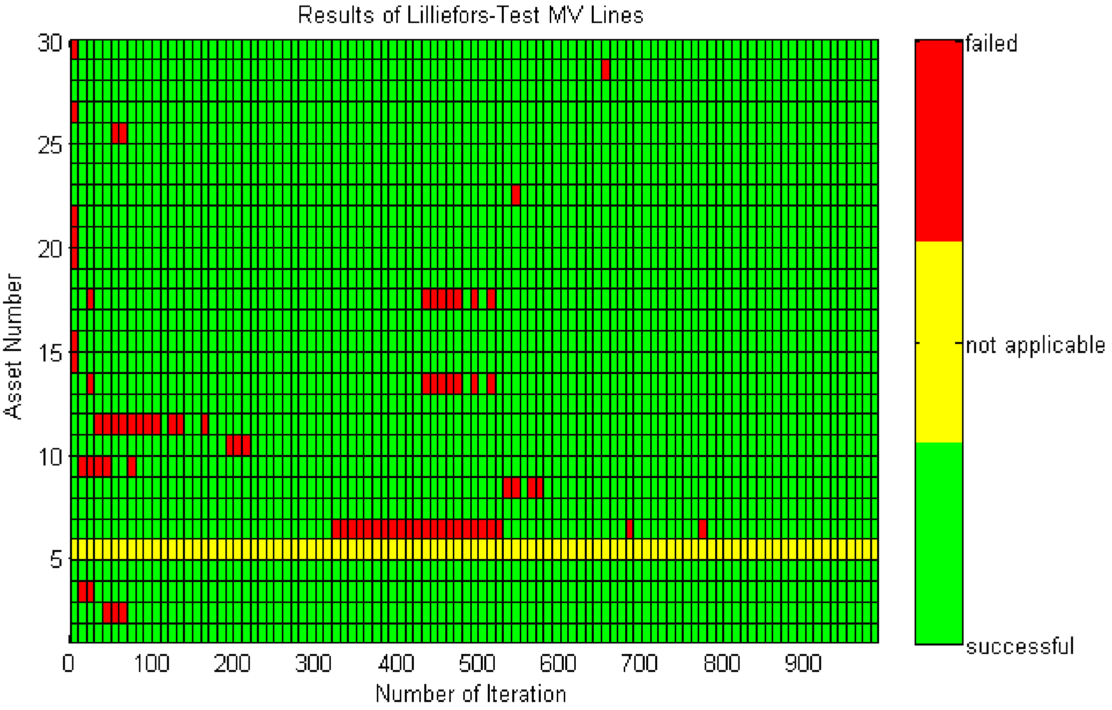


Figure 13: Results of the Lilliefors-Test in dependence of the number of iterations

The description of the load of the assets with a normal distribution (and thus only two paramters, mean value μ and a standard deviation σ) has two main advantages:

Firstly, not all the results have to be stored: With a number of iterations of 200 only two instead of 200 values have to be stored. With regard to the number of scenarios simulated in the G4V project and the number of grids, this is a significant gain and leads to results databases of some hundred gigabytes instead of Terabytes.

Secondly, the results can easily be interpreted with the help of normal distributions, which is described with Figure 14: If the loading of an asset is given with the normal distribution and the corresponding (μ,σ)-combination, there is only a 5% probability, that the asset is loaded higher value than μ+1.64*σ. In other words: With a probability of 95% the loading of the asset at this specific point of time is lower than the value μ+1.64*σ.

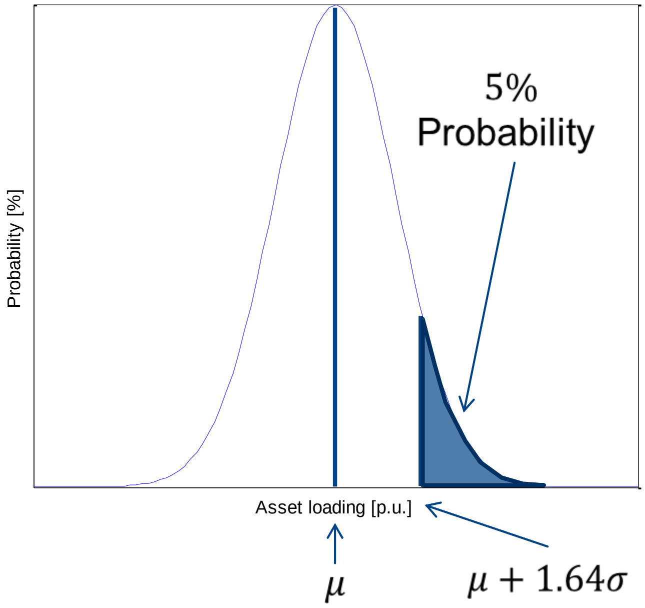


Figure 14: Probability of loading for a normal distribution

4 Overall Load profile for the different grids

The following chapter deals with the overall load profile and the influence of different parameters on the overall load profiles of chosen distribution grids. It will be shown the influence of the penetration rate, the influence of the charging power and the influence of the charging infrastructure on the overall load profile.

Whereas the fixed loads or the pool of smart meter data stays the same for each scenario, the parameters for the behaviour of the electric vehicles are changed. For each of the driving patterns of the pool of 20.000 vehicles it is known, at what instant of time the vehicle is driving (with the respective driven distance) or parking (at home, at work, elsewhere). The driving patterns are derived from a German mobility study from 2008 [2]. Due to a lack of specific data for other countries, this data set had to be used for all calculations.

4.1 Format of Results

To compare the effects of different penetration rates, charging strategies, infrastructure etc., always four examples will be compared in the following chapters. To provide a better understanding of those results, Figure 15 is introduced as an example to the results format.

This type of diagram consists of four main aspects: the load per unit axis, that asset number axis, the time axis and the one-per-unit-layer (1 p.u. layer). Each of the lines in the diagram is drawn for one individual asset along the time axis (for one full day) and represents the load of this assets as a per unit value. The lines are ordered by their maximum, i.e. the asset number in this diagram is in no way correlated with the asset name or number possibly given by the grid operator and therefore it is also not correlated with the position of the asset in the grid. The one-per-unit-layer is introduced as an aid to identify the number of assets, which are operated at loads above their given limit. The longer the line remains above the 1 p.u. layer, the longer the asset is operated above its limits.

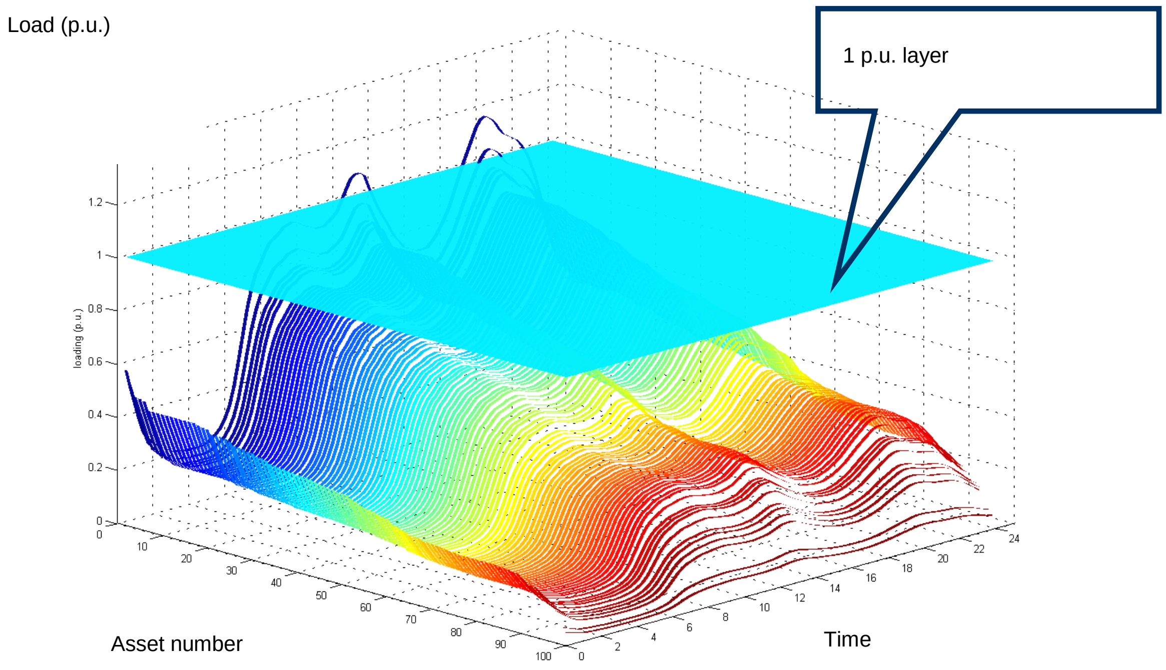


Figure 15: Result format example

4.2 Influence of Penetration Rate

The penetration rate is the share of conventional vehicles, which have been replaced by electric vehicles and was varied in the simulations in 5% steps from a penetration rate of 0% to 100%. It has been shown in Chapter 2.2, how the number of electric vehicles is allocated to the busses. The number of vehicles calculated there is equivalent to a penetration rate of 100%. Accordingly, the number of electric vehicles at a penetration rate of 20% is only 20% all the conventional vehicles calculated in chapter 2.2.

As an example, the influence of the penetration rate in this chapter is shown with an exemplary medium voltage grid (Italian grids have been used for all examples). As an exemplary asset, the influence on the secondary substations is shown in the following figure. The situation of the grid without electric vehicles can be seen in the top left of Figure 15 with a penetration rate of 0%. The figure shows the load in p.u. (z-axis) as a function of the asset number (about 100 secondary substations, y-axis) and time (in 15 minutes resolution for one day, x-axis). The load at each instant of time is here the 95% security interval according to chapter 2.3, thus mean value μ+1.64σ. One can see that two secondary substations are slightly overloaded in the evening, one of them also around noon. With a penetration rate of 35%, already about 10 assets are overloaded in the evening according to the top right figure. With a penetration rate of 100% already more than half of the secondary substations are slightly overloaded in the evening.

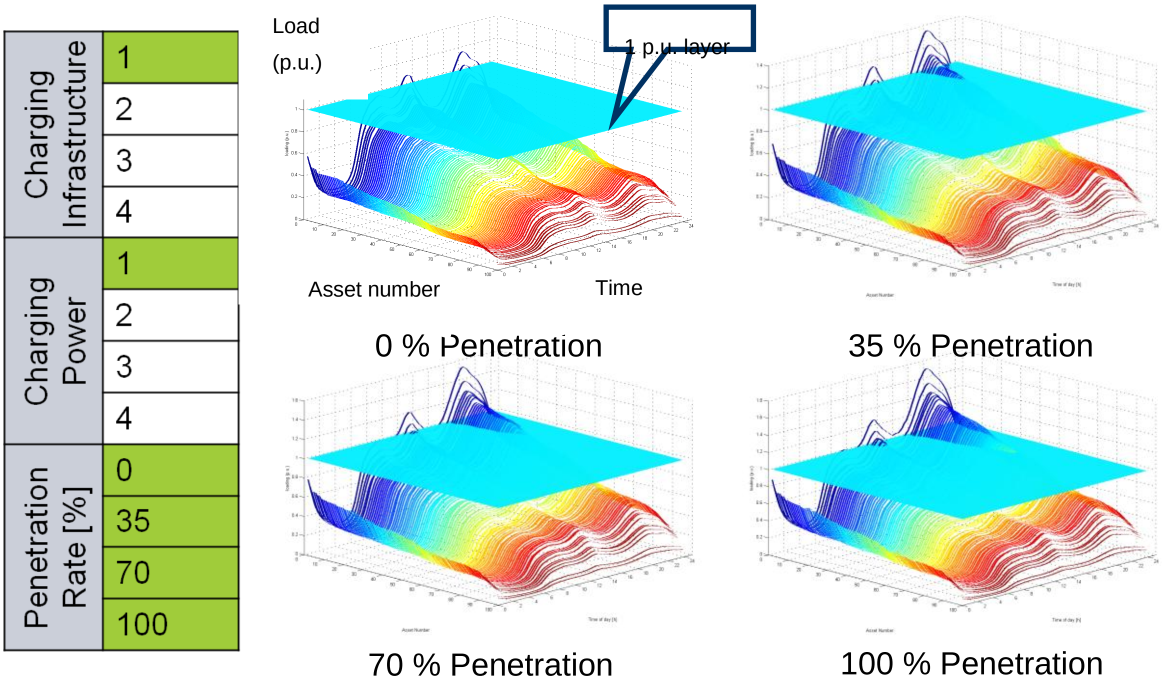


Figure 16 Loading of MV transformer in exemplary grid, charging at home, 3.7 kW

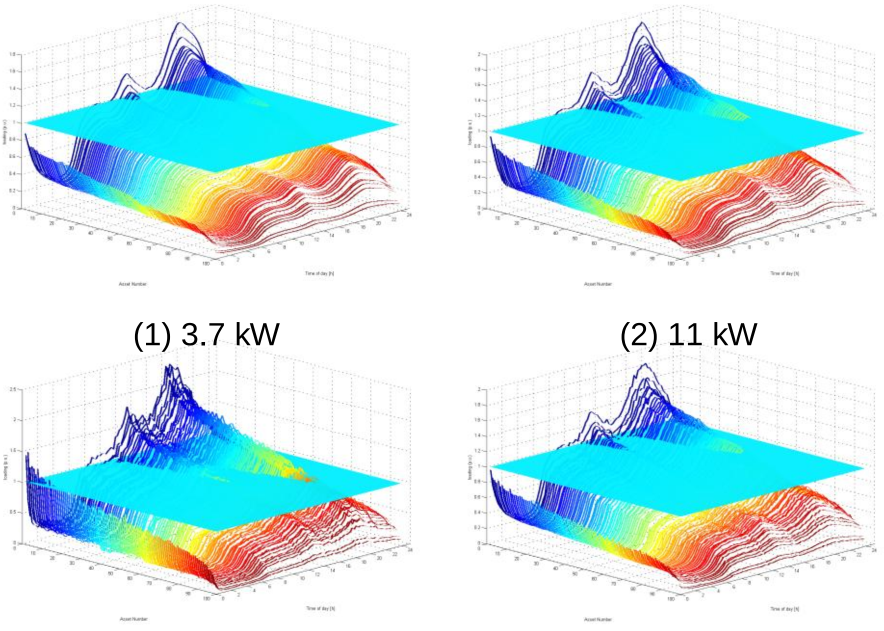
4.3 Influence of Charging Power

The charging power is the maximum connection power of the electric vehicles to the grid. There have been analysed four kinds of charging powers:

- 3.7 kW (AC, 1 phase, 16 A) (1)
- 11 kW (AC, 3 phase, 16 A) (2)
- 55 kW (DC, fast charge) (3)
- A mix of the charging strategies: 70% of (1), 20% of (2), 10% of (3).

The results for one exemplary grid are depicted in Figure 17: Generally the load of the secondary substation – especially in the evening – increases with an increasing connection power. Though the charged energy is the same, the high concurrency of vehicles arriving at these instances of time leads to higher overloads in the secondary substations. With a charging power of 55 kW almost all the secondary substations are overloaded, because already a few vehicles charging at the same secondary substation can lead to an overload situation. One can also see effects on the probabilistic methodology: At very high connection powers especially for the standard deviation more than 200 iterations would have led to smoother load curves of the assets, since the standard deviation at these high connection powers needs more iteration in order to converge against the final value.

Charging Infrastructure	🟩 1
	2
	3
	4
Charging Power	🟩 1
	🟩 2
	🟩 3
	🟩 4
Penetration Rate [%]	0
	35
	70
	🟩 100


(1) 3.7 kW

(2) 11 kW

(3) 55 kW

(4) Mix (70%, 20%, 10%)

Figure 17: loading of secondary substation shown for different connection power ratings at home", 100% penetration

4.4 Influence of Charging Infrastructure

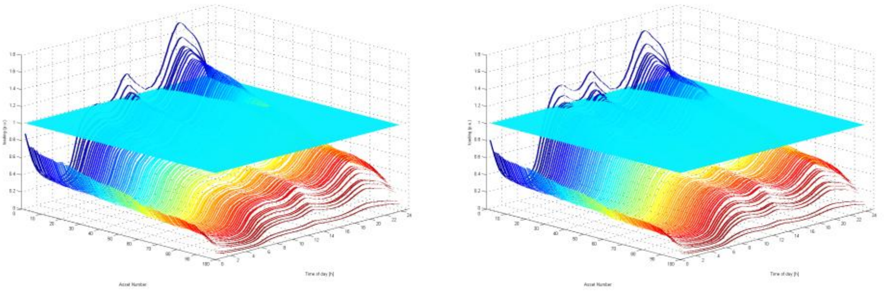
Another important parameter is the charging infrastructure. For the simulations, four kinds of charging infrastructures have been simulated:

- At home
- At home and at work
- Everywhere
- At home and at work, but at work outside the considered grid.

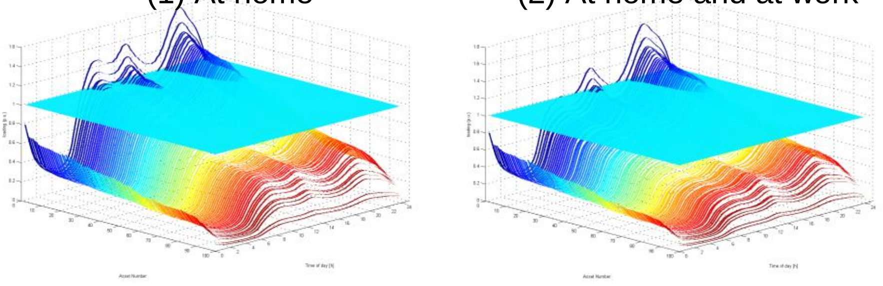
The last charging infrastructure represents the case that a grid with residential customers is considered, who charge their vehicles outside the considered grid at a work charging infrastructure. That means that the vehicles are charged at work, but the necessary energy is not delivered by the secondary substations in the considered grid.

The results of the influence of the different charging infrastructures can be seen Figure 18: In the charging infrastructure “at home” the peak load occurs in the evening when the vehicles come back from their workplaces. The peak in the evening in the “at home” scenario is much higher than the peak at noon, where only some vehicles are able to charge. This changes when it comes to the scenario “At home and at work” and “everywhere”: In these scenarios a part of the charging energy is shifted from the evening hours to noontime, since the vehicles are not only able to charge at home (mostly in the evening), but also at work or places different from at home and at work.

Charging Infrastructure	🟩 1
	🟩 2
	🟩 3
	🟩 4
Charging Power	🟩 1
	2
	3
	4
Penetration Rate [%]	0
	35
	70
	🟩 100



(1) At home (2) At home and at work



(3) Everywhere (4) At work in a different grid

Figure 18: Loading of secondary substations with different places of charging 3.7kW, 100% penetration

5 Load profiles of EVs used for the load flow calculations

The load profiles of the electric vehicles are mainly influenced by three parameters:

- Assumptions and technical description of the battery behaviour
- Influence of the scenarios concerning charging power and charging infrastructure
- Influence of different kinds of control mechanisms to influence the load curves.
- The third aspect is explained in detail in the G4V WP6.

5.1 Battery behaviour

Batteries and their behaviour during charging and discharging operations are very complex. To model the behaviour of Li-Ion-Batteries, a simplified charging curve has been implemented in the simulations. This charging curve is based on a constant-current constant-voltage behaviour. One main aspect of this charging curve is, that up to States of Charge (SOC) of 70% the battery can be charged almost with the full power of the charging connection, but the last 30% of the battery's capacity are charged with a reduced charging power. This behaviour is depicted inFigure 19:

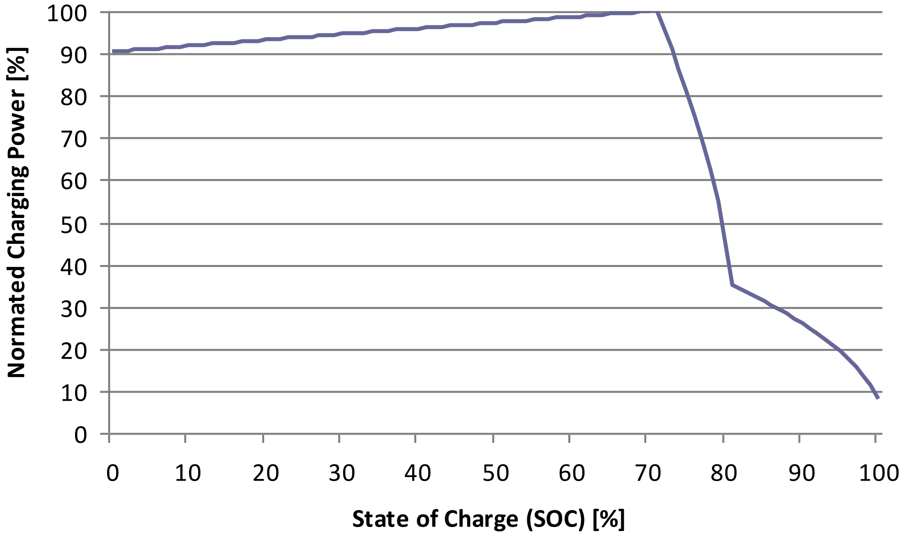


Figure 19: Relation between State of Charge and Charging Power of a Li-Ion-Battery

This also has an influence on the time needed for a complete charging procedure: Since the battery cannot be charged at full power during the last 30% of the battery capacity, the charging procedure needs about 60% of the time to charge the last 30% of the battery, while the first 70% of the battery are charged with only 40% of the overall time. This relation is shown in Figure 20:

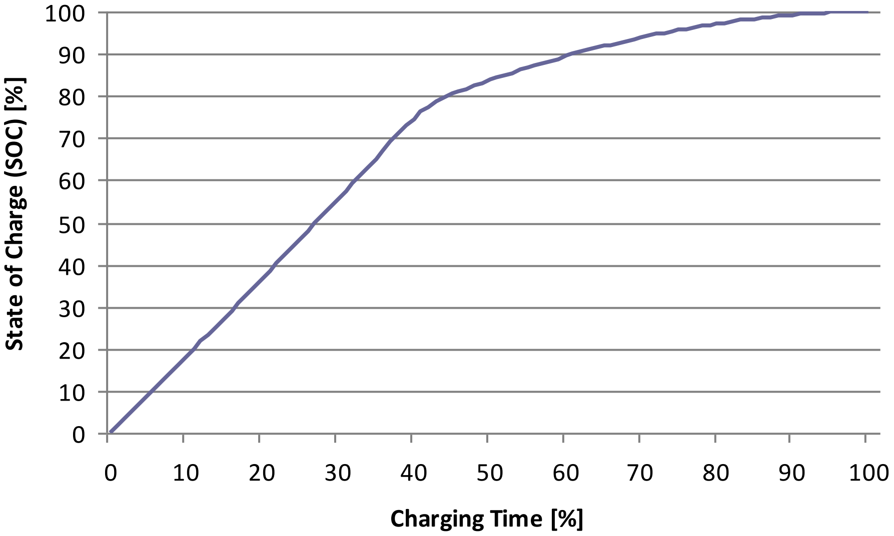


Figure 20: Relation between State of Charge and Charging Time of a Li-Ion-Battery

5.2 Influence of scenario parameters

This section briefly illustrates the influence of the scenario parameters charging power and charging infrastructures on the load profiles of the electric vehicles. Exemplary influences of these parameters have already been given in section 3.2 and 3.3, whereas this section is dedicated to the load of the electric vehicles only.

In the following figure the influence of the charging infrastructure on the sum of the load of the 20.000 vehicles in the vehicle pool used for the simulation is depicted for a charging power of 3.7 kW. The charged energy, in other words the area beneath the curve is the same except for the case, where the vehicle charges at work outside the grid only. In the “at home” scenario, the peak load appears in the evening, while in the scenarios “at home and at work” and “everywhere” a significant amount of energy is charged earlier, already in the morning and around noon.

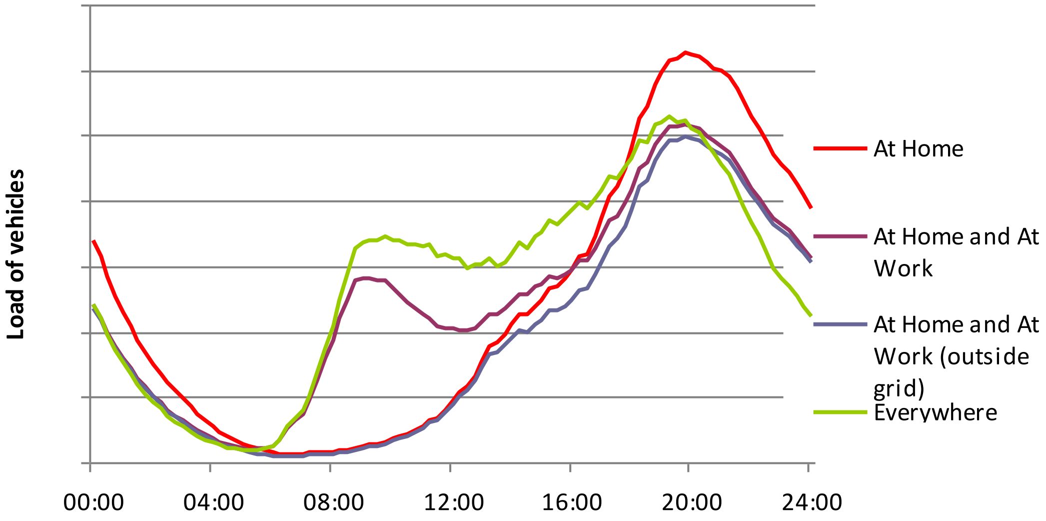


Figure 21: Influence of the charging infrastructure on the load of the vehicles

Figure 22 depicts the influence of the charging power for the charging infrastructure scenario "Everywhere". One can see that a higher charging power leads to higher loads, especially at those instants of time, where many cars come to a charging infrastructure at the same time (in the morning and in the evening). At these instants of time, the overall load is higher than with a connection power of 3.7 kW and the charging procedures are finished sooner than in the 3.7 kW scenario, so that the load is reduced faster than in the 3.7 kW scenario. The load of electric vehicles with a charging power of 55 kW in the morning is almost twice as high as in the 3.7 kW case.

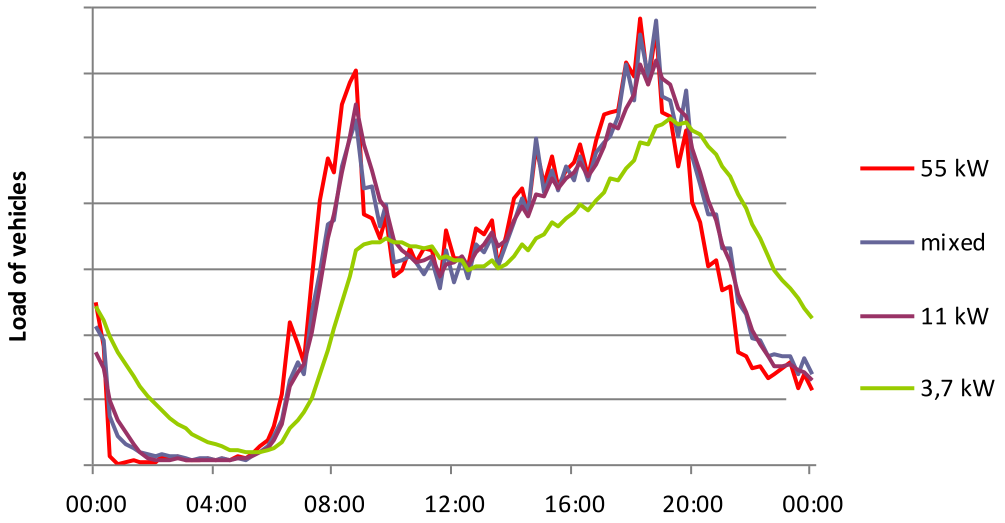


Figure 22: Influence of the charging power on the load of the vehicles

5.3 Influence of charging strategies

In the G4V WP6 (see [4]) several charging strategies have been described. Charging strategy in this context means a control mechanism of some kind in order to directly control the charging of electric vehicles by controlling the charging power directly or indirectly influence the charging of electric vehicles by giving price incentives to the owner of an electric vehicle in order to shift the charging procedure from a peak load situation to an off-peak load situation. The considered 8 charging strategies have been segmented to three differently advanced regimes concerning the communication and implementation complexity: Conservative World, Advanced World and Visionary World.

5.3.1 Conservative World

Strategies in the conservative world can be implemented in the near future with almost no communication complexity between the electric vehicles, the DSO or any other party involved. An overview over the different charging strategies can be seen in the following figure, described by the average charging power of each vehicle in kW over time. The charging strategies are

Uncontrolled strategy

In this strategy the electric vehicles are charged whenever they stop at a charging infrastructure valid in the respective infrastructure scenario: In the at home scenario that means that whenever a vehicle stops at a charging infrastructure “at home”, it is plugged in and starts charging immediately. A precondition is, that there are always enough charging connections available, insofar the “ideal case” is regarded. This uncontrolled case is the basis for all the results shown so far in this report. Since not all vehicles charge at the same time and with a very low state of charge, the maximum average charging power is about 0.5 kW/vehicle with a maximum connection power of 3.7 kW in the evening.

Time centered charge

This strategy implies that the charging procedures of all vehicles are centered around 3 a.m., starting at the earliest at 0 a.m. and finishing the latest until 6 a.m.. With regard to the charging curve described in chapter 4.1 the resulting load curve is unsymmetrical, because the vehicles, which begin their charging procedure first, are those with the lowest state of charge and thus will start charging with a higher power than the vehicles, which are finishing their charging procedures with high states of charge close to 6 p.m.. This leads to very high concurrency factors and (in the case of a peak connection power of 3.7 kW) to average charging powers of 2 kW/vehicle in the beginning of the period decreasing to 1 kW/vehicle at 3 a.m.

Times of Use (TOU) tariffs

The last charging strategy in the Conservative World is the strategy with TOU tariffs. Within this strategy a certain price incentive is given to a share of customers to charge their vehicles in a certain time frame. As an example, the three tariff time frames and the share of customers using them has been simulated like the following:

- 30% of the customers charge from 9 p.m. to 5 a.m.
- 40% of the customers charge from 10 p.m. to 4 a.m.
- 30% of the customers charge from 12 p.m. to 3 p.m.

The maximum average charging power per vehicle (total load of the vehicles divided by the total number of vehicles) with this charging strategy is 1.6 kW/EV in the beginning of the 3rd TOU tariff and therefore much higher than in the uncontrolled case.

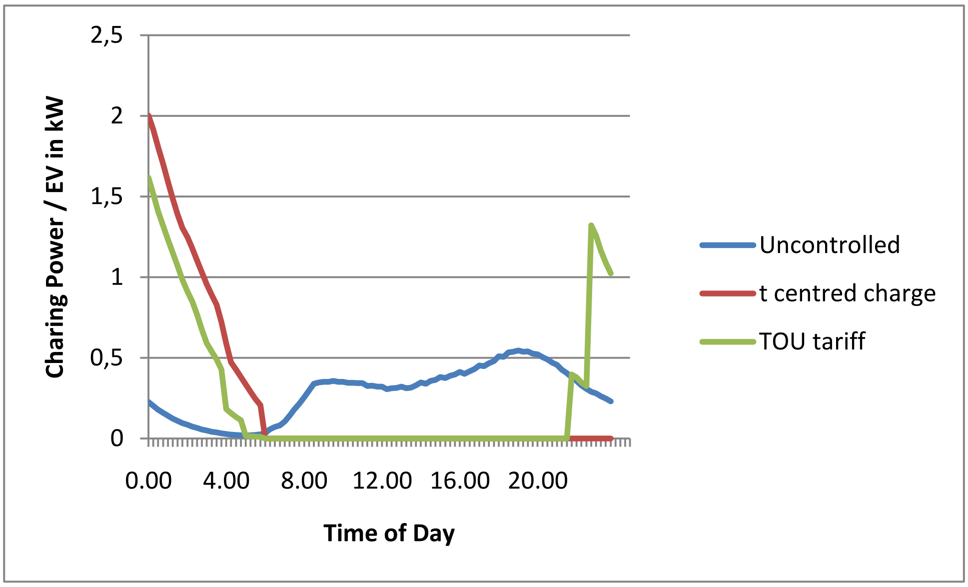


Figure 23: Charging strategies in the Conservative World

5.3.2 Pragmatic World

In contrast to the Conservative World, in the pragmatic world more communication complexity is required.

Time of use tariffs with real time adjustments

The main element of this charging strategy is a closed loop control mechanism between the electric vehicles and the secondary substations managed by the DSO. In case of an overload at a secondary substation, a signal is sent by the DSO to the electric vehicles allocated to that secondary substation to reduce the charging power adequately. This control mechanism makes sure, that overloads are not caused by electric vehicles. The drawback of the strategy is, that in overload situations as emergency situations the charging of the vehicles is delayed. In comparison to the conservative world, the charging profiles of the electric vehicles are not known in advance, but are highly dependent on the load situation in the specific grid. An example for the load of electric vehicles in one specific medium voltage grid can be seen in the following picture: Due to an overload situation the load of the vehicles is reduced to 0 kW from 3 to 9 p.m. in order to make sure no grid congestions occur during the day.

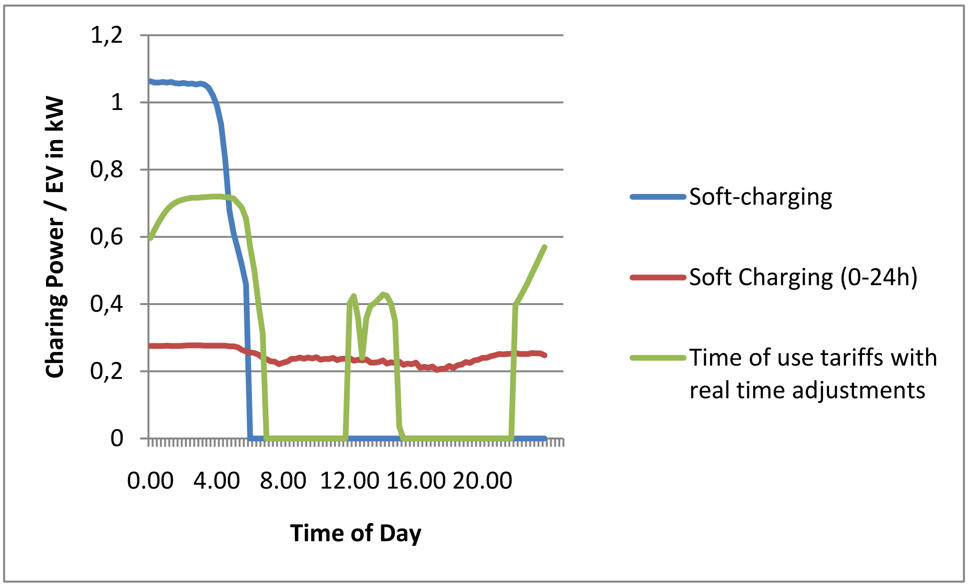


Figure 24: Charging power of electric vehicles in the pragmatic scenario

Soft Charging

The scope of the soft charging strategy is to flatten the load curve of the vehicles in a certain time frame. The charging energy a vehicle needs is therefore evenly distributed among the time, the vehicle is connected to a charging infrastructure in the respective time frame. In the simulations of the soft charging time two different strategies have been simulated:

- Soft-charging when EVs are charged in the morning (0-6 a.m.
- BAU soft charging, EVs are charged throughout the whole day (0-24h

With these two strategies the maximum average charging power per vehicle is limited to 1.1 kW/EV in the case with the limited time frame and to 0.5 kW/EV in the case of the maximum 24 hours time frame.

5.3.3 Visionary World

In the visionary world even more complex charging strategies are being simulated. These strategies do not take into consideration the actual loading of secondary substations in order to avoid congestions, but they consider the overall load in a national grid on TSO-level (“Aggregator Model”) or the regional load curve of the superior transformer of the distribution grid (“Powermatcher Model”).

EV flexibility aggregation

The EV flexibility aggregation Model (elaborated by Chalmer) is based on the overall load profiles of a country and tries to integrate the electric vehicles into the load profile in order to minimize the cost of the overall system. This charging strategy is independent of the situation in one specific distribution grid and is only dependent on the load profiles on transmission system level. As it can be seen in the following picture, the load of the electric vehicles is mainly shifted from load peak hours (noon and evening) to off-peak hours (in the morning). This charging strategy is explained in detail in [4].

Distributed Market-based Model

The Distributed Market-based Model (based on ECN's Powermatcher ® tool) is an approach to integrate the load of the electric vehicles into the distribution grid load curve of the respective superior transformer in order to flatten the resulting load curve. In the figure it can be seen that a part of the evening load is shifted to the night hours. Also this charging strategy is explained in detail in [4].

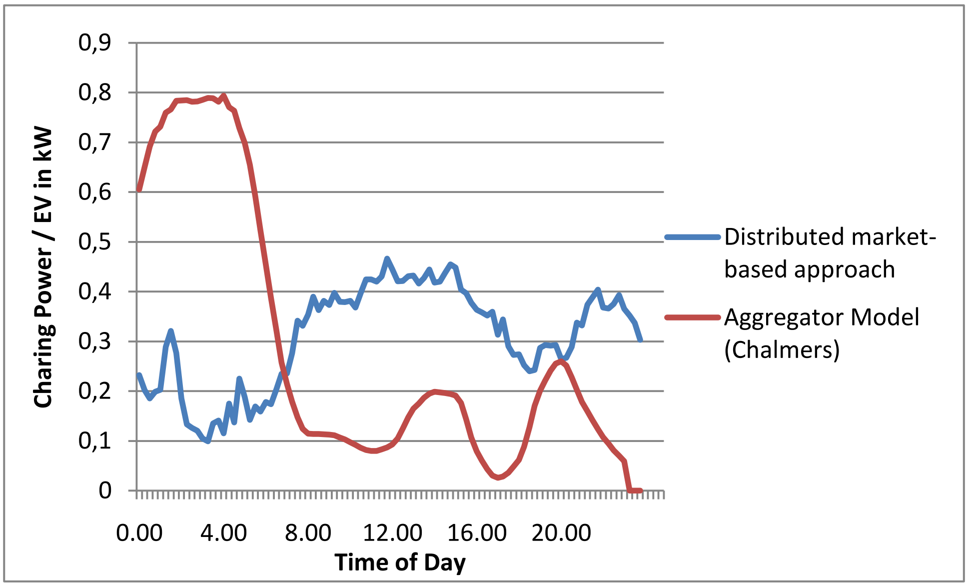


Figure 25: Charging power of the EVs in the Visionary World

6 Technical Results

Because of the broad variety of scenario parameters and grids, in this section only exemplary results can be described. The detailed comparison of the achieved results will be done in WP7, taking into account the grid enhancement costs resulting from the loading of the different assets. This chapter focuses on the description of the simulation complexity, the technical output data of the simulations and the description of exemplary technical results.

6.1 Simulation complexity

In the load flow simulations a number of scenario parameters have been considered. The most important parameters are:

- 4 connection powers (3.7 kW, 11 kW, 55 kW, mix)
- 4 charging places (At Home, At Home and At Work, Everywhere, …)
- 21 penetration rates (0%, 5%, …, 100%)
- 202 distribution grids
- 96 time steps (1 day)
- 200 iterations per time step
- 8 charging strategies

While a single load flow calculation takes only some milliseconds, the variety of input parameters make the calculation of all parameters and all grids more complex and time consuming. With the help of massive parallelization in the RWTH Aachen computational centre, the time needed to perform the load flow calculations was reduced from about 8 years on a single desktop computer to about a week per charging strategy.

6.2 Output of the simulations

The most interesting output parameters of the load flow calculations concerning the grid reinforcement costs are the following:

- Load of High Voltage (HV)/Medium Voltage (MV) transformers and secondary substations
- Load of MV and LV lines

- Voltage of all MV and LV lines in a grid.

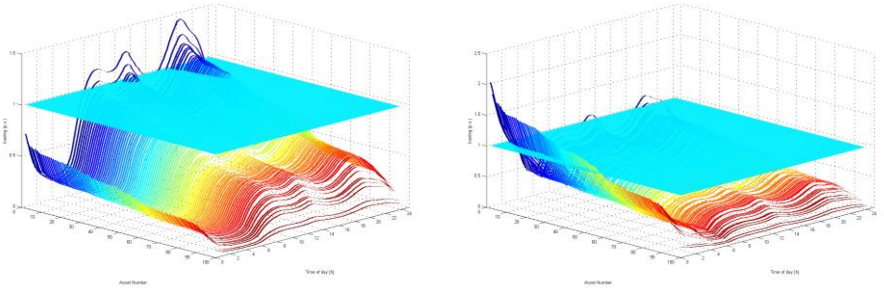
The permitted load of the transformers and lines is limited due to thermal limits: If an asset is overloaded at a certain level for a certain time, the insulation is damaged, the asset fails and has to be replaced. In the case of voltage stability certain voltage bands have to be complied with. These requirements are covered in detail in chapter 5.3.

6.3 Description of simulation results

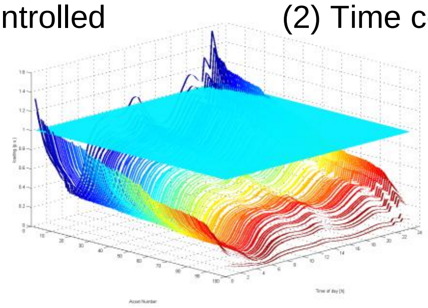
Since not all the technical results of all grids can be described in detail, some exemplary results will be analyzed in this chapter, showing some basic influences of charging strategies on some technical output parameters.

The following figure shows the loading of the secondary substation of the exemplary MV grid with the charging infrastructure “Everywhere”, a charging power of 3.7 kW and a penetration rate of electric vehicles of 100% for 3 charging strategies of the Conservative World. In the uncontrolled case (1) around one fourth of the secondary substations is loaded with a load higher than 1 p.u. (represented by the green layer), especially in the evening. With the “TOU tariffs” charging strategy, the peak load shifts towards the late evening hours, but the synchronous start of charging of a high share of electric vehicle at this instant of time leads to high peaks in the transformer loads and results in about the same number of overloaded secondary substations. With the time centered charging strategy (around 3 a.m). more secondary substations are overloaded in the early morning hours than in the uncontrolled case. One can conclude that at least in this case the two charging strategies are not able to enhance the overload situation of the secondary substations in the uncontrolled case.

Charging Infrastructure	1
	2
	3
	4
Charging Power	1
	2
	3
	4
Penetration Rate [%]	0
	35
	70
	100



(1) Uncontrolled (2) Time centered charging



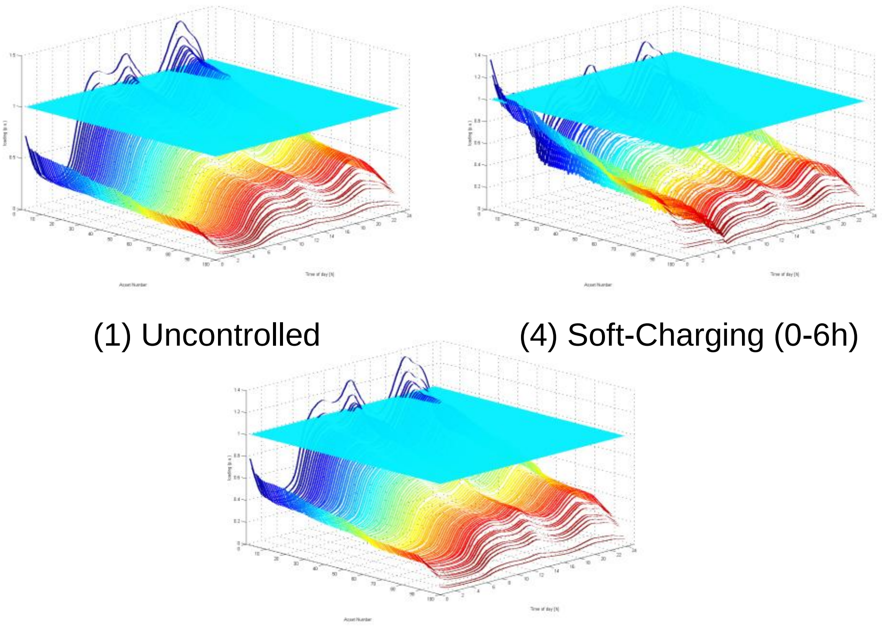
(3) TOU tariffs

Figure 26: Influence of charging strategies 1-3, charging everywhere, 3.7 kW, 100 % penetration

With the other strategies the situation is different: The soft gharging strategies reduces the number of overloaded secondary substations independently from the chosen time frame:

- the „Soft-charging” charging strategy (in the Pragmatic Charging Strategies family) moves all the recharges in the time frame from 0 a.m. to 6 a.m. In this case most of the overloads occur at the beginning of the soft charging period
- The „BAU Soft Charging“ strategy (in the Conservative Charging Strategies family) moves all the recharge in the time frame of 24 hours. In this case the peak load is in the evening peak of the conventional load.

Charging Infrastructure	1
	2
	🟩 3
	4
Charging Power	🟩 1
	2
	3
	4
Penetration Rate [%]	0
	35
	70
	🟩 100



(1) Uncontrolled

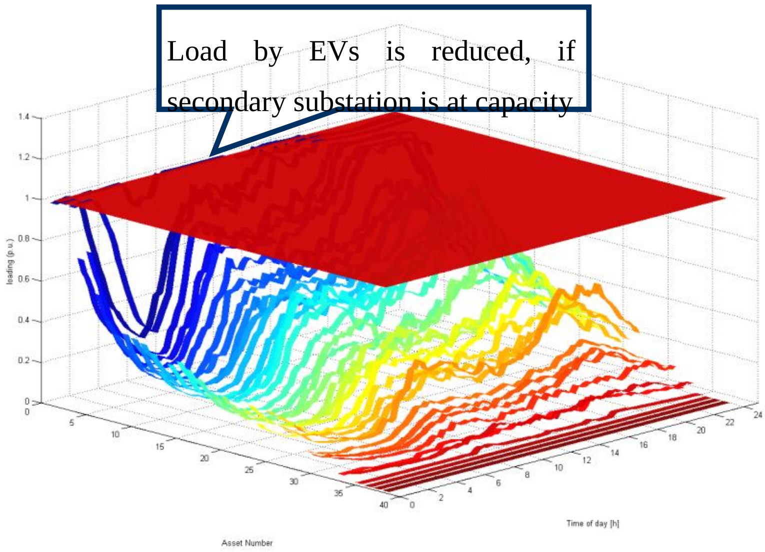
(4) Soft-Charging (0-6h)

(5) BAU Soft charging (0-24h)

Figure 27: Influence of the charging strategies 4-5

With the “Closed loop control “ charging strategies of the Pragmatic World, overloads of secondary substations can almost be avoided completely: if a secondary substation is loaded close to its maximum load, the load of the electric vehicles is decreased accordingly. One exemplary result is shown in the following figure: the secondary substation with the highest load is operated at its power capacity almost for the complete day. This means that the charging of the vehicles allocated to this secondary substation is delayed, on the other hand an overload of the secondary substations caused by electric vehicles is excluded. If the sum of loads other than EV causes an overload of a substation, this cannot be compensated by this strategy.

Charging Infrastructure	1
	2
	3
	4
Charging Power	**1**
	2
	3
	4
Penetration Rate [%]	0
	35
	70
	100

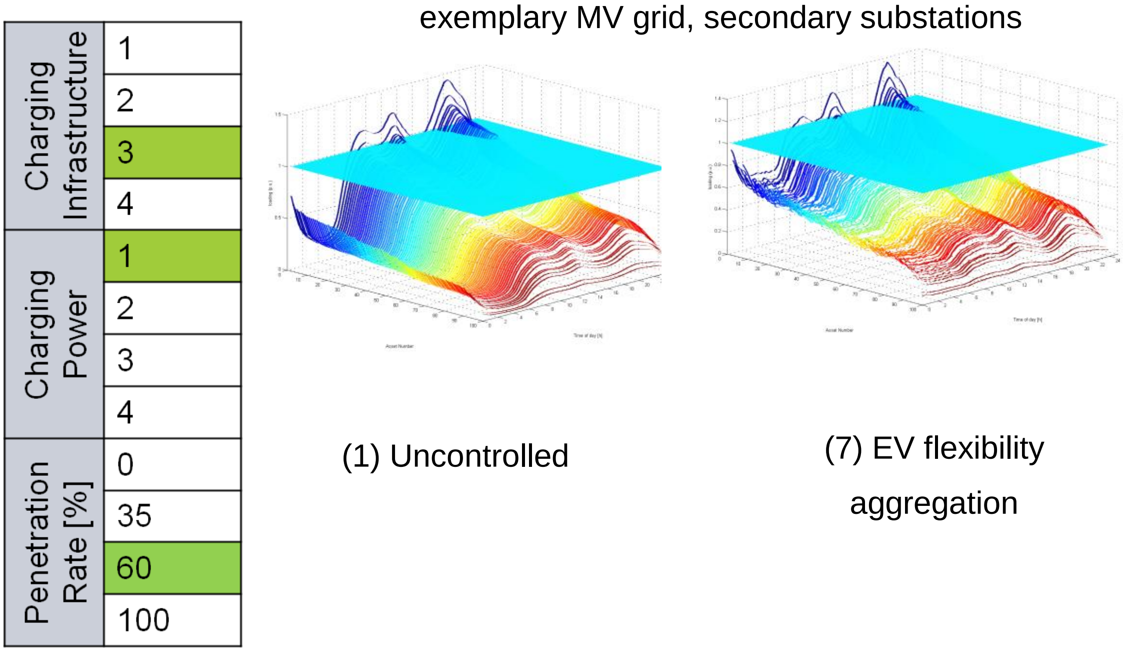


Load by EVs is reduced, if secondary substation is at capacity

(6) Closed loop control

Figure 28: Influence of “Day-Ahead with realtime adjustment” Charging Strategy

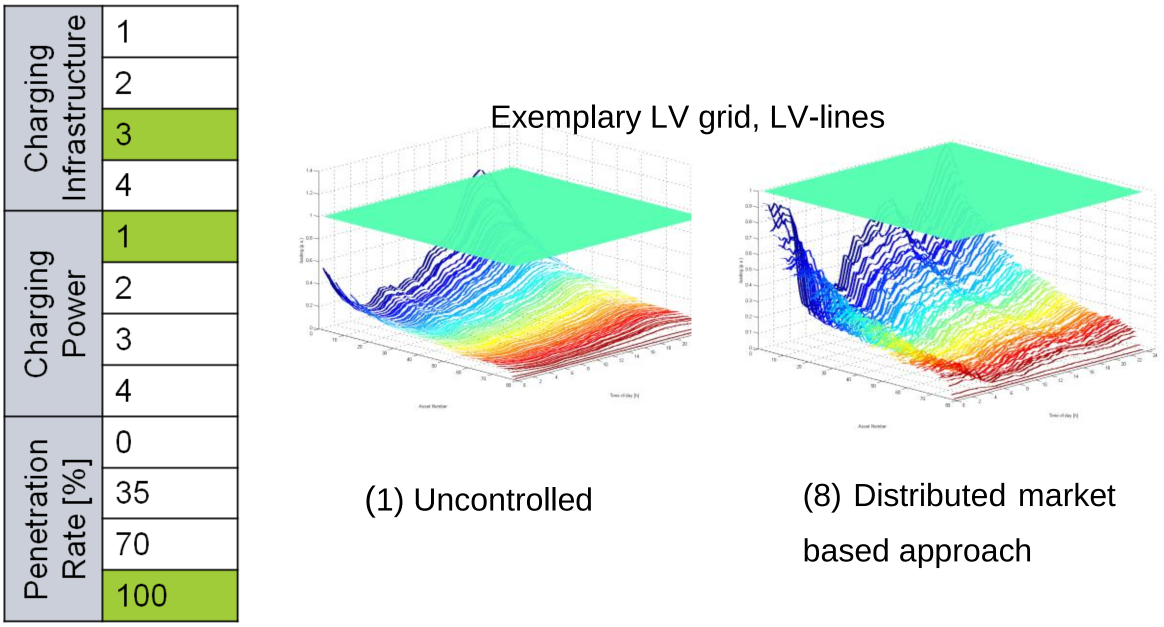
With the “EV flexibility aggregation” strategy representing a charging strategy from the Visionary World, the number of overloaded secondary substations is also reduced: As it can be seen from the following figure, the “EV flexibility aggregation” strategy shifts the load from noon and evening to the early morning hours. This charging strategy foresees an active role of the Distribution System Operator (DSO), which shall have the possibility of directly influencing the EVs charging behaviour in cases of constraints are detected in the distribution grid.



Charging Infrastructure	1
	2
	3
	4
Charging Power	1
	2
	3
	4
Penetration Rate [%]	0
	35
	60
	100

Figure 29 Influence of the EV flexibility aggregation charging strategy

The following figure shows the results for the “Distributed market based” strategy (based on ECN’s PowerMatcher ®) on the lines of the exemplary LV grid. In the uncontrolled case one line is overloaded in the evening. By controlling the electric vehicles with the “Distributed market based” strategy, an overload of the line can be avoided. However, since the “Distributed market based” strategy does not directly take the loading of lines into account, this cannot be seen as a general conclusion.



Charging Infrastructure	1
	2
	3
	4
Charging Power	1
	2
	3
	4
Penetration Rate [%]	0
	35
	70
	100

(1) Uncontrolled

(8) Distributed market based approach

Figure 30: Influence of Distributed market based approach

7 Conclusions

The main objective of this simulation has been the development of an innovative tool to evaluate the impact of electric vehicles over the distribution grid. This study shows that, to define the right strategy to integrate EVs load, detailed analysis techniques should be used to evaluate the effect on the grid caused by EVs because such effect depends on a multitude of parameters.

Due to the large number of simulated grids and the all the combinations of parameters, it is not possible to include in a single deliverable the overall set of results. Instead, the results have been used in WP7 in order to derive the roadmaps (Deliverable D7.1 System Analysis and definition of the roadmap). Anyway some high-level conclusions can be derived.

Results show that, among the almost 200 networks simulated, some need already reinforcement even without EVs, while others can integrate 100% EVs even without any charging strategy. This variety appears in all the countries.

With charging strategies, it is possible to postpone reinforcements for considerable penetration levels, hence reducing the amount of investment needed for grid reinforcement. However, application of charging strategies does not provide effects to the networks that are close to their limit even without EVs; those grids shall be reinforced before they could host EVs.

A very promising family of charging strategies foresees an active role of the Distribution System Operator (DSO), which shall have the possibility of directly influencing the EVs charging behaviour in cases of constraints are detected in the distribution grid. These charging strategies require evolution of existing technological and regulatory situation:

- The DSO shall equip its distribution grid with devices able to detect grid constraints
- In those networks where it is needed, charging stations shall be equipped with communication devices able to receive commands from DSO systems and propagate them to the connected EVs.

An evolution of this solution envisages advanced charging strategies which involve more actors and pursue multiple objectives such as:

- Balance intermittent production of renewable sources
- limitation of the overall system costs

In any case, it is always needed taking into account local congestions in the distribution grid (MV and LV) which is the main precondition to allow the other goals.

In all cases, regulatory changes (more or less significant depending on the country) are needed to permit the implementation of charging strategies. Further considerations on this topic are in G4V Deliverable 3.1. In addition, smart metering and grid-monitoring instruments should be adopted in order to improve the quality of the grid studies and provide DSOs with a detailed knowledge of the status of their grid.

Finally, to confirm and further develop the results, it is recommended to apply this methodology to a larger number of grids. Therefore the European Commission, on one hand, should promote further researches and demonstration on active demand and smart grids and, on the other hand, provide recommendation in terms of regulatory framework to facilitate the integration of EV flexibility into system operation.

8 References

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