Bachelor Thesis

Impact of Future E-Mobility Fleets on suburban Medium-Voltage Grids

By

Guillermo Moraleda

angefertigt am

Karlsruher Institut für Technologie (KIT)

Institut für Elektroenergiesysteme und Hochspannungstechnik

Institutsleiter: Prof. Dr.-Ing. Thomas Liebfried

Betreuer: Dipl.-Ing. Simon Wenig

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1 Abstracto

La electromobilidad se refiere a la electrificación del tren de potencia en los vehículos. En este proyecto nos referiremos como Vehículos Eléctricos (VE) a todos los vehículos en los que el motor eléctrico sea la principal fuente de propulsión. Se definirán dos tipos de VE: Plug-in Hybrid Electric Vehicle (PHEV), vehículo híbrido enchufable; Battery Electric Vehicle (BEV), vehículo eléctrico de batería.

1. Introducción

En los últimos años, en Europa se ha iniciado una fase de adopción de la movilidad eléctrica. El gradual aumento del momento detrás de la adopción de los VE, ambas desde lado de los consumidores como de la industria automovilística, sugiere que los VEs jugarán un importante papel en la movilidad en Europa en un futuro. Las principales razones para creer en la expansión de los VE son:

- Conciencia medioambiental
- Aumento del precio del petróleo
- Reducción del precio de las baterías gracias a la economía de escala

Los próximos años será un periodo de maduración de la tecnología existente apoyada por iniciativas estatales. Como resultado, una nueva infraestructura de carga será desarrollada para proporcionar puntos de carga a los usuarios. La futura expansión de dicha estructura de carga puede suponer un reto para las redes eléctricas actuales. Los operadores de red, tendrán que lidiar no sólo con un aumento en la demanda total de potencia eléctrica, sino que también con eventuales picos de demanda debido a la simultaneidad de los procesos de carga.

Dicho impacto puede ser especialmente importante en Alemania, donde la demanda de potencia eléctrica presenta un pico durante las tardes, que es cuando se espera una mayor frecuencia de cargas de VEs.

Por lo tanto, con el objetivo de predecir posibles problemas que vengan con la nueva electro movilidad resulta necesario realizar estudios que puedan simular una respuesta de las redes eléctricas a la introducción de VEs. Estos estudios proporcionarían información a los operadores de la red, que podría planear las medidas necesarias para proporcionar una segura y más eficiente generación eléctrica.

El estudio del impacto de la futura electro movilidad en redes de baja tensión ya ha sido realizado en trabajos anteriores [1]; sin embargo, esta es la primera vez que dicho estudio se realiza en redes de distribución de media tensión. En este proyecto se partirá del software desarrollado en [2], donde se creó una función probabilística para generar las cargas de electromobilidad para una red dad.

2. Definición de los objetivos

El proyecto consiste en un estudio de la integración de vehículos eléctricos en una red de media tensión mediante la simulación de la carga de un determinado número de dichos vehículos. En las simulaciones realizadas también se estudiara las fluctuaciones en la generación de la energía eléctrica debido a la influencia de la generación fotovoltaica.

Se realizarán simulaciones en distintas épocas del año para tener una imagen completa del comportamiento de la red. Por otro lado, también se definirán dos futuros escenarios de electromobilidad:

- Escenario de 1 millón de vehículos eléctricos en Alemania: representa la proyección realizada para el año 2020.
- Escenario de 6 millones de vehículos eléctricos en Alemania: representa la proyección realizada para el año 2030.

Con los distintos escenarios propuestos se obtendrán las conclusiones pertinentes acerca del impacto que se espera que tenga la introducción de vehículos eléctricos a medio plazo en redes de media tensión

3. Metodología

Para alcanzar los objetivos propuestos, dos redes de 20 kV han sido proporcionadas. Estas redes son de gran valor debido a las características de sus cargas. Ambas poseen cargas domésticas e industriales así como generación convencional y renovable. Se espera que las redes eléctricas en un futuro tengan estas mismas características.

A lo largo del proyecto los programas más utilizados fueron Matlab y Power Factory. Las redes están definidas en el segundo programa. Sin embargo los valores relativos a las cargas son importados a Matlab donde se estimará la generación y el consumo total de la red (incluido el consumo de las recargas de los VEs). Una vez estos valores han sido obtenidos para un determinado minuto, los datos son exportados de nuevo a Power Factory donde se realizará una simulación de flujo de potencia.

Para obtener estos valores de generación y consumo, los siguientes puntos son realizados:

- Generación de las curvas de consumo convencional. Estas curvas mostrarán la suma de los consumos domésticos e industrial.
- Obtención de las curvas de generación. En estas redes, dicha generación consiste en centrales de: Biogás, centrales de calor y generación, fotovoltaica y generación eólica. Dadas las diferentes características de las distintas tecnologías la generación se dividirá en generación variable (fotovoltaica y eólica) y generación regulable.

- Definición de la infraestructura de recarga. Dicha infraestructura contendrá puntos de carga privados y públicos. El número de estaciones definidas dependerá del número de vehículos eléctricos definidos en la red.
- Generación de los perfiles de recarga de los VEs y posterior suma de dichos perfiles para definir la curva de consumo relativa a la electro movilidad.

Un vez hemos obtenido las curvas de generación y consumo, dibujaremos dichas curvas para seleccionar los periodos más críticos, que serán simulados en el flujo de potencia. La Figura 1 contiene las curvas de consumo y generación de un día de invierno de la segunda red.

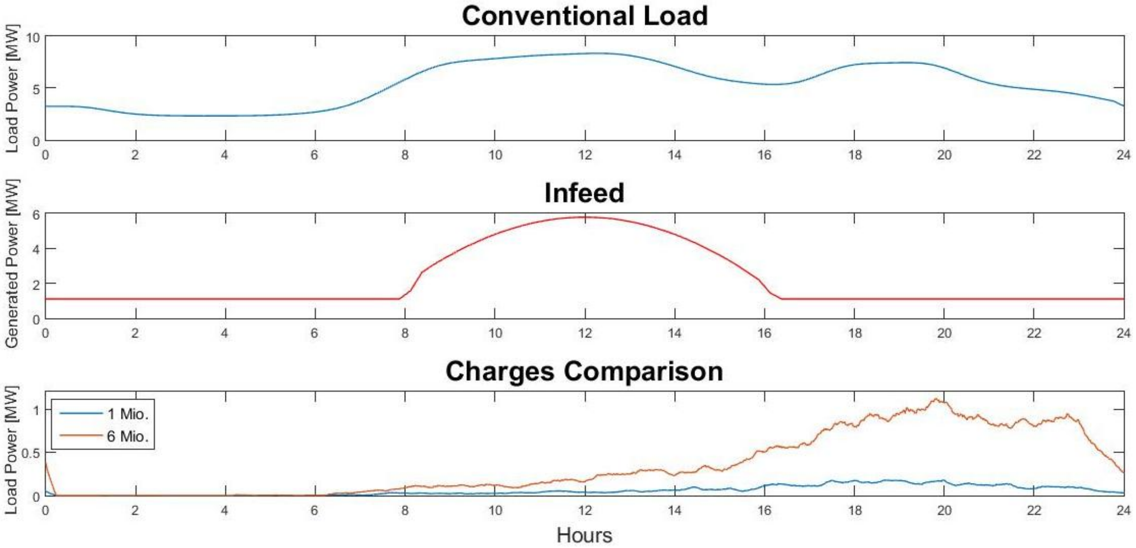


Figura 1: Curvas de Generación y Consumo

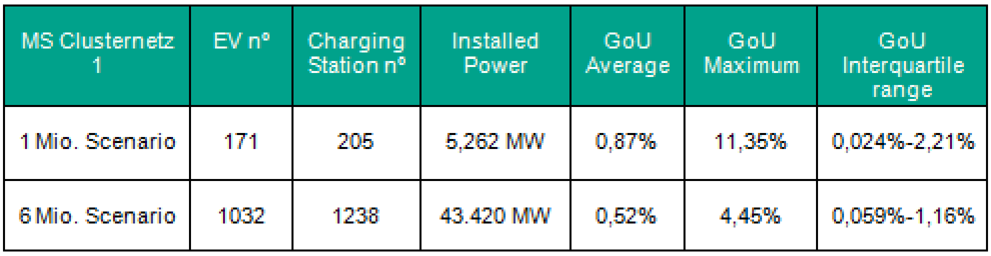
Durante las simulaciones de flujo de potencia realizadas en Power Factory, se perseguirá encontrar el caso más desfavorable (el asociado a valores más críticos). Los parámetros que determinarán dicho escenario son: la carga del centro de transformación de alta a media tensión; y la mayor carga obtenida en las líneas de distribución.

4. Resultados

La infraestructura de recarga de los vehículos eléctricos siguen las siguientes relaciones:

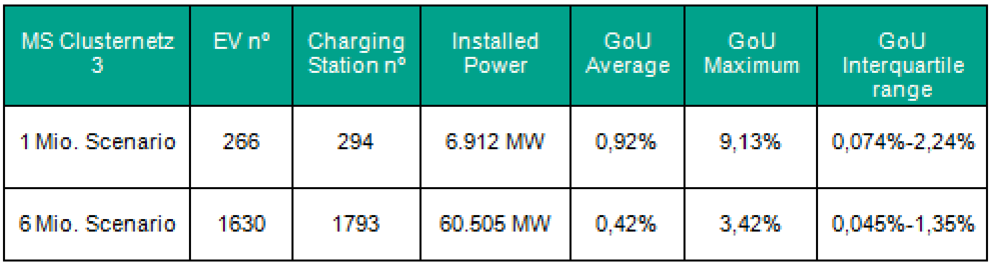
- Una estación de recarga privada por cada vehículo eléctrico
- Una estacione de recarga pública por cada diez VEs.

Con el objetivo de analizar estructura de recarga generada, se ha calculado el grado de utilización (Grade of Utilization) de las infraestructuras obteniéndose los siguientes resultados:



MS Clusternetz 1	EV nº	Charging Station nº	Installed Power	GoU Average	GoU Maximum	GoU Interquartile range
1 Mio. Scenario	171	205	5,262 MW	0,87%	11,35%	0,024%-2,21%
6 Mio. Scenario	1032	1238	43.420 MW	0,52%	4,45%	0,059%-1,16%

Tabla 1: Infraestructura de recarga de MS Clusternetz 1



MS Clusternetz 3	EV nº	Charging Station nº	Installed Power	GoU Average	GoU Maximum	GoU Interquartile range
1 Mio. Scenario	266	294	6.912 MW	0,92%	9,13%	0,074%-2,24%
6 Mio. Scenario	1630	1793	60.505 MW	0,42%	3,42%	0,045%-1,35%

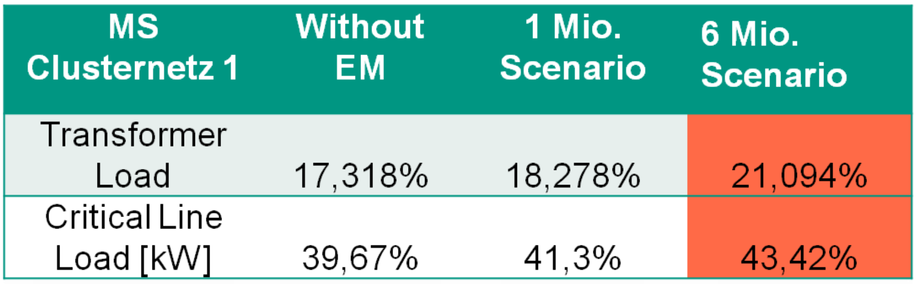
Tabla 2: Infraestructura de recarga de MS Clusternetz 3

Las simulaciones de flujo de potencia se ejecutaron en las dos redes dadas (MS Clusternetz 1) y (MS Clusternetz 3). Los periodos estudiados fueron:

- Simulación de un día de invierno en horas de media tarde
- Simulación de un día de verano durante el medio día
- Escenario más crítico

Para todos los periodos seleccionados, tres simulaciones se llevaron a cabo: la primera son VEs; la segunda con el escenario de 1 millón de vehículos eléctricos; y la última con la introducción del escenario de 6 millones de VEs.

La Tabla nº 3 muestra los valores de carga del transformador y máxima carga de las líneas obtenidas para el escenario más crítico. Este escenario coincide con un sábado de octubre a las 19:00.

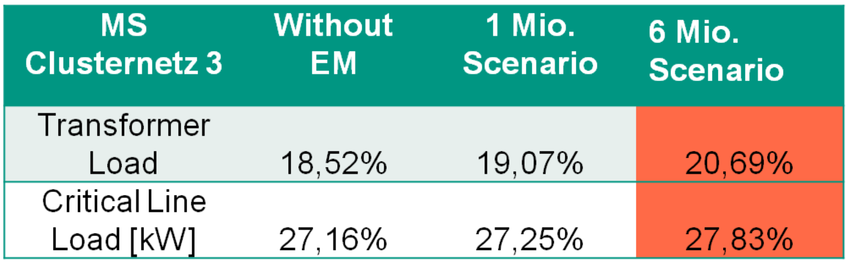


MS Clusternetz 1	Without EM	1 Mio. Scenario	6 Mio. Scenario
Transformer Load	17,318%	18,278%	21,094%
Critical Line Load [kW]	39,67%	41,3%	43,42%

Tabla 3: MS Clusternetz 1 escenario más crítico

Como podemos ver, el máximo valor obtenido para la carga del centro de transformación de lata a media tensión fue de 21,094%. Por otro lado el valor correspondiente a la línea más cargada fue de 43,42%. Ambos valores se muestran muy por debajo de valores críticos.

En la segunda red, los valores obtenidos para estos dos parámetros fueron similares, sin embargo, la línea de máxima carga mostró valores ligeramente inferiores a los obtenidos en MS Clusternetz 1. La Tabla 4 muestra los valores obtenidos para el escenario más crítico en esta red, que consiste en un sábado de enero a las 19:00.



MS Clusternetz 3	Without EM	1 Mio. Scenario	6 Mio. Scenario
Transformer Load	18,52%	19,07%	20,69%
Critical Line Load [kW]	27,16%	27,25%	27,83%

Tabla 4: MS Clusternetz 3 escenario más crítico

En esta red los valores obtenidos tanto de generación como de consumo fueron mayores a los obtenidos en la primera red. Sin embargo la carga del centro de transformación sólo llego al 20,69% y las líneas más cargadas mostraron un valor inferior al 28%. Ambos valores por debajo de valores críticos de operación.

5. Conclusión

El Grado de Utilización obtenido demuestra que la infraestructura generada está sobredimensionada en ambos casos. El máximo valor obtenido fue de 13,35% mientras que los valores medios se mantuvieron por debajo del 1%.

En los resultados obtenidos también se observó que al pasar del escenario de 1 millón a 6 millones de VEs la dispersión y el valor medio de los datos disminuía. Una menor dispersión se esperaba dado el mayor número de VEs sin embargo se debe analizar la reducción de los valores medios.

Al cambiar de escenario de VEs la tecnología de estos también cambia. Hemos supuesto que en un futuro los VEs tengan unas baterías con mayor capacidad y mayor potencia de carga. Esto resultará en procesos de mayor potencia pero más breves y además que tendrán lugar cada más tiempo. Por lo tanto el Grado de Utilización disminuye al cambiar de escenario.

De los valores obtenidos en las simulaciones de flujo de potencia podemos determinar que: en el medio plazo, la introducción de vehículos eléctricos en las redes de media tensión aquí disponibles, no provocará una alteración de su funcionamiento.

Resulta interesante estudiar el aumento del consumo total de electricidad tras introducir los VEs en ambas redes:

- MS Clusternetz 1 en el escenario de 2020: 4,7%
- MS Clusternetz 1 en el escenario de 2030: 20%
- MS Clusternetz 3 en el escenario de 2020: 1,7%
- MS Clusternetz 3 en el escenario de 2030: 7,5%

Como podemos observar, el impacto de la electro movilidad será mayor en la primera que en l segunda red. Esto se debe a que la segunda red consiste en una red rural en la que a potencia doméstica instalada por habitante tiene un valor más alto. Esto resulta en una menor influencia de las recargas de los vehículos enchufables.

Por último, esta tendencia de aumento de VEs se espera que continúe, y a largo plazo es posible que se tenga que gestionar las cargas generadas. Por ello se proponen tres estrategias que se englobarían en lo que se conoce como ‘Redes Inteligentes’. Estas son desplazamiento en el tiempo de la carga provocada por VEs; alimentación por parte de los VEs con fines de allanar la curva de demanda; y gestión del coste eléctrico de las viviendas mediante la carga y descarga de estos vehículos.

6. Bibliografía

[1] ALEXANDER C. PROBST, MARTIN BRAUN, JÜRGEN BACKES AND STEFAN TENBOHLEN: *Probabilistic Simulation of voltage bands stressed by electro mobility.*

[2]SCHULZE, WOLF: *Probabilistische Netzsimulation von Mittelspannungsnetze*

Abstract

Electric mobility relates to the electrification of the power train. In this Thesis we will refer to EVs (Electric Vehicles) as all the vehicles for which an electric motor is their main source of propulsion. All these EVs will be assumed as wired charging vehicles: we differ between plug in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs).

1. Introduction

In the past years, Europe has gone through an initial adoption phase of electric mobility. The gradually increasing momentum behind EV adoption, both from the side of the consumer and the automotive industry, suggests that EV will play an important role in Europe’s mobility in the future. The main reasons to believe in a spread of electric vehicles in a future scenario are:

- Environmental consciousness
- Oil price increase
- Battery price decrease due to economy of scale

The next few years will be a period for further maturation of the existing technology supported by government initiatives. In result, a new charging infrastructure will be developed to provide charging points to the users. The upcoming spread of charging stations could represent a challenge for the actual power grids. Grid operators will have to deal not only with an increase in the total energy demand, but also with eventual demand peaks due to the simultaneous characteristic of the charging procedures.

This impact may be especially sensitive in Germany. There, the electric power demand curve shows a peak during evening hours, which is the time where most electric vehicles are expected to be charged.

In order to predict possible issues coming along with the new automotive car reality it is necessary to carry out studies which can simulate the grid response to an e-mobility fleet introduction. This will provide precious information to grid operators which could plan the needed strategies in order to provide reliable and more efficiently generated electricity.

The study of the impact of future e-mobility fleets on low voltage-grids was already carried out for this kind of networks [1]; however, this is the first time that this investigation is carried out in medium-voltage networks for Germany. This investigation continues with the studies made out in [2], where a probabilistic function was created in order to generate the e-mobility load on a given grid.

2. Tasks Description

This Bachelor Thesis will handle the issue of electro mobility integration in the grid by simulating the charging of a certain number of electric vehicles in two medium-voltage networks. These simulations will also show the fluctuating infeed of renewable energies.

During the simulations different EV and time scenarios will be studied in order to discuss the upcoming problems which may appear. Therefore the goal of the Thesis is to provide a good view of the main challenges that the grid operators will have to face in the following years to maintain a safe operation and assure the energy provision in a medium-voltage grid.

3. Methodology

In order to achieve this goal, two German medium-voltage electrical networks are available. These grids are of great value due to their loads characteristic. They both have residential and industrial areas as well as conventional and renewable infeed. All these characteristics will be found in typical future grids.

During this project, the software which was most frequently used was Matlab and Power Factory. The grids are defined in the second program, therefore, all the values have to be imported to Matlab, where all the infeed and load values are generated, and then exported again to Power Factory to run the power flow simulations.

In order to fulfill the given tasks, the first step will be to define the load and infeed characteristics. In order to do so, the next steps are accomplished:

1. Generation of conventional load curves. These curves will show the industry and the household consumption.
2. Generation of the Infeed curves. The generation will proceed from Biogas, Heat and Power plants, PV and Wind generation. In the project we will divide them in variable (Wind and PV) and fixed generation.
3. Definition of a charging infrastructure that will hold private and public charging stations. The number of stations will depend on the electric vehicle number.
4. Generation of the e-mobility charging profiles and acquisition of the aggregated e-mobility load curves.

Once that we have the needed load and generation curves we will generate plots to compare the results given and select the most critical time periods. Figure 1 shows the load and infeed curves for a whole day during a winter period.

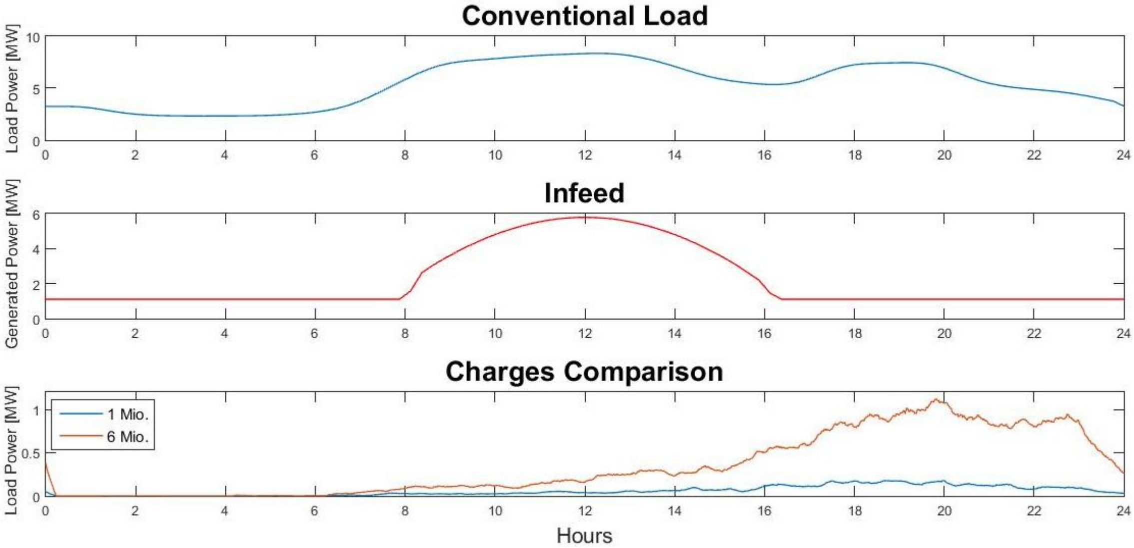


Figure 1: Main Grid Features

Power flow simulations of the most interesting time periods were executed. During these simulations, we searched for the Worst Case Scenario. The most interesting power flow parameters are the transformer load and the higher line load obtained.

4. Results

The charging infrastructure is generated following the next relations:

- One private charging station per electric vehicle
- One public charging station per 10 electric vehicles

In order to study the behavior of the generated infrastructure, the Grade of Utilization of this structure is calculated, this value is obtained dividing the charging power by the total installed power.

The values obtained were:

MS Clusternetz 1	EV nº	Charging Station nº	Installed Power	GoU Average	GoU Maximum	GoU Interquartile range
1 Mio. Scenario	171	205	5,262 MW	0,87%	11,35%	0,024%-2,21%
6 Mio. Scenario	1032	1238	43.420 MW	0,52%	4,45%	0,059%-1,16%

Table 1: MS Clusternetz 1 Charging Infrastructure

MS Clusternetz 3	EV nº	Charging Station nº	Installed Power	GoU Average	GoU Maximum	GoU Interquartile range
1 Mio. Scenario	266	294	6.912 MW	0,92%	9,13%	0,074%-2,24%
6 Mio. Scenario	1630	1793	60.505 MW	0,42%	3,42%	0,045%-1,35%

Table 2: MS Clusternetz 3 Charging Infrastructure

The power flow simulations were executed on the two given grids (MS Clusternetz 1 and MS Clusternetz 3). The most interesting simulations were:

- Winter simulation during after work hours.
- Summer simulation during midday.
- Worst Case Scenario.

For all time scenarios three simulations were made; one of them without electric vehicles, another one with the 1 million EV scenario and the final one with the 6 million EV scenario.

Table 3 shows the Worst Case Scenario of grid 1, which consisted on a Saturday evening of October.

MS Clusternetz 1	Without EM	1 Mio. Scenario	6 Mio. Scenario
Transformer Load	17,318%	18,278%	21,094%
Critical Line Load [kW]	39,67%	41,3%	43,42%

Table 3: MS Clusternetz 1 Worst Case Scenario

The highest transformer load obtained in the simulations was of 21.094% and the highest line load of 43.42%. However, these values are kept under critical limits.

In the second grid, the values obtained for the transformer load were similar but the highest line load was kept smaller. In this case the Worst Case Scenario consisted on a Saturday evening in January.

MS Clusternetz 3	Without EM	1 Mio. Scenario	6 Mio. Scenario
Transformer Load	18,52%	19,07%	20,69%
Critical Line Load [kW]	27,16%	27,25%	27,83%

Table 4: MS Clusternetz 3 Worst Case Scenario

The power values obtained in MS Clusternetz 3 are bigger due to the size of the grid. However, the maximum transformer and line loads are lower in this network, the transformer load never exceeds 21% and the maximum line load obtained is 27.83%.

5. Conclusion

The Grade of Utilization results given shows that the infrastructure defined was oversize. The maximum value obtained was of 13.35% and the average values were always under 1 percent.

Also, in the analysis of the Grade of Utilization results it was observed that when the electric vehicle scenario was changed from the 1 million to the 6 million the average and the dispersion of the values dropped.

A decrease in the average value is due to a change in the EV characteristics. In the 6 million scenario, the vehicles will have larger battery capacities and higher charging power. This will result in charging procedures of higher power values. However, these procedures will be shorter and they will take place less often. All this conclude in smaller Grade of Utilization values.

Out of the results obtained in the power flow simulations we can determine that in the middle term, the introduction of e-mobility loads will not disturb the operation of the given electric networks.

However, it is interesting to study how the e-mobility introduction increased the total load. The obtained results for the Worst Case Scenario were:

- MS Clusternetz 1 in the 1 million scenario: 4.7%
- MS Clusternetz 1 in the 6 million scenario: 20%
- MS Clusternetz 3 in the 1 million scenario: 1.7%
- MS Clusternetz 3 in the 6 million scenario: 7,5%

Due to these results, it can be concluded that the impact of e-mobility fleets will be higher on the first grid than on the MS Clusternetz 3. This is due to the characteristics of the grids. The second grid is rural and the installed power per inhabitant is higher, therefore the introduction of electric vehicles will have a smaller impact.

6. Bibliography

[1] ALEXANDER C. PROBST, MARTIN BRAUN, JÜRGEN BACKES AND STEFAN TENBOHLEN: *Probabilistic Simulation of voltage bands stressed by electro mobility.*

[2]SCHULZE, WOLF: *Probabilistische Netzsimulation von Mittelspannungsnetze unter Einfluss zukünftiger Elektromobilität,* 2014.

I guarantee hereby, that I have done my Project Work by myself, and under consideration of the scientific rules of the Karlsruhe Institute of Technology (KIT). I have not used more sources or help than the ones specified in the project.

Karlsruhe, the August 28th 2015.

Guillermo Moraleda.

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2 Introduction

Electric mobility relates to the electrification of the power train. In this thesis we will refer to EVs (Electric Vehicles) as all the vehicles for which an electric motor is their main source of propulsion. All these EVs will be assumed as wired charging vehicles: we differ between plug in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs).

2.1 Motivation

In the past years, Europe has gone through an initial adoption phase of electric mobility. The gradually increasing momentum behind EV adoption, both from the side of the consumer and the automotive industry, suggests that EV will play an important role in Europe’s mobility in the future. The main reasons to think that e-mobility will eventually play an important role in a future scenario are:

- Environmental consciousness
- Oil price increase
- Battery price decrease due to economy of scale

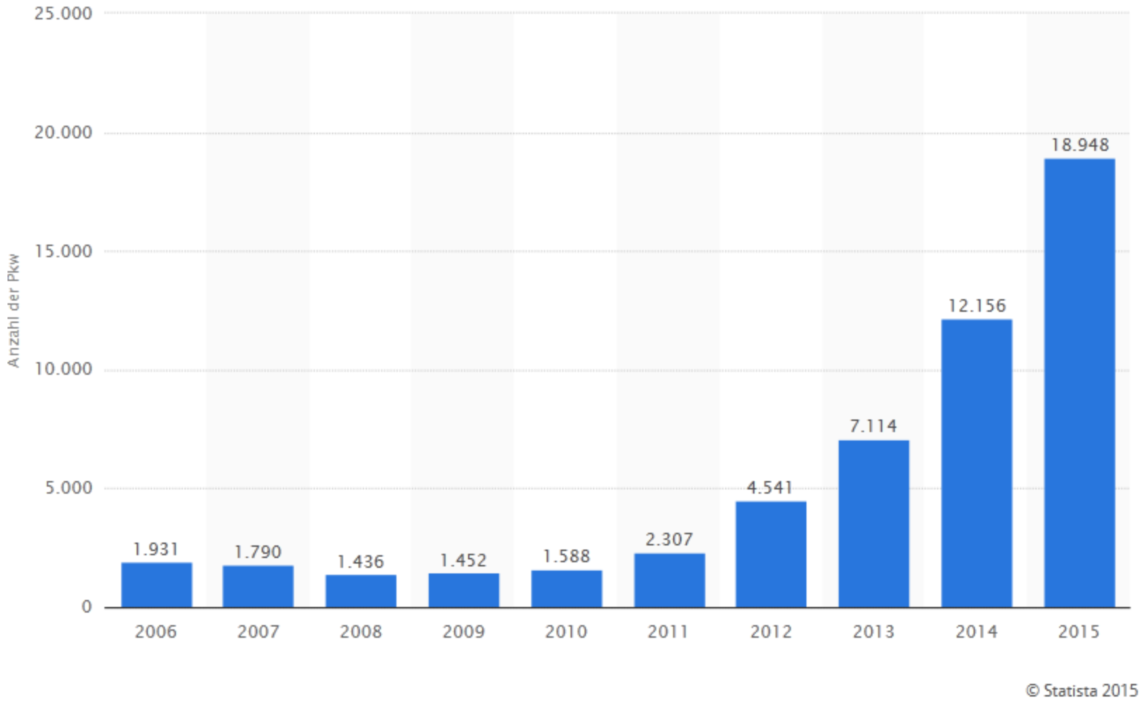


Figure 1.1: EV number in Germany

According to Figure 1.1 the number of EVs in Germany increased by 70.87% between years 2013 and 2014 and by 55.87% between 2014 and 2015. Although the actual number represents only a 0.0423% share of all the personal vehicles, if the actual sales growth keeps on this tendency, in a few years it will become a direct competitor of Internal Combustion Engine (ICE) vehicles.

The next few years will be a period for further maturation of the existing technology supported by government initiatives. In result, a new charging infrastructure will be developed to provide charging points to the users. The upcoming spread of charging stations could represent a challenge for the actual power grids. Grid operators will have to deal not only with an increase in the total energy demand, but also with eventual demand peaks due to the simultaneous characteristic of the charging procedures.

This impact may be especially sensitive in Germany. There, the electric power demand curve shows a peak during evening hours, which is the time where most electric vehicles are expected to be charged.

In order to predict possible issues coming along with the new automotive car reality it is necessary to carry out studies which can simulate the grid response to an e-mobility fleet introduction. This will provide precious information to grid operators which could plan the needed strategies in order to provide reliable and more efficiently generated electricity.

2.2 Task Description

This Bachelor Thesis will handle the issue of electro mobility integration in the grid by simulating the charging of a certain number of electric vehicles in two medium-voltage networks. These simulations will also show the fluctuating infeed of renewable energies.

During the simulations different EV and time scenarios will be studied in order to discuss the upcoming problems which may appear. Therefore the goal of the Thesis is to provide a good view of the main challenges that the grid operators will have to face in the following years to maintain a safe operation and assure the energy provision in a medium-voltage grid.

In order to achieve this goal two medium-voltage electrical networks are available. These grids are of great value due to their loads characteristic. They both have residential and industrial areas as well as conventional and renewable infeed. All these characteristics will be found in typical future grids.

The definition of the conventional load (household and industry load) as well as the infeed and the new generated e-mobility loads, will be included in the network for the power flow simulations. The conventional load values will depend on the season selected according to meteorological considerations. These considerations will also have to be considered when generating the photovoltaic infeed.

The e-mobility loads will be introduced by generating a charging infrastructure that will supply two different electric car scenarios. One of them will represent the possible case in the year 2020, with 1 million Plug-In vehicles in Germany, and the other case will represent the year 2030, with 6 million EVs.

Once the simulations are carried out, different diagrams of both grids will be studied. The most important parameters are considered to be the Grade of Utilization (GoU) of the charging infrastructure and the different load values in the grid. In attempt to obtaining reliable results, a comparison between both grids as well as both e-mobility scenarios are carried out.

2.3 Methodology

The information related to the grid was given by means of two POWERFACTORY networks as well as an Excel sheet specifying the number of households in the second grid. First of all, the data related to the power generation and consumption (nominal values and power factors) as well as the zone distribution is obtained from the POWERFACTORY files and introduced into an Excel sheet. The second step is to import the data into MATLAB. MATLAB functions will:

- generate the household and industry conventional loads
- generate the conventional and renewable energy infeed
- introduce an e-mobility charging infrastructure
- generate the EV aggregated loads
- export the MATLAB data into an Excel sheet

This MATLAB functions are obtained from [1], however the given functions had to be slightly modified as a new function was introduced. The new function developed is called *Diagram_V3.m* and it generates two different graphs which will show both the Grade of Utilization (GoU) of the charging infrastructure and a boxplot diagram for the given time and number of simulations.

This procedure will be repeated in each grid for both the 1 and the 6 Million Scenario. The complete simulations have to be carefully chosen so that the most interesting time periods are shown.

Figure 1.2 shows the methodology followed in this Thesis to obtain a complete view of the e-mobility impact on the given electric networks.

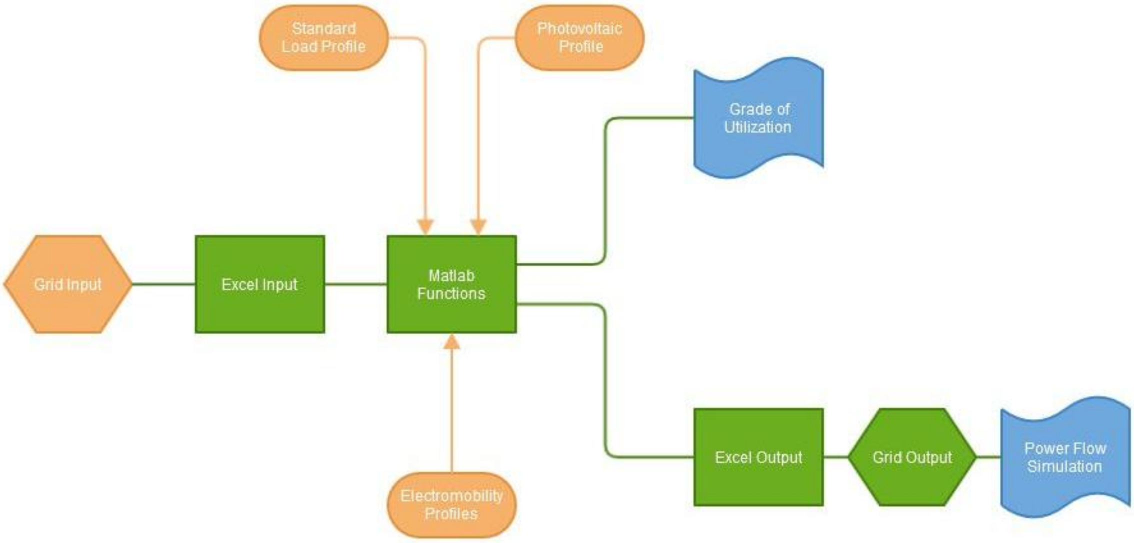


Figure 1.2: Load Flow Structure

3 Background Framework

In order to run the power flow simulations, different MATLAB tools developed in previous projects have been used. The use of these tools enables the user to generate:

- Household and industry loads
- Conventional and renewable infeed
- Charging infrastructure with its corresponding e-mobility loads.

3.1 Bachelor Thesis Wolf Schulze

[1] Consisted on a grid simulation in a medium-voltage grid. Therefore, it is necessary to carry out an explanation of the previous project, so that the different functionalities are properly understood.

In [1], MATLAB tools were developed to prepare the grid data in six different steps:

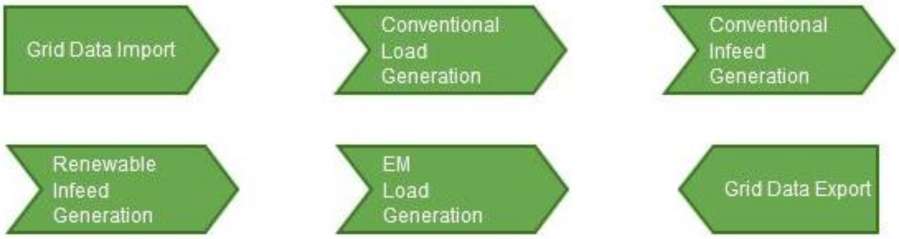


Figure 2.1: Thesis Structure according to [1]

3.1.1 Grid Data Management

In [1], new e-mobility loads were generated on MS *Clusternetz 1*; this will be one of the two networks which will be studied. The grid consist of a radial network, this is means that in normal conditions, the grid will be connected with the high-voltage level by means of one transformer station. However, in case of grid failure it can also be supplied by two other transformer stations placed at both sides of the grid.

This distribution network holds a total of 119 loads. 82 of them are household loads (H0: Standard Household) while the other 37 substations are considered industrial loads (G0: Standard Industry).

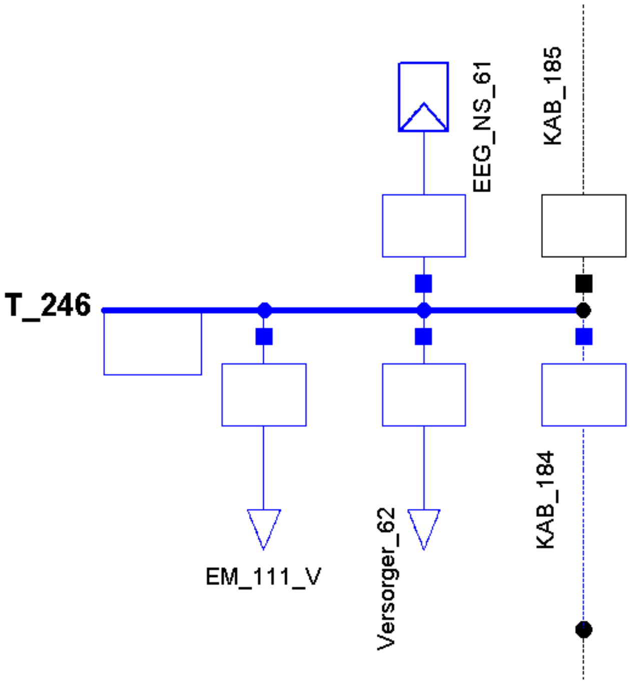
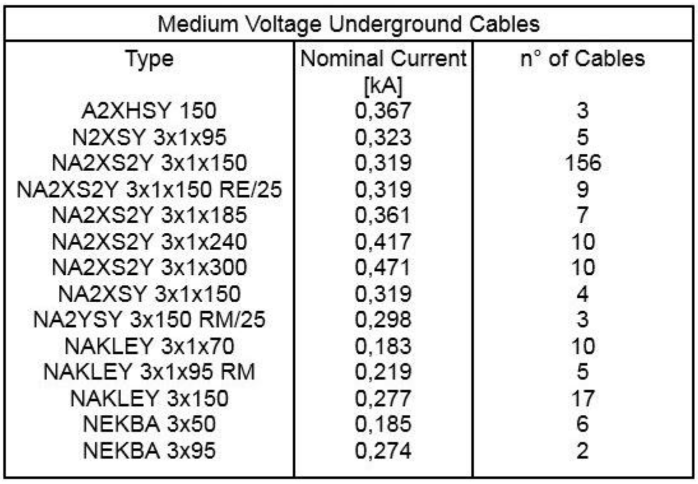


Figure 2.2: ***MS Clusternetz 1*** **node example**

There is one load with a given nominal apparent power per node. All these Loads have a 0.9 inductive power factor. Apart from the domestic and industrial loads, also renewable infeed can be found at the substations. There are a total of 88 renewable generators, where 83 of them are solar panels and the other 5 are biogas- or combined heat and power plants. 23 of the plants feed in at a medium-voltage level while the other 65 supply at a low-voltage level.

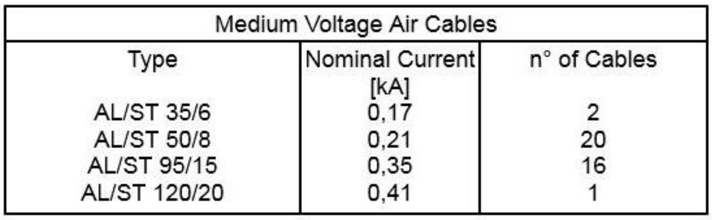
A power factor of $\cos \varphi = 1$ is applied for the biogas- or combined heat and power plants, as well as for 75 solar generators. From the other eight, seven of them have a $\cos \varphi = 0,95$ and one a $\cos \varphi = 0,9$.

There is a total of 286 cables connecting the low-voltage networks among each other and to the transformer station. A great number of them (247) are underground cables, while the 39 others are overhead transmission lines. Table 2.2 shows the different cables used as well as the maximum current supported by the conductors.



Medium Voltage Underground Cables		
Type	Nominal Current [kA]	n° of Cables
A2XHSY 150	0,367	3
N2XSY 3x1x95	0,323	5
NA2XS2Y 3x1x150	0,319	156
NA2XS2Y 3x1x150 RE/25	0,319	9
NA2XS2Y 3x1x185	0,361	7
NA2XS2Y 3x1x240	0,417	10
NA2XS2Y 3x1x300	0,471	10
NA2XSY 3x1x150	0,319	4
NA2YSY 3x150 RM/25	0,298	3
NAKLEY 3x1x70	0,183	10
NAKLEY 3x1x95 RM	0,219	5
NAKLEY 3x150	0,277	17
NEKBA 3x50	0,185	6
NEKBA 3x95	0,274	2

Table 2.1: Medium-Voltage Underground Conductors



Medium Voltage Air Cables		
Type	Nominal Current [kA]	n° of Cables
AL/ST 35/6	0,17	2
AL/ST 50/8	0,21	20
AL/ST 95/15	0,35	16
AL/ST 120/20	0,41	1

Table 2.2: Medium-Voltage Air Conductors

In order to proceed with the simulations, the POWERFACTORY data is introduced into an EXCEL Grid Data document, this file will contain the following information:

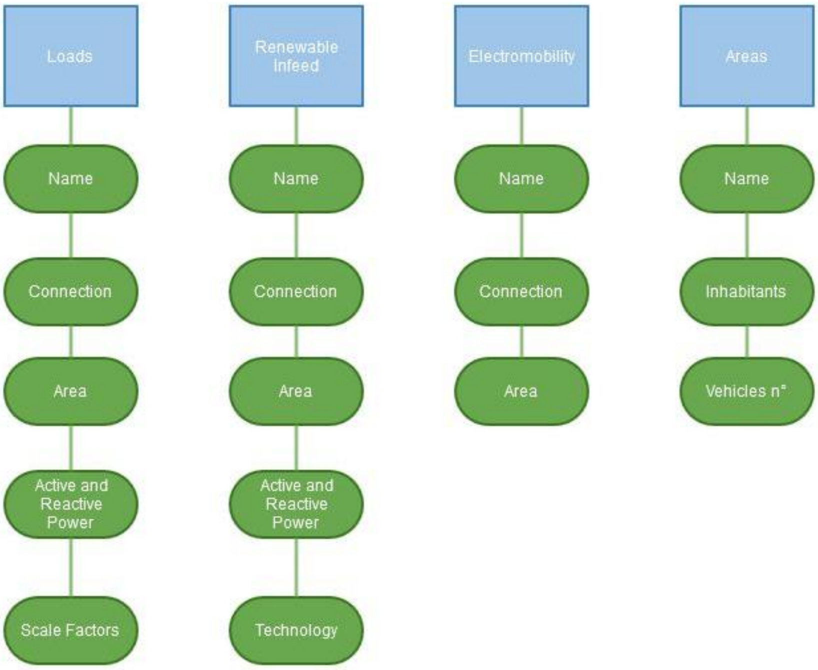


Figure 2.3: EXCEL Grid Data

3.1.2 Generation of Grid Loads and Infeed

In this paragraph the conventional load and infeed as well as the renewable infeed generation will be handled. In order to shape the ‘conventional load’, load profiles from BDEW are applied [2]. These provide daily, weekly or even annual information about the load profiles of different demanding groups.

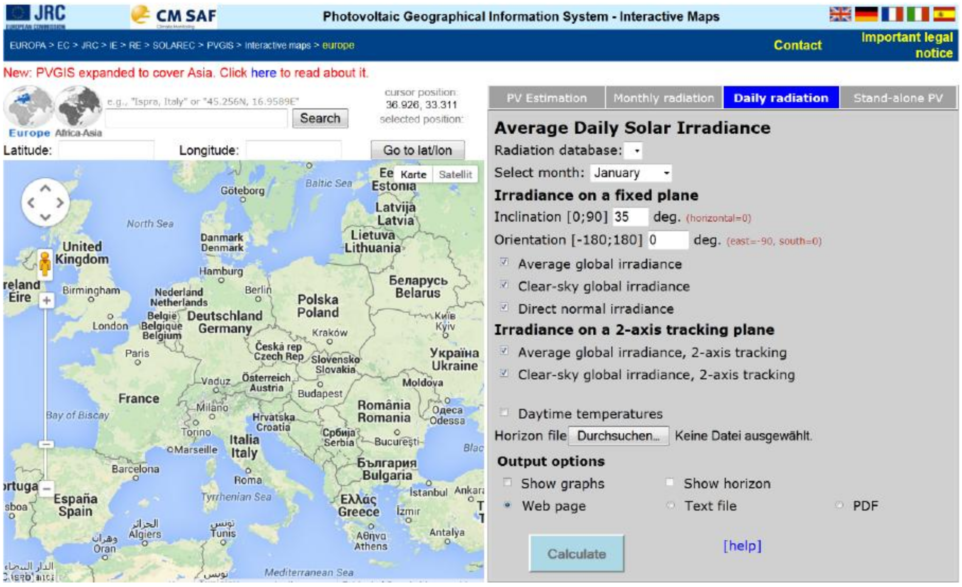
Given the lack of additional information just two kinds of loads are assumed. These are ‘G0: Standard Industry’ and ‘H0: Standard Household’. Different load characteristics are given depending the time of the year:

- Winter: 01.11. until 20.03.
- Summer: 15.05. until 14.09.
- Transitional Period: 21.03. until 14.05. and 15.09. until 31.10.

Additionally each week is divided into three types of days:

Figure 2.4: Day type

The tool *Photovoltaic Geographical Informational System* (PVGIS) will provide the required data to generate the photovoltaic infeed profiles. This software calculates the solar radiation every 15 minute for the whole month given a certain location. The results are used to generate a daily solar radiation profile. With these values and the given nominal power of the panels the PV Infeed is generated. On the other hand all the conventional generators will be feed the grid at nominal power.



New: PVGIS expanded to cover Asia. Click here to read about it.

e.g., "Ispra, Italy" or "45.256N, 16.9589E"

cursor position: 36.926, 33.311

selected position:

Latitude:

Longitude:

Average Daily Solar Irradiance

Radiation database:

Select month: January

Irradiance on a fixed plane

Inclination [0;90] 35 deg. (horizontal=0)

Orientation [-180;180] 0 deg. (east=-90, south=0)

☑ Average global irradiance

☑ Clear-sky global irradiance

☑ Direct normal irradiance

Irradiance on a 2-axis tracking plane

☑ Average global irradiance, 2-axis tracking

☑ Clear-sky global irradiance, 2-axis tracking

☐ Daytime temperatures

Horizon file Keine Datei ausgewählt.

Output options

☐ Show graphs ☐ Show horizon

● Web page ○ Text file ○ PDF

Figure 2.5: Screenshot of the PVGIS

Both the conventional load and the renewable infeed are generated by *Complete_Scaling_V4* in two different steps: *Load_Scaling* and *EEG_Scaling*; the third function which includes this tool is the *EM_Load_Selector* which is related to the e-mobility load generation explained in the following paragraph.

3.1.3 Electromobility Load Generation

The electric vehicles loads are implemented in two steps:

1. Generation of a charging infrastructure
2. Generation of the e-mobility load profiles

The charging infrastructure generation is accomplished by the MATLAB script: *Grid_Data_Generator_V5.m.* In order to fulfill the task the script has to cover the following points:

First, it obtains the number of EVs in the Grid. In order to determine this value two different Scenarios are proposed. The first scenario (1 Million EVs in Germany) assumes that by the year 2020, 2.28% of all the vehicles will have electric propulsion. The second option which predicts a scenario by the year 2030, assumes that 13.68% of all vehicles are electric (6 Million EV in Germany).

According to the previous information, once that the total vehicle number in the grid is determined the estimation of the number of EVs can be calculated. In the case of *MS Clusternetz 1*, given that the exact location of the grid is known, the number of inhabitants can be easily obtained. The vehicle number was established applying the ratio one vehicle each 1.6 inhabitants.

The e-mobility technology definition was carried out in [5]. Here, the EV distribution was determined for both the 1 and the 6 million scenario. This distribution is considered to be accurate enough in order to study the e-mobility load impact.

Now that the number and the characteristic of the EVs are known, it is possible to establish the number and the maximum power of the charging stations. Each EV will have its corresponding private charging station. Also for every 10 EVs one public charging station will be added. For private charging stations the maximum power will be the corresponding charging power of the EV; on the other hand in public stations each car will be charged at its maximum power. An efficiency of 90% and an inductive power factor of 0.97 are assumed for the charging procedure.

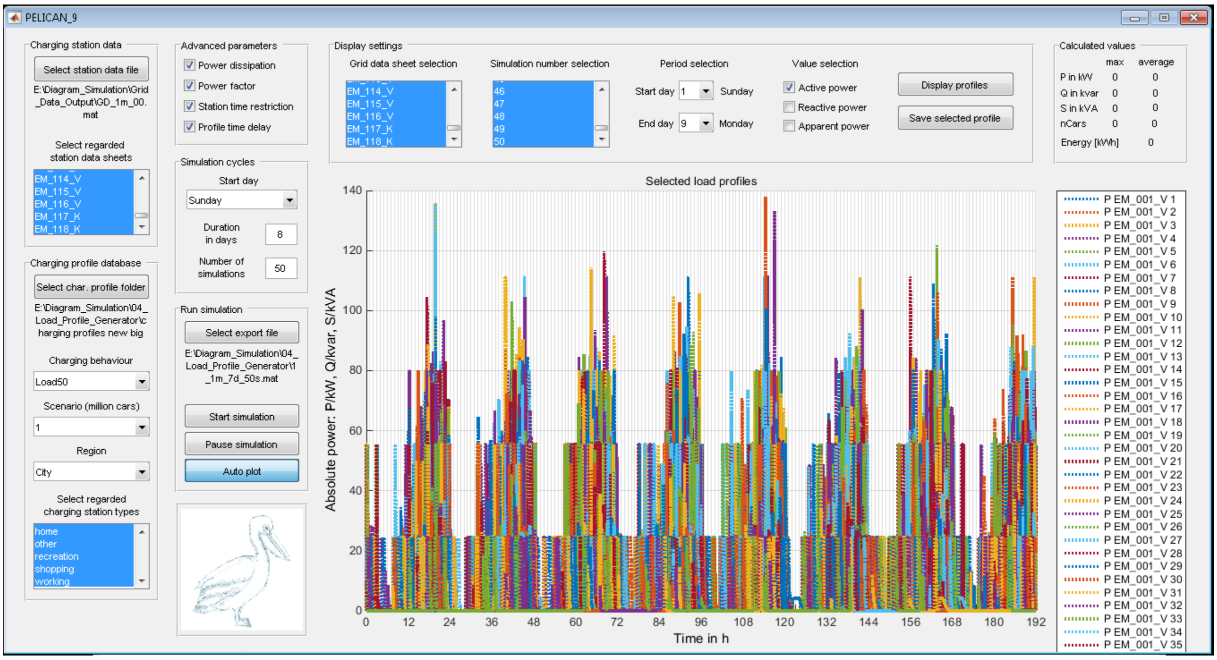
[1] Will create a matrix for each grid substation which will only need the aggregated charging profile of the charging stations to generate the EV Loads. These matrixes will show all the necessary information including the charging stations ID number and the type of station.

For public charging stations different locations are described: work, shopping, recreation or other. Due to the lack of information this stations are distributed equally.

The generation of the e-mobility load profiles is carried out by the script *Pelican_9.m*. This tool generates an aggregated load profile by using charging load profiles obtained from [3]. *Pelican_9.m* allows the user to:

- select the precise grid
- choose the EV scenario
- choose the simulation length, selecting the starting weekday
- determine the number of simulations

This tool requires both the charging infrastructure and the charging profile data as inputs. This second file is obtained from [3], which implements the charging strategy *Load50* to determine the user behavior.


PELICAN_9

Charging station data
Select station data file
E:\Diagram_Simulation\Grid_Data_Output\GD_1m_00.mat
Select regarded station data sheets: EM_114_V, EM_115_V, EM_116_V, EM_117_K, EM_118_K

Charging profile database
Select char. profile folder
E:\Diagram_Simulation\04_Load_Profile_Generator\charging profiles new big
Charging behaviour: Load50
Scenario (million cars): 1
Region: City
Select regarded charging station types: home, other, recreation, shopping, working

Advanced parameters
☑ Power dissipation
☑ Power factor
☑ Station time restriction
☑ Profile time delay

Simulation cycles
Start day: Sunday
Duration in days: 8
Number of simulations: 50

Run simulation
Select export file
E:\Diagram_Simulation\04_Load_Profile_Generator\1_1m_7d_50s.mat
Start simulation
Pause simulation
Auto plot

Display settings
Grid data sheet selection: EM_114_V, EM_115_V, EM_116_V, EM_117_K, EM_118_K
Simulation number selection: 46, 47, 48, 49, 50
Period selection
Start day 1 Sunday
End day 9 Monday
Value selection
☑ Active power
☐ Reactive power
☐ Apparent power
Display profiles
Save selected profile

Calculated values

	max	average
P in kW	0	0
Q in kvar	0	0
S in kVA	0	0
nCars	0	0
Energy [kWh]	0	

Figure 2.6: *Pelican_9.m* interface

3.1.4 Grid Simulation

After all the data obtained from the MATLAB tools is generated and analyzed, a power flow simulation can be executed. For the power flow simulation [1] chose to simulate different day types (Workday, Saturday and Sundays) of May and November during midday and after work hours. The results obtained showed that the point with the highest load values corresponds to a workday in November. This case was studied with great detail.

The point of maximal conventional load with a maximum value of 7,202 MW was found at 12:00. However, at this time the generation reached its peak value with a total infeed of 6,460 MW. This meant that at this time the load was balanced by the grid generation.

During this day an evening peak appears at 18:00. At this time the e-mobility load presents its maximum values. The total load graph will have the next curves.

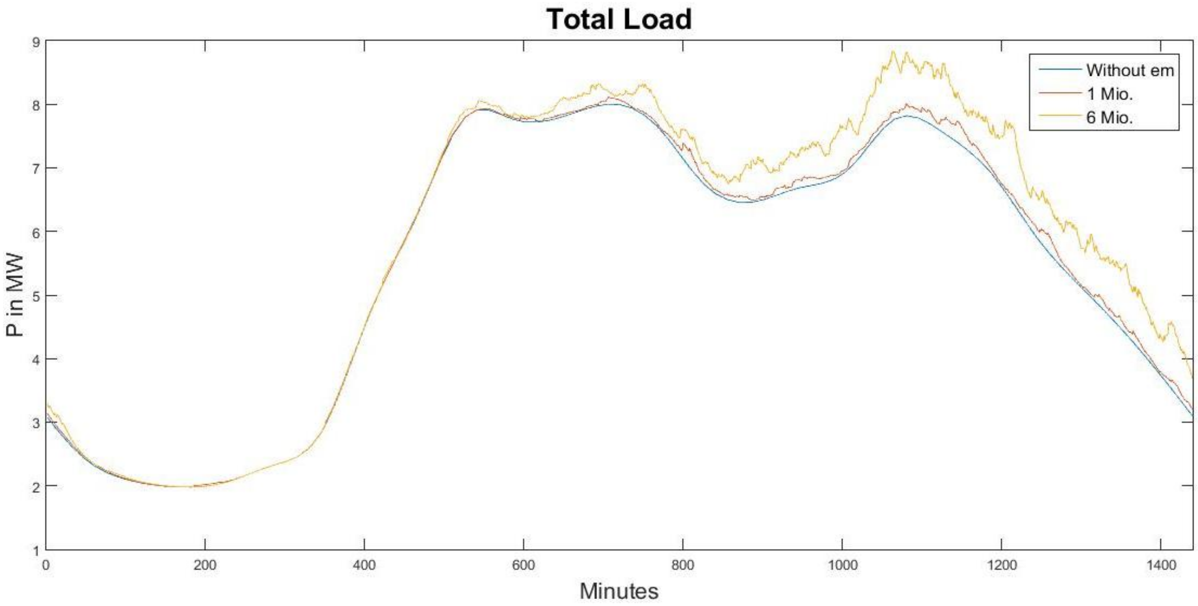


Figure 2.7: Total Load November *MS Clusternetz 1*

The most significant values obtained from a workday in November at 18:00 with and without e-mobility were:

MS Clusternetz 1	No EM Load	6 Mio. Scenario
Transformer Load	15,28%	18,65%
Highest Loaded Cable	37,06%	40,31%
Maximal Voltage Difference	1,34%	1,66%

Table 2.3: Simulation November *MS Clusternetz 1*

3.2 EV Charging Characteristic

The information about the charging profiles and the probabilistic behavior of the charging processes is obtained from the Master Thesis *‘Modeling of the driving and charging behavior of the Electric Vehicles’* [4] and the Bachelor Thesis: *‘Simulation and Analysis from probabilistic Electromobility Load Profile*’ [5].

3.2.1 Master Thesis Simon Marwitz

[4] Studies the EV driver behavior. In order to accomplish this task, a java-model is created. The first target of the project is to model the driving behavior. Therefore the study ‘Mobility in Germany’ is used as a pattern [6]. This Study handles with information related to the driving behavior of the German population. Due to the extension of the sample and the relative up-to-date information (2008), the survey can be considered as valid for predicting the charging procedures.

This survey allows the user to obtain the information of a specific region as well as the type of urban settlement. More than 190.000 travels with the corresponding information about goal of the travel, length, vehicle type and departure time are registered. All this information is introduced in [4] in terms of a probability density functions.

In this Thesis various assumptions were made: first of all an EV type distribution is applied (see table 2.4), second, the availability of the charging stations depends on the destination of the travel.

EV Type	Battery Capacity [kWh]	Max. Charging Power [kW]	E-Consume [kWh/100km]	Frequency [%]
PHEV 1	4,5	3,6	18	32
PHEV 2	12	10,8	21	55
PHEV 3	15	10,8	15	10
PHEV 4	30	10,8	18	3

Table 2.4: EV distribution from Marwitz [4]

Finally, a State of Charge (SOC) is given for every EV. As expected, the State of Charge will decrease during the driving times and will increase during the charging periods. For the generation of the final output two different charging strategies are implemented:

- Charging after the last ride of the day
- Charging after every ride

3.2.2 Bachelor Thesis Tobias Gebel

The '*Simulation and Analysis from probabilistic E-mobility Load Profile*' Bachelor Thesis is based on [4]. In this Thesis a new charging strategy called *Load50* is introduced. With the new strategy, the e-mobility users will charge their vehicles after a drive if:

- The State of Charge (SOC) is under 50%
- It was the last drive of the day.

This strategy assumes a constant charging availability.

In [4] a new EV distribution is proposed (see table 2.5). This distribution was used in [1] and will also be used in this thesis; therefore the EVs distributions of the two future e-mobility scenarios (1 and 6 million EV in Germany) are estimated. In the 1 million EV scenario the distribution adopted shows today's e-mobility state of art, while in the 6 million EV scenario two more EV types with larger battery capacity and higher charging power are introduced.

EV Type	Battery Capacity [kWh]	Max. Charging Power [kW]	Frequency [%] 1 Mio. Scenario	Frequency [%] 6 Mio. Scenario
PHEV 1	18,8	50	15	12,5
PHEV 2	10	3,7	20	10
City BEV 1	17,6	22	50	30
City BEV 2	18,8	11	15	12,5
Future PHEV	40	50	0	20
Future BEV	60	50	0	15

Table 2.5: EV distribution from Gebel [5]

Given the limited range of EV, the maximum drive length will be assumed to be 100 km. This means that for all travels which covered longer distances 100 km value will be assigned.

With this data, charging profiles of 10.000 vehicles and duration of one week were generated. In Figure 2.8 the output information is described.

Figure 2.8: Output Information Gebel

During later work, an update was introduced to simulate the constant current/constant voltage charging characteristic. This strategy is used by most EVs manufactures in order to achieve rapid charging of Li-Ion batteries without reaching current or voltage overloads. This meant that the EVs are not charged at a constant power anymore. As we can see in Figure 2.9, the power load will diminished once a certain SOC is reached.

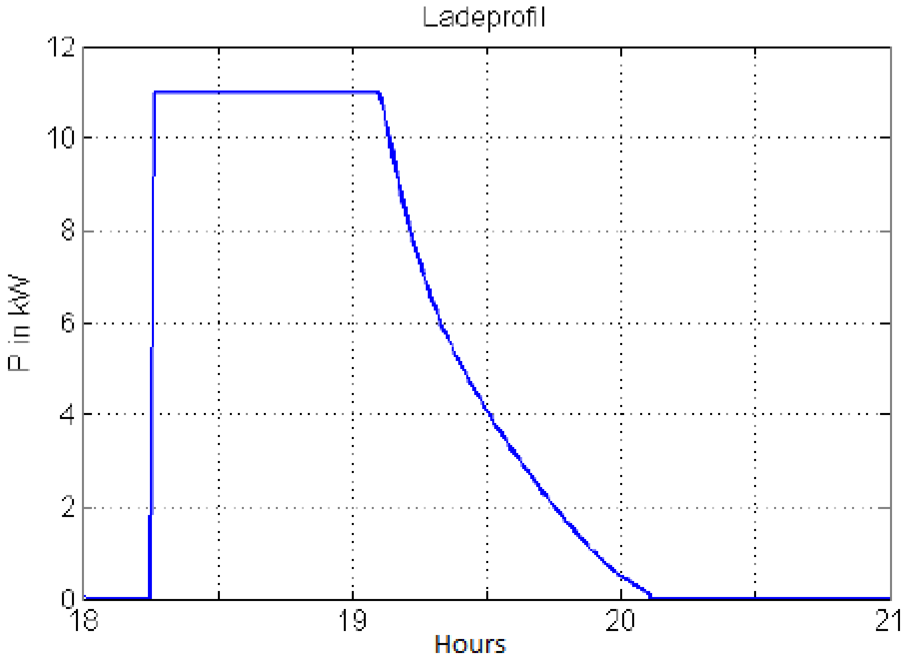


Figure 2.9: Charging Characteristic Gebel

4 Realization

The study of the impact that e-mobility fleets may have on medium-voltage electric networks requires a full grid behavior understanding, which will be obtained through:

- Grid data analysis
- Aggregated e-mobility load generation
- Grade of Utilization (GoU) analysis
- Power flow simulations

4.1 Net Data

In order to realize the e-mobility load simulations, two medium-voltage grids are given: *MS Clusternetz 1* and *MS Clusternetz 3*, both of them are 20 kV grids. The first task of the project is to analyze the new grid *MS Clusternetz 3* and then import the data to MATLAB.

MS_Clusternetz_3 consist on a radial medium-voltage distribution network. The customers are supplied by one central transformer station which includes two transformers, each one with a nominal power of 40 MVA. Additionally, other possible emergency transformer stations can be connected in case of failure. This represents the typical configuration for rural or suburban areas.

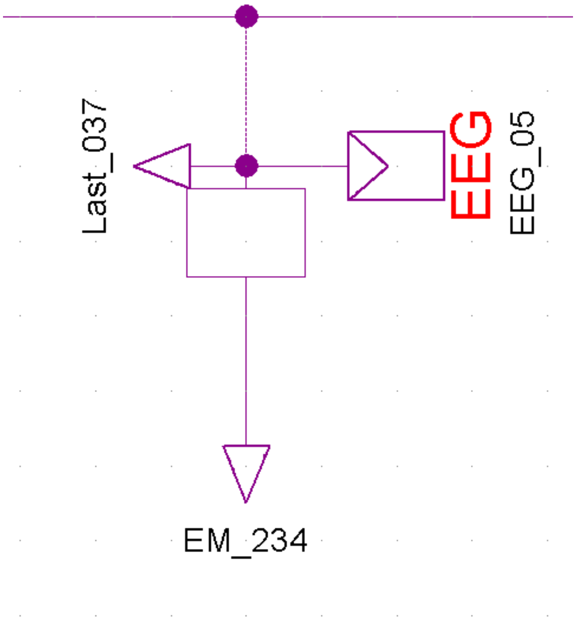


Figure 3.1: ***MS Clusternetz 3*** **node example**

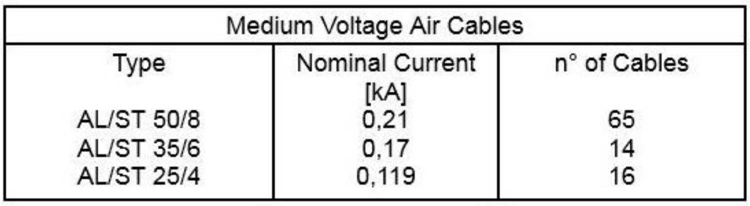
The grid holds a total of 304 loads. From these loads, 200 represent household loads (defined as H0: Standard Household) and 104 are industrial loads (defined as G0: Standard Industry). The distinction between the two types of loads was not obtained from the POWERFACTORY data but from the *Zuordnung_MSClusternetz_3_extern* EXCEL sheet given, where all the loads in which a number of households figured are considered domestic and the rest are assumed as industrial.

From the 304 loads 298 have a power factor of *cos φ* = 0.95; 5 of them have a power factor of *cos φ* = 0.9 and one of them was assigned a *cos φ* = 0.712.

It was observed, that in the initial POWERFACTORY grid two scaling factors are applied to the loads. One of them, the Area Scaling Factor, is applied to both active and reactive power of the grid elements, while the other one, the Grid Scenario Factor, is just applied to the active Power of the loads. This second factor represents the grid status, which can be Low Load, High Load and Maximum Load with values of 0.3, 0.8 and 1 respectively; due to its characteristics, this factor will change the power factor of the loads.

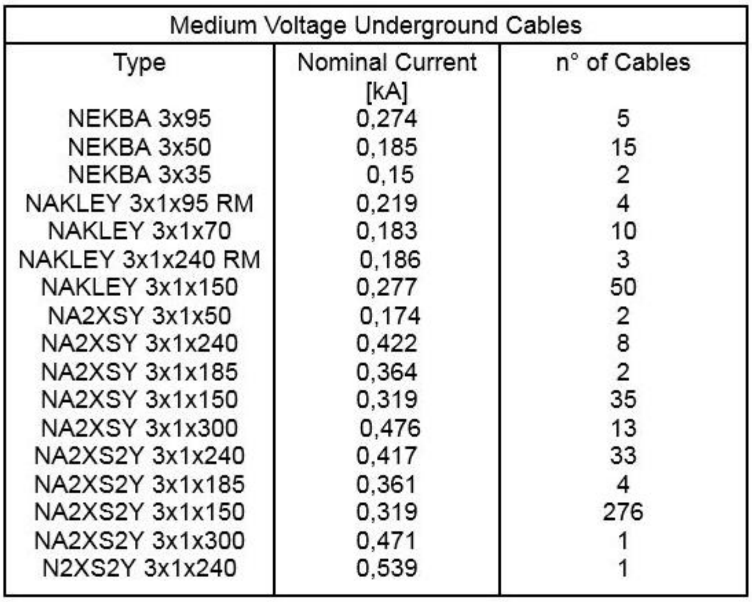
Renewable infeed is also connected to the grid. There is total number of 57 generators. From them, 34 are photovoltaic generators, 19 are renewable generation, 3 are static generators and there is also one wind turbine. All the infeed is connected at the medium-voltage level. Due to its generation characteristics, the generators are divided in two groups: the first group is defined as the fixed generators, it consist on the 22 renewable and the 3 static generators, while the other group, defined as the variable generators includes the 34 photovoltaic panels and the wind turbine.

There are a total number of 628 conductors. 465 from them are underground, while the 163 resting are air cables. The conductor's distributions are shown in Tables 3.1 and 3.2.



Medium Voltage Air Cables		
Type	Nominal Current [kA]	n° of Cables
AL/ST 50/8	0,21	65
AL/ST 35/6	0,17	14
AL/ST 25/4	0,119	16

Table 3.1: ***MS Clusternetz 3*** **air cables**



Medium Voltage Underground Cables		
Type	Nominal Current [kA]	n° of Cables
NEKBA 3x95	0,274	5
NEKBA 3x50	0,185	15
NEKBA 3x35	0,15	2
NAKLEY 3x1x95 RM	0,219	4
NAKLEY 3x1x70	0,183	10
NAKLEY 3x1x240 RM	0,186	3
NAKLEY 3x1x150	0,277	50
NA2XSY 3x1x50	0,174	2
NA2XSY 3x1x240	0,422	8
NA2XSY 3x1x185	0,364	2
NA2XSY 3x1x150	0,319	35
NA2XSY 3x1x300	0,476	13
NA2XS2Y 3x1x240	0,417	33
NA2XS2Y 3x1x185	0,361	4
NA2XS2Y 3x1x150	0,319	276
NA2XS2Y 3x1x300	0,471	1
N2XS2Y 3x1x240	0,539	1

Table 3.2: *MS Clusternetz 3* underground cables

As explained before, the number of the grid's households is given in the Excel sheet. Once that the household number is known the number of inhabitants can be determined by applying a ratio of 2.47 inhabitants per household. With the previous information, a total number of 19.157 Inhabitants were assigned to the grid. Known the population in the area we can determine the number of vehicles by using [6] data. With this relationship we obtain a total number of 11.925 vehicles.

4.2 Electromobility

After analyzing the main grid features all the data can be introduced in an EXCEL sheet. This will allow the introduction of the e-mobility loads as well as generating the conventional load and the power infeed corresponding to a specific time period. This will be done by the MATLAB tools developed in [1].

Thanks to the vehicle number estimation done in the last paragraph, it is possible to introduce the EV number. This value will depend on the scenario chosen and will follow the percentages given in [5].

EV Number	*MS Clusternetz 1*	MS Clusternetz 3
1 Mio. Scenario	171	266
6 Mio. Scenario	1032	1630

Table 3.3: EV number

The number of charging stations will just depend on the number of EVs defined in the grid. The charging stations distribution was defined in [5]:

- One private charging station per EV
- One public charging station every 10 EVs

Charging Stations nº	*MS Clusternetz 1*	MS Clusternetz 3
1 Mio. Scenario	205	293
6 Mio. Scenario	1238	1793

Table 3.4: Charging Stations number

Now that the number of charging stations is known, the EM loads are introduced. As explained before, this will be done by the MATLAB script *Pelican_9.m.* In order to have a good view on the grid behavior the next simulations were made:

Figure 3.2: EV simulations

The name of the file refers to the following information:

- Grid n°: 1 stands for *MS_Clusternetz_1* while 3 stands for *MS_Clusternetz_3*
- Scenario: 1 million or 6 million EV scenarios
- Simulation length: number of days simulated
- N° of simulations

The simulation length chosen is seven days so the characteristic of a whole week can be analyzed. Actually, in the *Pelican_9.m* tool a total number of 8 days will be chosen, however the first day will be omitted as it doesn´t show feasible values.

In order to have a reasonable number of results, a large number of simulations were arranged. The number of simulation chosen were 50 for the 1 Million Scenario and 20 for the 6 Million one. These simulations give enough data to proceed with a complete impact study.

4.2.1 Grade of Utilization

The Grade of Utilization (GoU) determines the level of usage of the charging infrastructure for all the given simulations. These values are obtained to study the generated charging network behavior. The tools developed will:

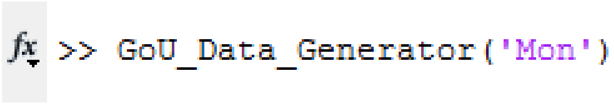
- Created a matrix with the Grade of Utilization (GoU) values
- Generate a plot with the GoU values
- Generate a box plot diagram

For the achievement of the previous tasks, new MATLAB functions were developed. First of all, the version *Grid_Data_Generator_V6.m* was updated to create an output file, called *Diagram Data*, with information related to the charging infrastructure:

- Number of charging stations
- Number of EV
- EV type distribution.

Once that all the input information is created the function *GoU_Data_Generator.m* can be used. The input used by the function will not only be the *Diagram Data,* but also the grid with the introduced charging infrastructure (generated by *Grid_Data_Generator_V6.m*) and the aggregated e-mobility loads (generated by *Pelican_9.m*).

In order to run *GoU_Data_Generator.m* a time period has to be selected. This time period can either be a day of the week (from Monday to Sunday) or the whole week. Once that all the inputs are correctly defined the function will generate a Grade of Utilization matrix. This matrix will contain the GoU values for each minute of the selected period for all the simulations considered (defined in *Pelican_9.m*). In Figure 3.3 an example of *GoU_Data_Generator.m* called is shown.



```
>> GoU_Data_Generator('Mon')
```

Figure 3.3: *GoU_Data_Generator* **call**

The Grade of Utilization is obtained by the equation described in Figure 3.4:

$$GradeofUtilization = \left(\sum Pev\right) / Pci$$

Figure 3.4: Grade of Utilization equation

In the previous equation, '*Pev*' represents the total sum of e-mobility loads at a specific time period (in this case a minute) and '*Pci*' will represent the total charging infrastructure active power. For the analysis of the medium-voltage grid only the active power will be considered. This is due to the fact that an inductive power factor of 0.97 is applied to the charging procedure making the consumed reactive power negligible.

Once the GoU data has been generated, the two plots can be reproduced. This task is accomplished by *GoU_Plot.m*. The function will receive the previously generated Grade of Utilization matrix as well as certain simulation characteristics of the corresponding simulation:

- The selected time period
- The EV scenario

The function will be totally defined when the interval length to be applied at the box plot is assigned. As shown in Figure 3.5 this will be done when calling the function.

```
>> GoU_Plot(3)
```

Figure 3.5: *GoU_Plot* **call**

Once that the input has been defined, the function will generate a plot of all the grade of utilization values obtained. However, due the size and dispersion of the data, a box plot will be generated for a better understanding of the results. The box and whiskers plot definition is described in Figure 3.6.

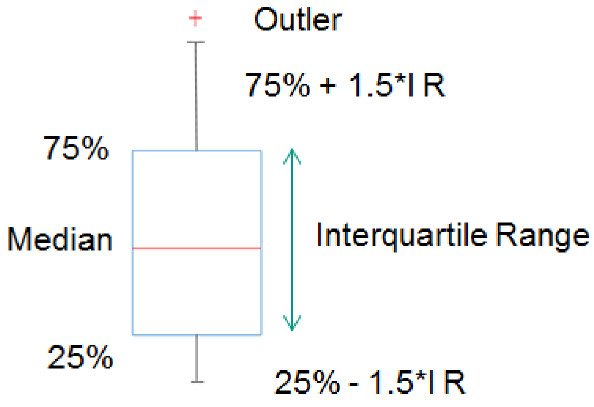


Figure 3.6: Box plot definition

By changing the length interval of the box plot (which is defined in hours), it is possible to obtain a good overview of: the dispersion of the generated data (interquartile range); the value of the outler points; and the charging behavior by analyzing the median values of the different time intervals. Finally the sequence to obtain the Grade of Utilization plots is described in Figure 3.7.

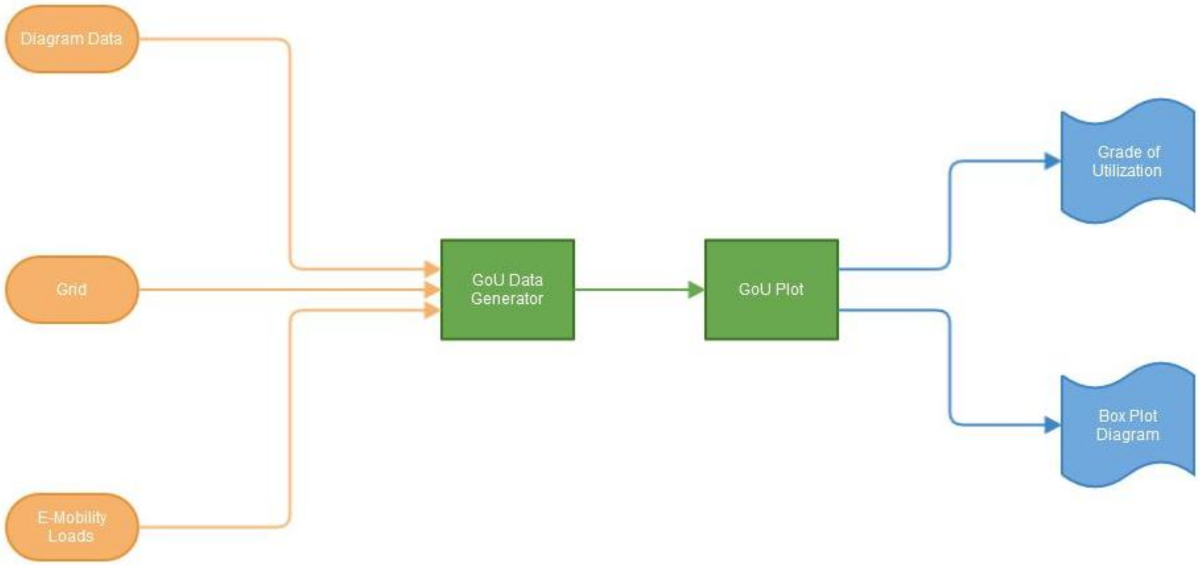


Figure 3.7: Scheme of GoU

4.3 Power Flow Simulation

Finally, the medium-voltage grid response to the new electromobility loads will be analyzed through a power flow simulation executed by POWERFACTORY software. In order to achieve an accurate simulation the following steps are taken.

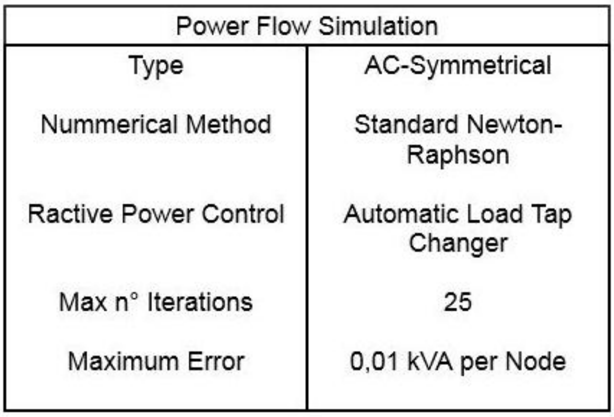
The first step consists on the introduction of the new electromobility loads. Every single low-voltage load will be assigned an EM load, this means that every industrial and household low-voltage load will have its correspondent EM load.

Once that the EM loads are introduced, it is necessary to select one day of the year to be studied. Both the conventional load and the infeed are generated by the function *Complete_Scaling_V4.m* and will depend on the day chosen.

In the second step the new generated MATLAB values are introduced in the POWERFACTORY grid. These final values are obtained by the MATLAB script *Data_Export_V4.m* developed in [1].

The task of *Data_Export_V4.m* will be to select a day minute and create an EXCEL sheet following POWERFACTORY data structure. Once all the new data is stored, it can be manually copied from the EXCEL sheet columns to POWERFACTORY.

The last step will be running the power flow simulation. Simulations of the most interesting time periods (at load and infeed peaks) will be executed. The sequence followed will be executing without e-mobility loads and then introducing the 1 and the 6 million EV scenarios. After the power flow simulations a deep analysis of the results will be made to determine the highest loaded grid components and how the introduction of e-mobility will affect these values. The technical data of the power flow simulation is shown in Table 3.5.



Power Flow Simulation	
Type	AC-Symmetrical
Nummerical Method	Standard Newton-Raphson
Ractive Power Control	Automatic Load Tap Changer
Max n° Iterations	25
Maximum Error	0,01 kVA per Node

Table 3.5: Power Flow Characteristics

5 Result Analysis

The impact of e-mobility fleets on the given grids will be estimated following the next steps:

1. Import of the POWERFACTORY grid data to MATLAB.
2. Introduction of the new e-mobility charging infrastructure
3. Simulation of power infeed and conventional loads
4. Generation of the e-mobility aggregated loads
5. Study of the charging infrastructure Grade of Utilization
6. Export the selected scenarios from MATLAB data to POWERFACTORY
7. Run the power flow with the new data

This process has been applied two both *MS Clusternetz 1* and *MS Clusternetz 3*. During this paragraph the given grid data as well as the obtained results will be analyzed. This will allow us to obtain a complete overview of the e-mobility loads impact.

5.1 Grid Comparison

The first step of the result analysis will consist on a description of the given electric networks.

Both grids are medium-voltage grids of 20kV which feed both industries and households low-voltage networks. They include infeed coming from different renewable sources. The structure of both grids is radial, with just one transformer station operating but with auxiliary transformer stations which could be connected to the grid in case of fault. This arrangement is commonly used in rural and suburban areas.

The most representative features of both grids are showed in Table 4.1:

Grid Comparison	MS Clusternetz 1	MS Clusternetz 3
Users	12.119	19.157
Load nº	119	304
Industry Load	31,1%	34,21%
Household Load	68,1%	65,79%
Generators nº	103	60
Fixed Generation	6,80%	41,67%
Variable Generation	93,1%	58,33%
EV 1 Mio. Scenario	171	266
EV 6 Mio. Scenario	1.032	1.630

Table 4.1: Grid Comparison

Out of the previous information it can be concluded that the second grid covers a more widely-spread and less-populated area than the first grid. It can also be stablished that the impact of a fluctuating power infeed will be bigger on the first grid than on the second one. This is reflected on Figure 4.1.

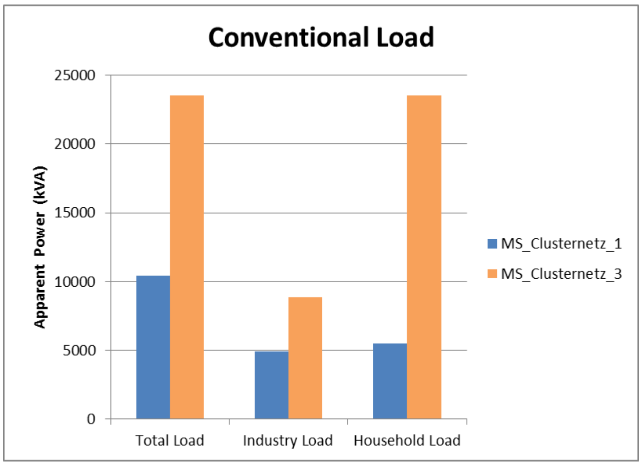


Figure 4.1: Conventional Load Comparison

MS Clusternetz 1 presents an inductive power factor of 0.9 for every conventional load, while in *MS Clusternetz 3* the power factors are defined as 0.95 inductive. On the other hand the generation distribution is shown in Figure 4.2.

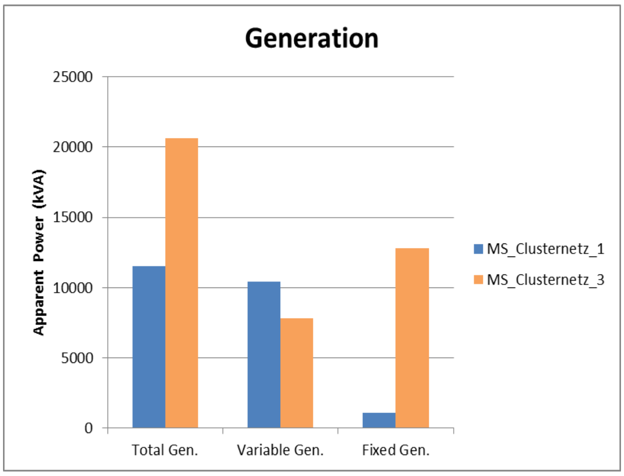


Figure 4.2: Generation Comparison

The power factors of the photovoltaic and wind generators are assumed as 1, while the conventional generators present a power factor of 0.95. These power factors are always between 0.9 and 1.

In the previous figure, a distinction between variable infeed (which represent photovoltaic and wind generation) and fixed infeed is made. The graphic shows that the dependency of both grids on fluctuating infeed it´s considerably big and therefore it should be taken into account when studying the grid response to the generated loads.

5.2 Charging Infrastructure

EV charging has some marked differences from conventional ICE refueling, and as a result, drivers show a different charging behavior. In this paragraph the main tasks are:

- Charging infrastructure analysis
- Charging behavior overview

In approach to fulfill the given tasks, the Grade of Utilization (GoU) of the charging infrastructure will be studied showing both the percentage of usage of the installed charging infrastructure and charging behavior of e-mobility users.

In *MS Clusternetz 1* a total of 205 charging stations were installed for the 1 million scenario. This meant an average of 1.74 stations per low-voltage grid with an average power of 44.66 kW. The total installed power was 5.262 MW.

For the 6 million scenario, this grid holds a total of 1238 charging points with an average of 10.49 charging points and an average installed power of 367.913 kW per low-voltage connection. The total installed power raises to 43.420 MW.

On the other hand, for the 1 million scenario, *MS Clusternetz 3* holds a total of 294 charging stations with a total power of 6,912 MW. The average stations number per low-voltage connection is 1.01 with an average installed power of 23.75 kW.

For the 6 million scenario the charging point's number is 1793. Therefore an average of 6.16 stations with an average of 207.94 kW per connection will be found. The total installed power will be of 60.505 MW.

Two graphs are generated per grid showing the results from the 1 and the 6 million scenario Grade of Utilization. Showing the following results:

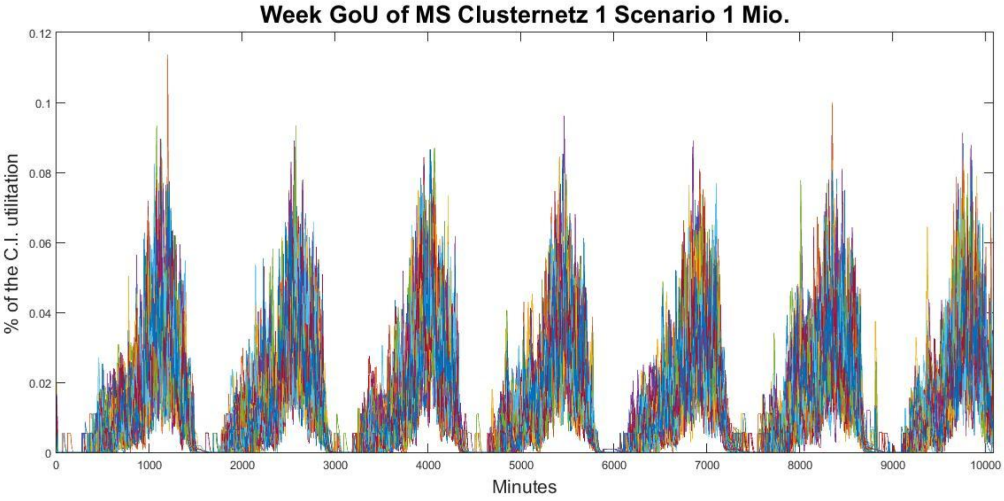


Figure 4.3: GoU Grid 1 Scenario 1 Mio.

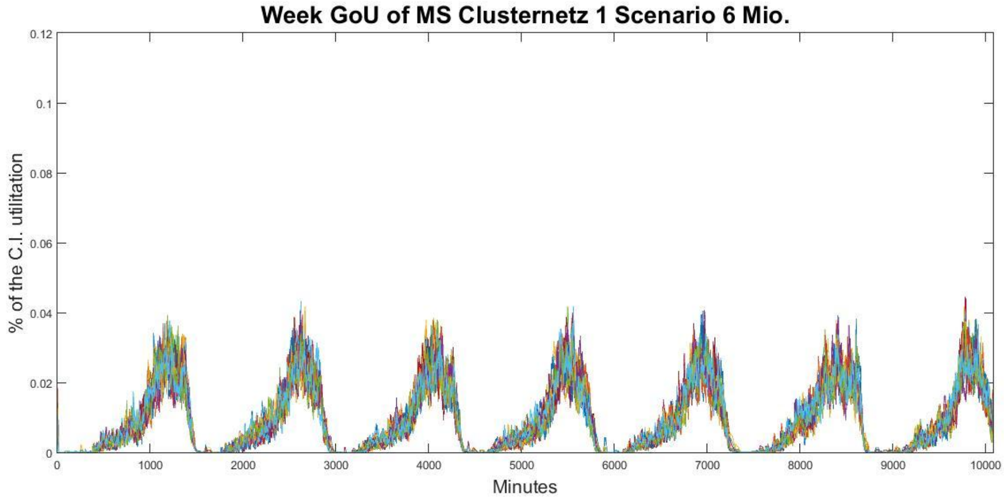


Figure 4.4: GoU Grid 1 Scenario 6 Mio.

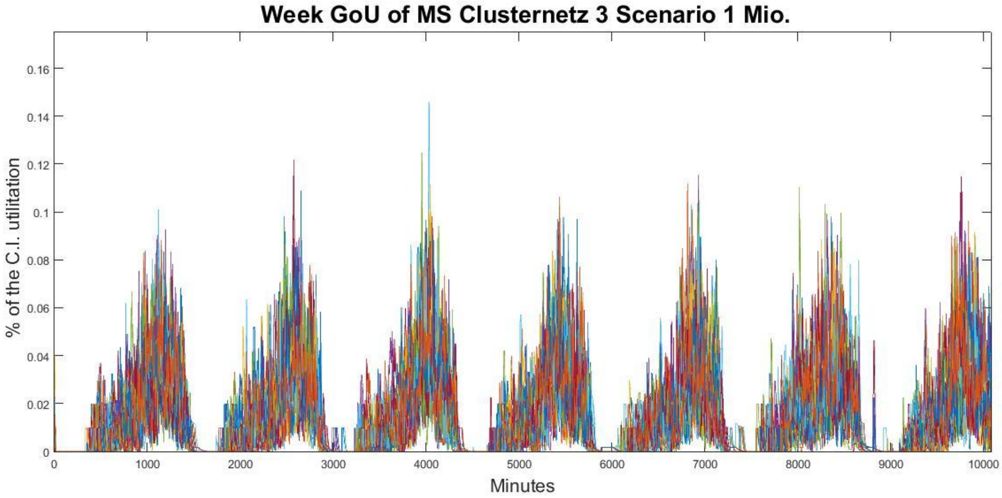


Figure 4.5: GoU Grid 3 Scenario 1 Mio.

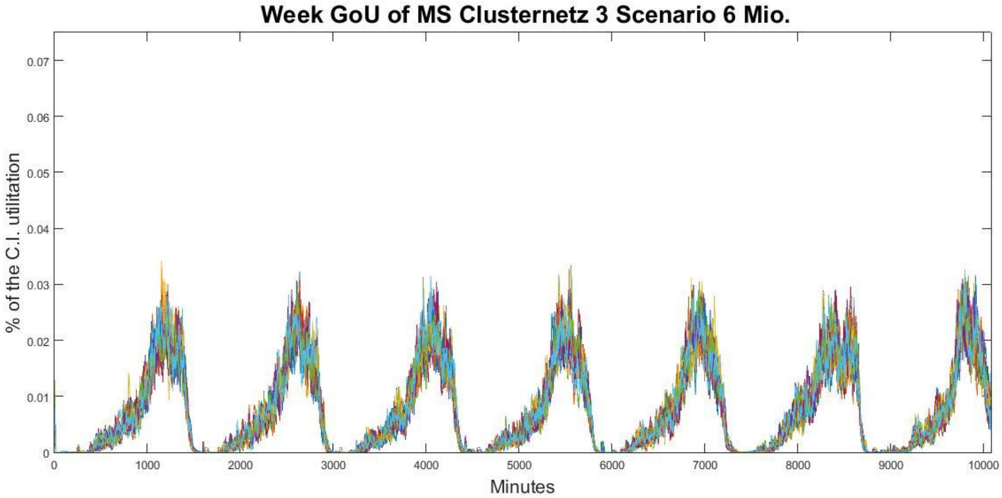


Figure 4.6: GoU Grid 3 Scenario 6 Mio.

In the previous four graphs the Grade of Utilization (GoU) of a whole week is shown for the two scenarios on both grids. The number of simulations for both grids was:

- 50 Simulations for the 1 million EV scenario
- 20 Simulations for the 6 million EV scenario

Table 4.2 and 4.3 show the most important features of the Grade of Utilization:

MS Clusternetz 1	EV nº	Charging Station nº	Installed Power	GoU Average	GoU Maximum	GoU Interquartile range
1 Mio. Scenario	171	205	5,262 MW	0,87%	11,35%	0,024%-2,21%
6 Mio. Scenario	1032	1238	43.420 MW	0,52%	4,45%	0,059%-1,16%

Table 4.2: *MS Clusternetz 1* GoU values

MS Clusternetz 3	EV nº	Charging Station nº	Installed Power	GoU Average	GoU Maximum	GoU Interquartile range
1 Mio. Scenario	266	294	6.912 MW	0,92%	9,13%	0,074%-2,24%
6 Mio. Scenario	1630	1793	60.505 MW	0,42%	3,42%	0,045%-1,35%

Table 4.3: *MS Clusternetz 3* GoU values

The previous values show that the charging infrastructure developed can handle the charging of the introduced electric vehicles. Furthermore, it might be determined that this infrastructure is oversized. The maximum GoU obtained was of 11.35%, while the average values were always below 1%. On the other side, no important differences were observed between the two electric networks.

The different EV technologies used in the 1 and the 6 million case scenario have a strong effect on the GoU behavior. Both distributions are shown in Table 4.3.

EV Type	Battery Capacity [kWh]	Max. Charging Power [kW]	Frequency [%] 1 Mio. Scenario	Frequency [%] 6 Mio. Scenario
PHEV 1	18,8	50	15	12,5
PHEV 2	10	3,7	20	10
City BEV 1	17,6	22	50	30
City BEV 2	18,8	11	15	12,5
Future PHEV	40	50	0	20
Future BEV	60	50	0	15

Table 4.4: EV Type distribution

The two magnitudes which changes with the distribution applied are the battery capacity and the maximum charging power; these factors directly affect the GoU values. In the 6 Million Scenario the charging procedures will demand a higher power, however these procedures will last shorter and take place less often due to a bigger battery capacity. This will conclude on a smaller Grade of Utilization of the charging infrastructure, which will see its average value reduced by a 40.23% on *MS Clusternetz 1* and 29.89% on *MS Clusternetz 3*.

It was also observed, that an increase in the numbers of EVs will reduce the divergence of the values. This explains why with a 6 million scenario the interquartile range is reduced. According to previous research, the application of standard load profiles for e-mobility will be valid for more than 1,000 electric vehicles [7]. Although in this case, the artificial coincident factor of 1 introduces inaccuracies.

When observing the day behavior, it can be concluded that the period with the highest values of utilization appear from 18:00 to 20:00. This corresponds to the time when the electric vehicles users arrive at their houses and begging to charge the batteries. This time concur with the conventional load peak, which increases the instantaneous demand of electric energy. This may be an issue for the Transmission System Operators (TSO); therefore it will be a topic of discussion on further paragraphs.

The following box plot describes a day distribution of the Grade of Utilization. It shows a Wednesday with a 1 million scenario EVs on *MS_Clusternetz_1*. As it can be observed the average GoU value at 20:00 is 3.96%; a value much higher than the average week value, 0.87%. In this case the Grade of Utilization of the charging infrastructure is always under 9%.

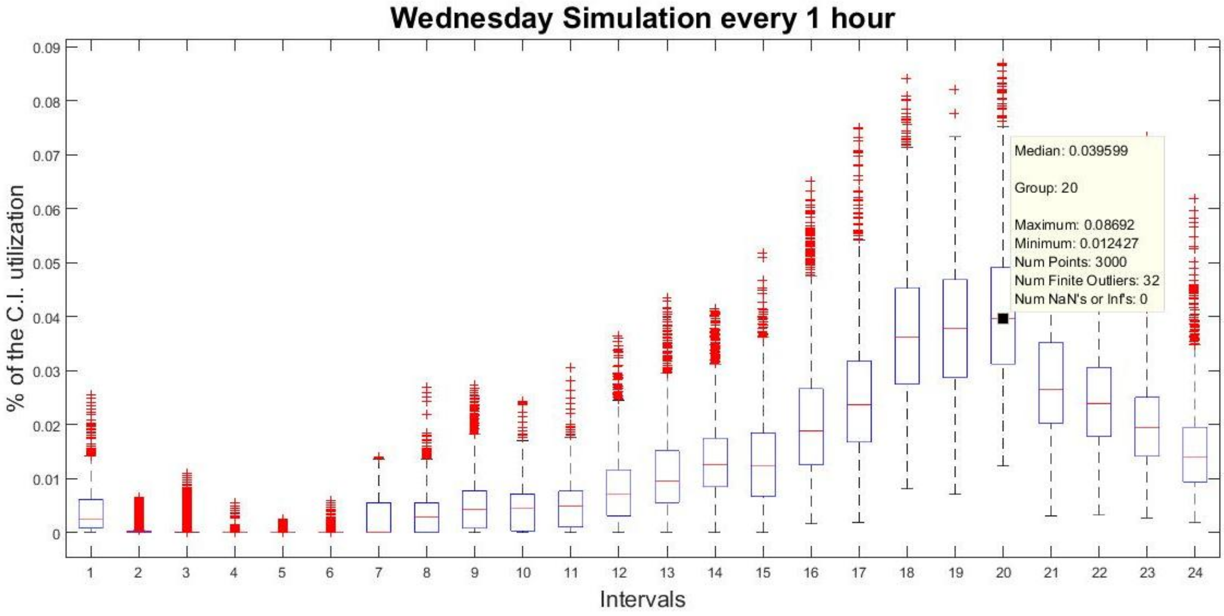


Figure 4.7: GoU Box Plot Simulation

5.3 Aggregated Load

Once that all the new MATLAB data has been generated a POWERFACTORY analysis can be completed. However, it is important to choose the right time periods for the power flow simulations; therefore in this paragraph both the infeed and the aggregated load (conventional and e-mobility) will be represented so that the right time scenarios are chosen for further analysis.

In order to obtain feasible results, different year seasons and different EV scenarios have been simulated. For each time period simulation, three different e-mobility scenarios will be studied.

Figure 4.8: Simulation Scenarios

The conventional load curve includes the industry and the household loads. It has been observed that there is a change in the daily load curve for different year seasons as well as for different day types.

Three day types have been defined: Weekdays, Saturday and Sunday. Figure 4.9 shows the load behavior for the different day types on a winter period.

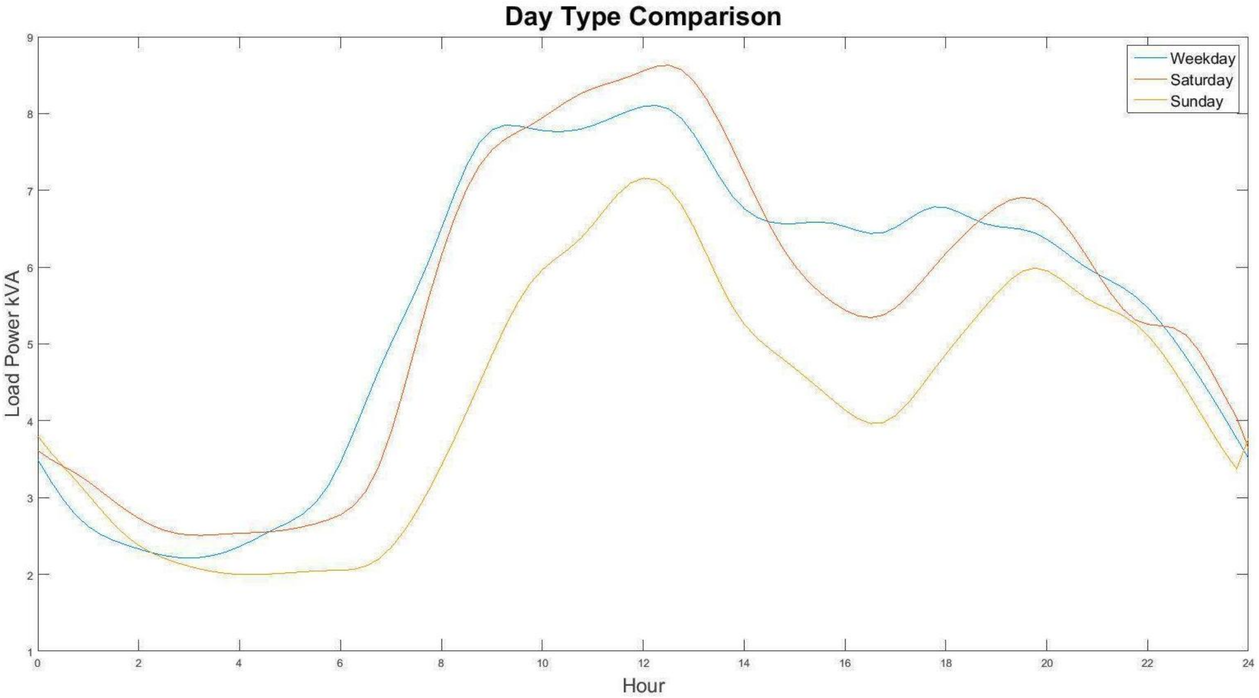


Figure 4.9: Day Type Comparison

The previous graph shows the day type comparison of a transitional month for *MS Clusternetz 1.* In this case the highest value is obtained at a Saturday at midday; this is due to a household load increase during the weekend. On the other side, Sunday shows lower load values explained by a sharp decrease in the industry load.

As explained in paragraph 2.1, three different time periods have been defined: winter, summer and transitional. During the winter months a load peak appears during the evening hours when a great increase in the household power demand takes place. However for transitional and especially for summer months the load maximum peak is higher at midday time. Figures 4.10 and 4.11 show the load behavior for both grids:

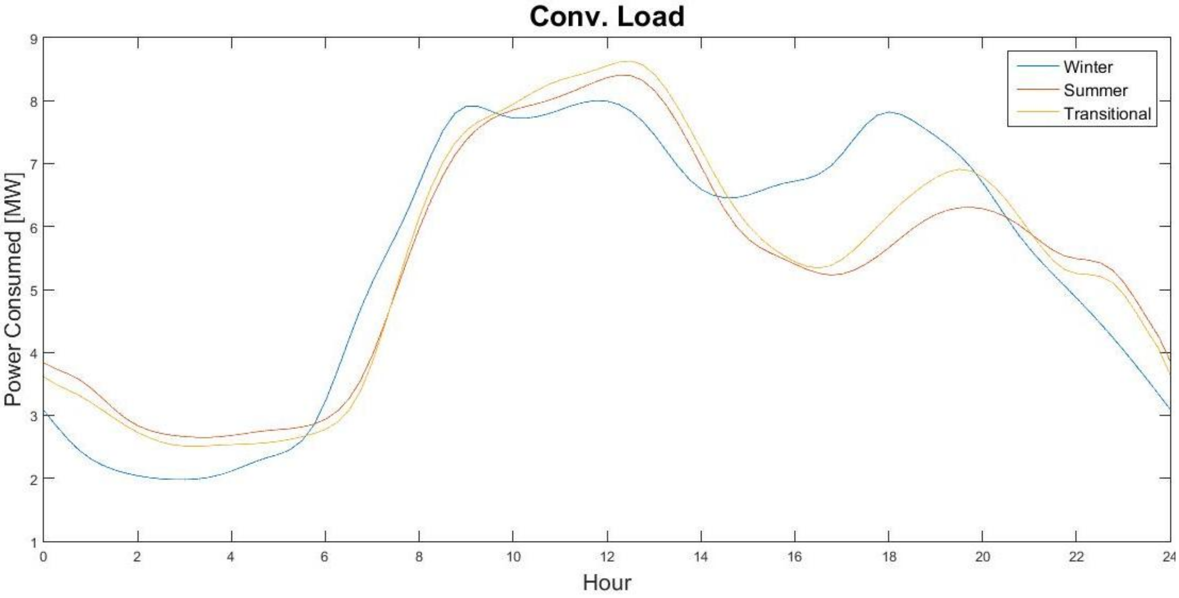


Figure 4.10: ***MS Clusternetz 1*** **Conventional Load Comparison**

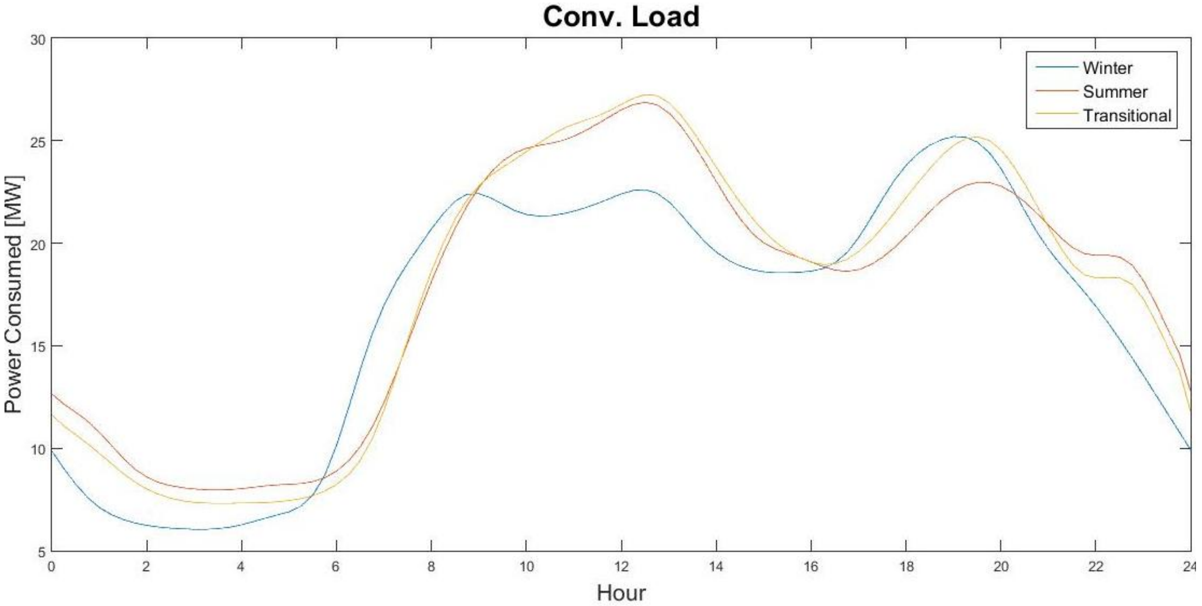


Figure 4.11: ***MS Clusternetz 3*** **Conventional Load Comparison**

It is possible to derive some conclusions from the previous two graphs.

- First, the behavior of the two grids is slightly different. It can be observed that the evening peak in *MS Clusternetz 1* is lower than in *MS Clusternetz 3*; this is due to the bigger share of household load in the second network.

- Second, during midday a load peak also takes place, this peak mostly represents the industry loads which have a stronger impact on the first grid. However, this peak will be balanced by the PV infeed, which will show its generation peak around 12:00.

There are also differences between the power generation on both grids. As shown in previous paragraphs, the PV infeed has a greater impact on *MS Clusternetz 1*. This means that the infeed fluctuation will also be bigger on the first grid. Due to its relatively high nominal power, the influence of the wind turbine operating on *MS Clusternetz 3* will also be analyzed. The Infeed behaviors are shown in Figures 4.12 and 4.13.

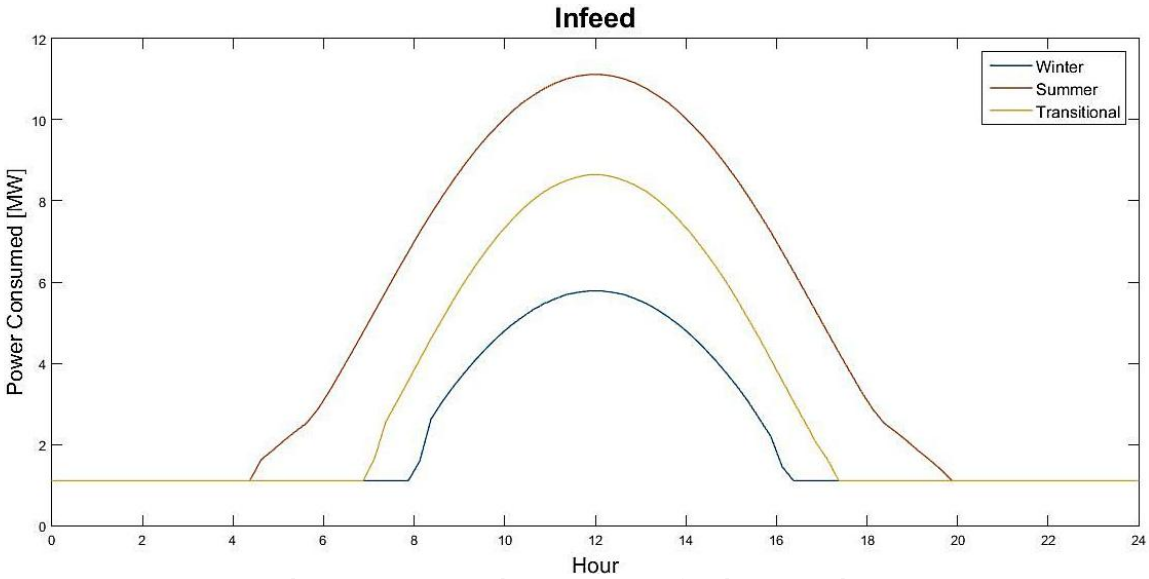


Figure 4.12: ***MS Clusternetz 1*** **Infeed Comparison**

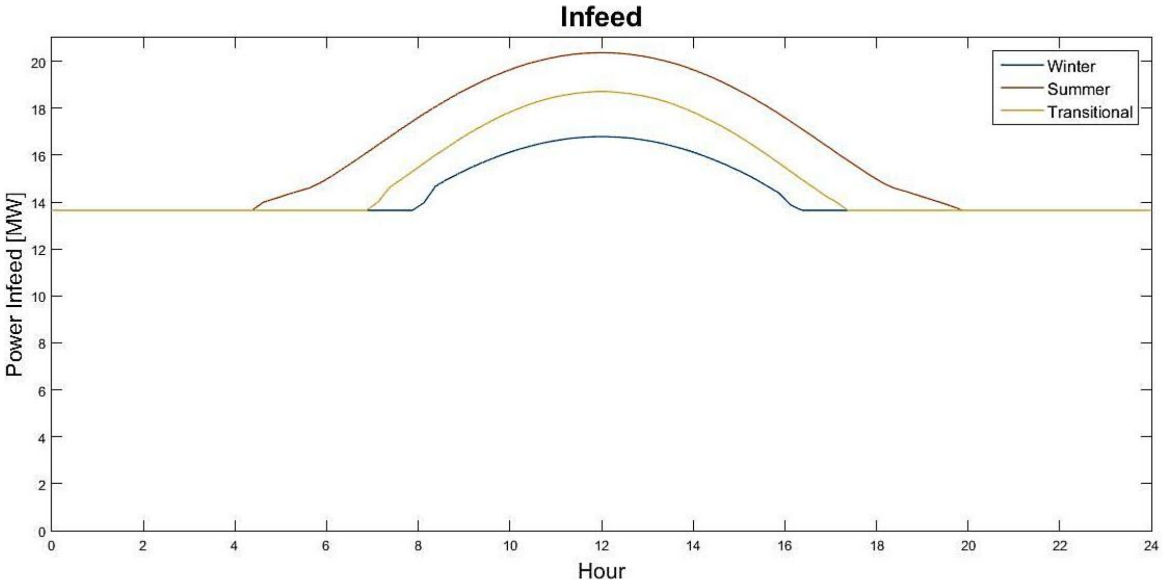


Figure 4.13: ***MS Clusternetz 3*** **Infeed Comparison**

Once that the conventional load, the infeed and the e-mobility load distribution are known, it is possible to determine the critical grid time periods. These time periods are searched in order to study possible overloads on the grid transformers or the conductors. The three curves are shown on Figure 4.14.

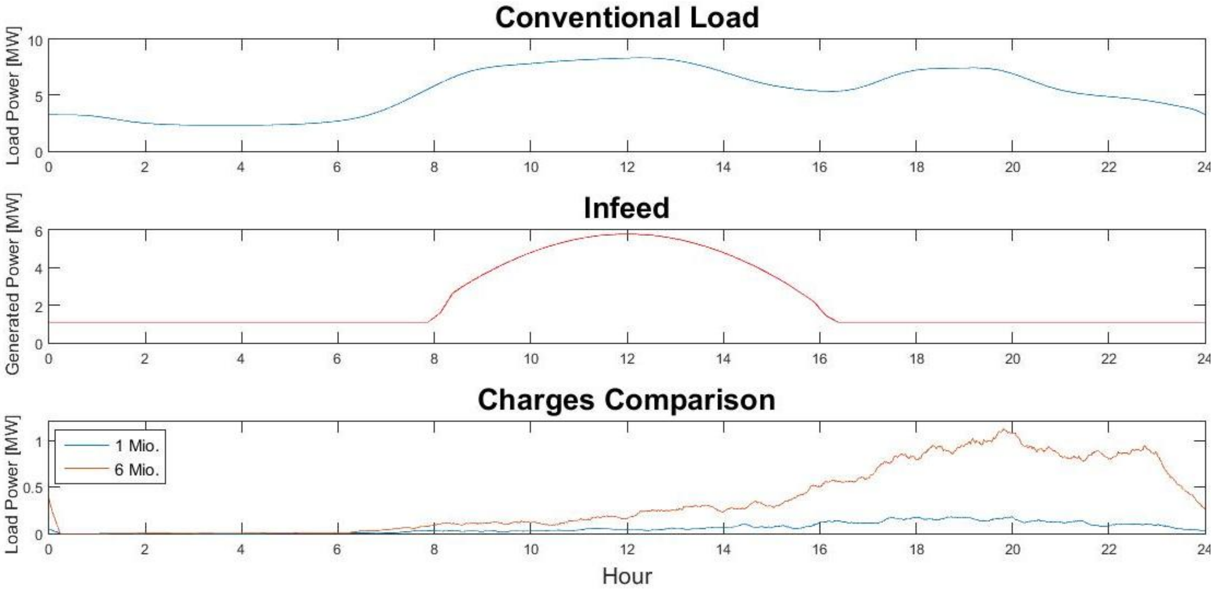


Figure 4.14: ***MS Clusternetz 3*** **Infeed and Loads distribution**

This comparison shows that there will be two main critical time periods: midday and evening hours. Around 12:00 the grid will shows a peak not only of load power, but also of generation maximum which will appear due to a maximum PV generation. Therefore a low transformer load but high line currents are expected around this time of the day.

On the other hand during after work hours (between 18:00 and 20:00) the conventional load will present a peak due to a household power demand increase. Also, at this time only the conventional generators will be feeding the grid, this result in a decrease in the power generation. Therefore this time will be especially interesting to study the impact of e-mobility in the grids as the aggregated e-mobility profiles will reach its maximum value from 18:00 to 20:00.

For all of these reasons the selected simulation times will be:

- Evening in winter
- Evening in transitional months
- Midday in summer

5.4 Power Flow Simulations

The power flow analysis of the previously defined time periods will give a good overview of the grid behavior: the influence of the solar and wind energy infeed and specially the impact of future e-mobility fleets.

From the power flows simulations of *MS Clusternetz 1*, the following points can be concluded:

On one hand, the consumption of electric power will be much higher than its generation in the case of a winter day during the evening hours. This is due to three facts: first, during the winter months a conventional load peak will occur between 18:00 and 20:00 hours; second, at this time the infeed will be exclusively fixed generation (and wind generation in the case of *MS Clusternetz 3*); third, the e-mobility load will reach its peak values. These conditions will provoke a relatively high transformer and line loads.

On the other hand, the midday summer scenario shows a different behavior. In this case, although the load values are high, the power infeed is even higher due to the PV generation. This means that the energy will flow from the medium-voltage to the high-voltage level. Also the impact of e-mobility will be relatively low according to the charging behavior. It has been observed that the power exchange won’t present big values, this situation results on a low transformer load value, however some lines can show high loads.

During the simulations a ‘worst case scenario’ was searched, this finally consisted on a Saturday evening of a transitional season period. This case showed the highest transformer station load as well as the highest line load. After the introduction of the electromobility loads the transformer load raised up to 21.094%. While the maximum line load showed a value of 43.42%. All the load values obtained were below critical boundaries.

In this paragraph only the worst case scenario is shown, the other power flow simulations will be attach in Appendix B.3.

October's Saturday at 19:00

MS Clusternetz 1	Without EM	1 Mio. EM	6 Mio. Scenario
Exchanged Power [kW]	6742	7115,9	8211,2
Transformer Load	17,318%	18,278%	21,094%
Generated Power [kW]	1105	1105	1105
Consumed Power [kW]	7765,96	8133,02	9211,07
Critical Line Load	39,67%	41,37%	43,42%

Table 4.5: ***MS Clusternetz 1*** **Worst Case Scenario**

On the other hand, *MS Clusternetz 3* simulations show the following characteristics:

The exchanged power is bigger than in *MS Clusternetz 1*. The power flow went from the high-voltage to the medium-voltage level for all simulated scenarios. On the other side, as it was expected, the PV infeed have a much smaller impact on the grid, this meant that the generated power will remain more constant than on the previous grid.

As explained previously, this grid presents a wind generator with a nominal power of 850 kW. This generator represents a fluctuating infeed which could change the transformer load in more than 8% in some cases.

It is also important to notice that the impact of the household loads will be bigger in this grid. This means that the evening hours will show a greater peak. Therefore the 'worst case scenario' is considered to be a Saturday evening in January. Once that the 6 million scenario load was introduced the transformer load went up to 20.69%, which was the highest value obtained in the simulations. The critical line load also registered its maximum value with 27.83%. It can be concluded that all the values obtained were kept under critical loads.

January’s Saturday at 19:00

MS Clusternetz 3	Without EM	1 Mio. Scenario	6 Mio. Scenario
Exchanged Power [kW]	14420,5	14870,07	16185,51
Transformer Load	18,52%	19,07%	20,69%
Generated Power [kW]	11043,37	11043,37	11043,37
Consumed Power [kW]	25293,61	25739,9	27041,01
Critical Line Load	27,16%	27,25%	27,83%

Table 4.6: *MS Clusternetz 3* Worst Case Scenario

6 Conclusion

6.1 Future EV Scenario

Research made on the actual e-mobility state of art demonstrate that charging procedures in private charging stations will not take place at the maximum charging power of the vehicles, but at lower power levels (around 7 kW).

On the other hand, public charging stations will reach these maximum values (up to 50 kW for DC charging stations). It is concluded, that the private station charging power should be reconsidered in further studies.

6.2 Grid impact results

Table 5.2 shows the maximal percentage of load increase due to the introduction of electric vehicles in the grids, these values are obtained by aggregating the e-mobility load to the conventional load values. These percentages are calculated for the worst case scenarios.

Load Increase	1 Mio. Scenario	6 Mio. Scenario
MS Clusternetz 1	5,69%	22,41%
MS Clusternetz 3	1,90%	7,66%

Table 5.1: Maximum load Increase due to e-mobility loads

The previous table shows that in the year 2030 the grid load could scale up to 22.41% in *MS Clusternetz 1,* if no further strategies are applied. In spite of this increase and due to the distributions of the loads and the oversized infrastructure of the electric networks, no overload is expected.

In *MS Clusternetz 3* the obtained values were also below critical limits. The maximum transformer load was 20.69% and the line loads were not higher than 28%. Given the results we can conclude that, in the medium term, the introduction of e-mobility loads will not disturb the operation of the two analyzed medium-voltage networks.

On the other hand, it was observed that different e-mobility load values were obtained from both grids. It can be concluded that the impact of e-mobility fleets will be higher on *MS Clusternetz 1.* This is due to the fact that *MS Clusternetz 3* represents an area with lower density of inhabitants and higher power consumption per household. Table 5.3 shows the installed power per inhabitant for both grids.

Household Installed Power	MS Clusternetz 1	MS Clusternetz 3
Power per Inhabitant	1,239 kW	2,519 kW

Table 5.2: Household Installed Power per Inhabitant

Given that the EV number will depend on the number of inhabitants, the total charging infrastructure installed power will represent a lower share of the total installed household power in *MS Clusternetz 3* (14.32% and 125.4% for the 1 and 6 million scenarios) than in *MS Clusternetz 1* (30% and 180% for the same scenarios).

MS Clusternetz 3 shows a relatively low share of variable infeed, this value rises to 7.81 MW when the PV and the wind power reach their maximum values. However, even at this scenario, this infeed will just represent a 28% of the conventional load. This means, that the grid operation will remain reasonably stable during different scenarios.

The characteristics of *MS Clusternetz 1* are considerably different. Here, the PV infeed can reach values of 10.41 MW. This represents more than a 90% of the total generation, and exceeds the grid load values. Therefore, due to meteorological variations, important power fluctuations are expected in this grid.

6.3 Consequences for future Grid Planning

Over the longer term, EVs will reach a large scale market penetration. Therefore, some charging strategies are proposed in order to optimize the grid response. The following strategies can be included in what is called *Smart Grid Initiatives*:

- Load Shifting: As shown in previous paragraphs, the charging frequency reaches the maximum values at after work hours. As seen before, this will be a time period of a high household load. A load management system could be installed to delay the charging procedures if possible.

- Vehicle to Grid (V2G): One step further will be providing electricity to the grid. The EVs could be charged at low demand and high generation time periods and release the stored energy during peaks of demand with lower infeed.

- Vehicle to Building (V2B): The battery capacity of the EVs could also be used to reduce the electricity costs of the grid users. Households could eventually consume their whole day energy demand (around 10 kWh per day) at low tariff stages and charge the EVs for a further consume.

The previous initiatives will definitely suit to the given medium-voltage networks. They will help to balance the electric power demand making it easier to provide a more sustainable energy mix as well as increasing the grid reliability. Electric vehicles could therefore bring a cleaner, more efficient and more reliable energy scenario.

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Appendix A

B.1 Box Plot Distribution

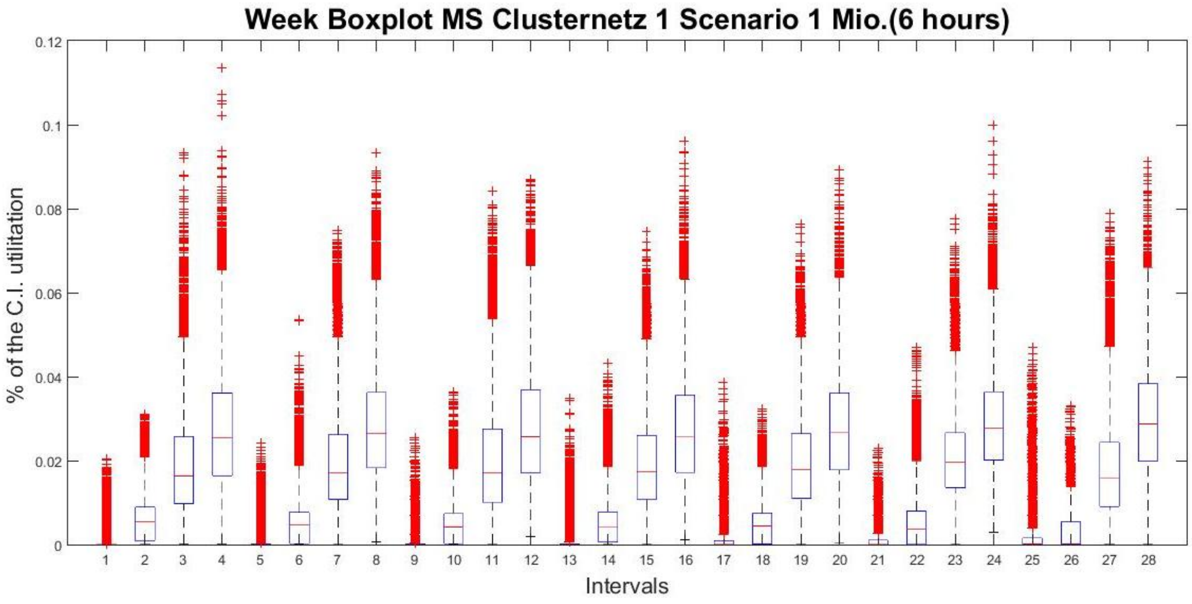

Figure B.1: Boxplot MS Clusternetz 1 Scenario 1 Mio.

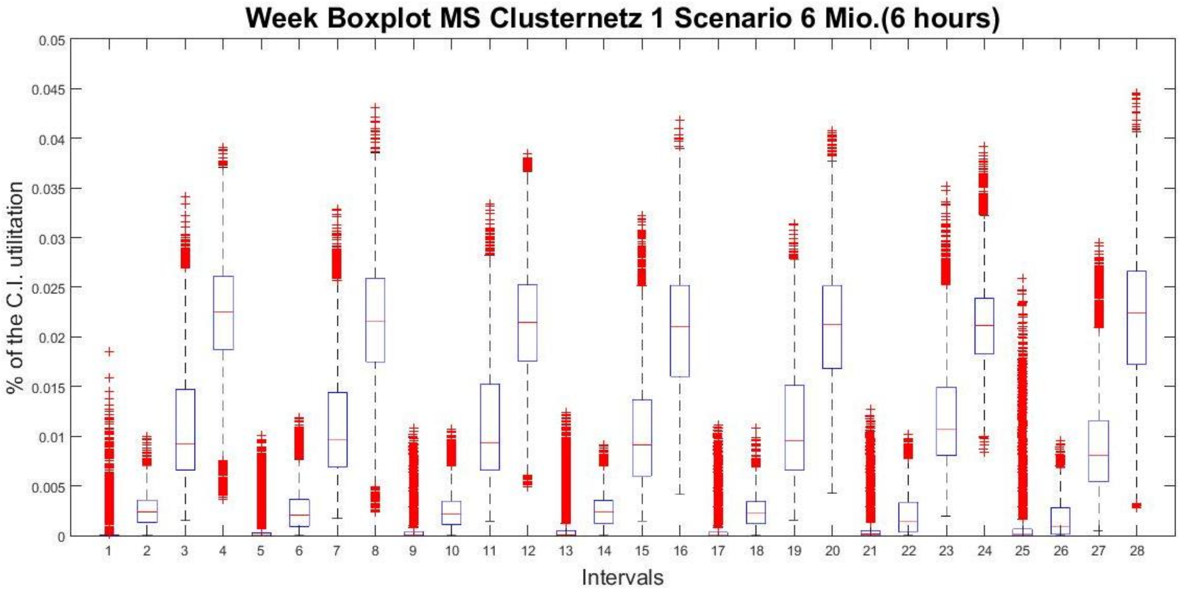

Figure B.2: Boxplot MS Clusternetz 1 Scenario 6 Mio.

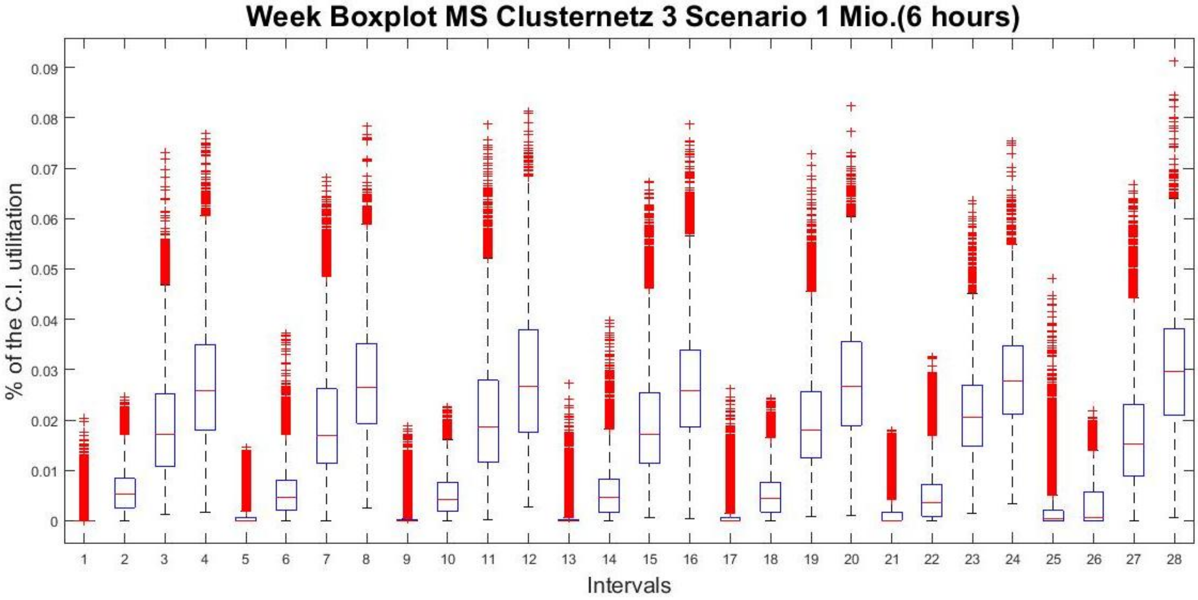

Figure B.3: Boxplot MS Clusternetz 3 Scenario 1 Mio.

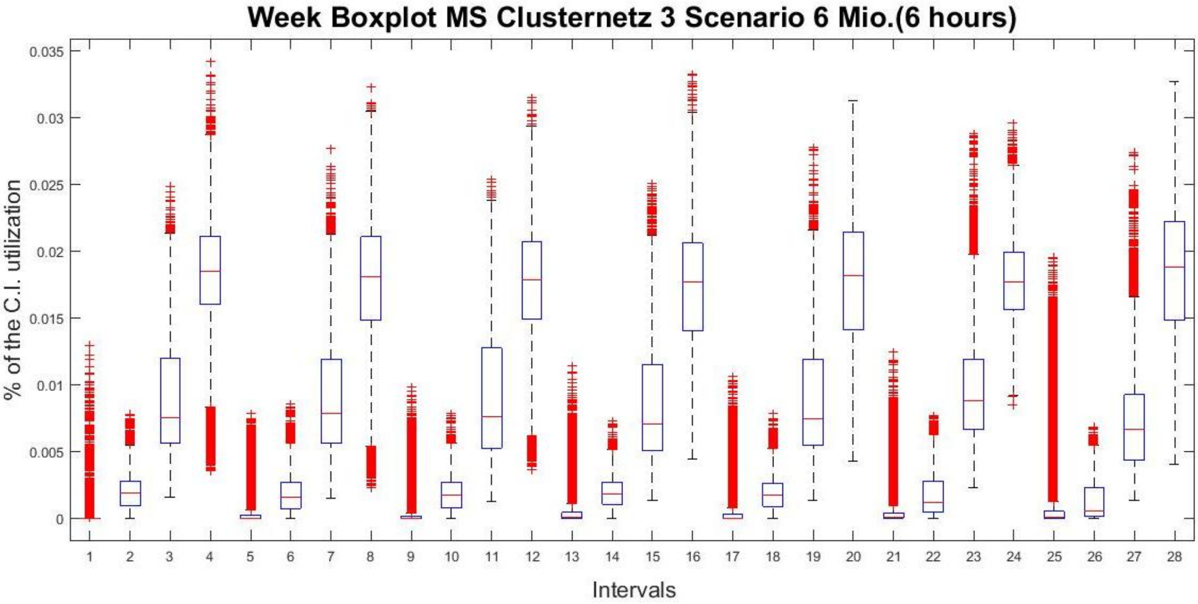

Figure B.4: Boxplot MS Clusternetz 3 Scenario 6 Mio.

B.2 Infeed and Load Day Distribution

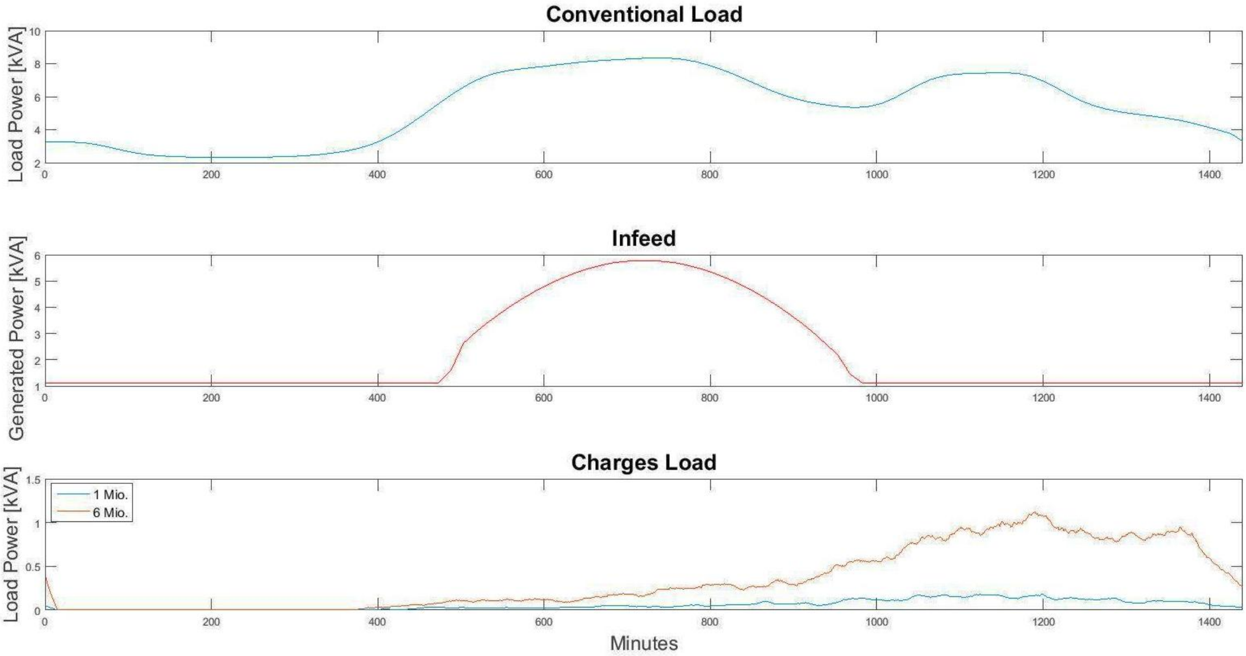

Figure B.5: MS Clusternetz 1 Graph Comparison

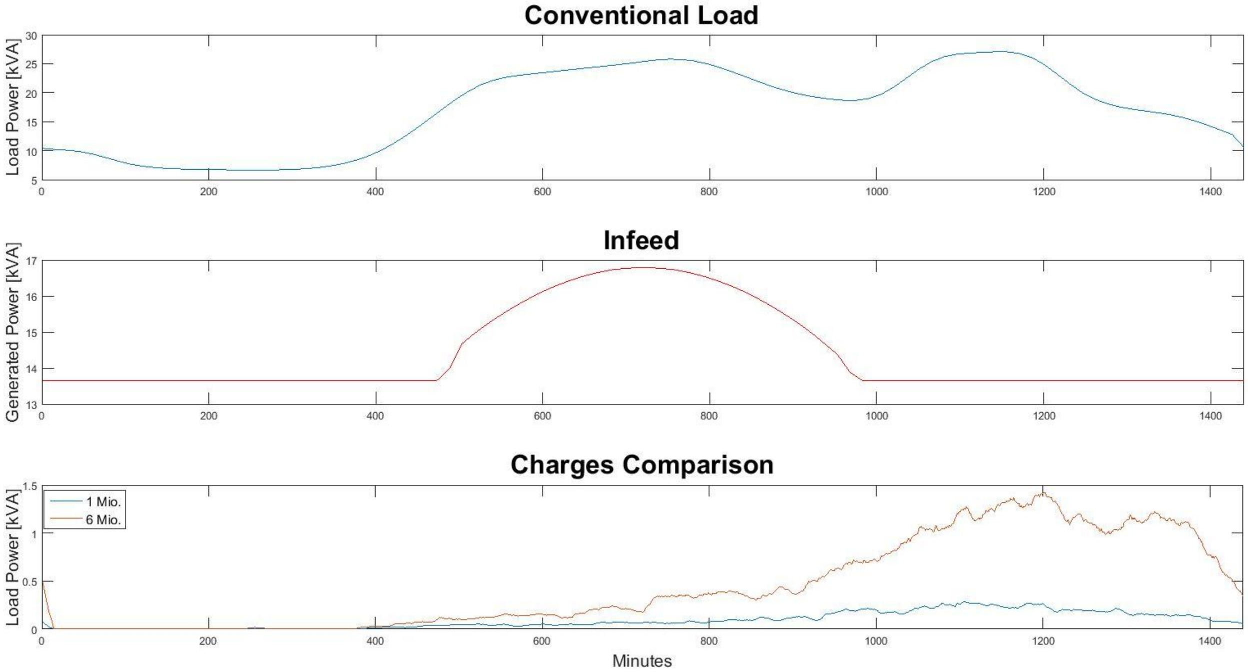

Figure B.6: MS Clusternetz 3 Graph Comparison

B.3 Power Flow Analysis

MS Clusternetz 1

1. January 15th at 19:00

MS Clusternetz 1	Without EM	1 Mio. Scenario	6 Mio. Scenario
Exchanged Power [kW]	5397,3	5698,6	6795,4
Transformer Load	13,635%	14,406%	17,212%
Generated Power [kW]	1105	1105	1105
Consumed Power [kW]	6447,29	6743,98	7828,12
Critical Line Load	28,37%	29,68%	30,99%

Figure B3.1: MS Clusternetz 1 Jan. Power Flow Sim.

2. July 15th at 13:00

MS Clusternetz 1	Without EM	1 Mio. Scenario	6 Mio. Scenario
Exchanged Power [kW]	-3234,8	-3085	-2879,5
Transformer Load	8,689%	8,36%	7,916%
Generated Power [kW]	10575,83	10575,83	10575,83
Consumed Power [kW]	7298,53	7448,9	7655,08
Critical Line Load	32,39%	33,4%	32,45%

Figure B3.2: MS Clusternetz 1 Jul. Power Flow Sim.

3. October Saturday at 19:00

MS Clusternetz 1	Without EM	1 Mio. Scenario	6 Mio. Scenario
Exchanged Power [kW]	6742	7115,9	8211,2
Transformer Load	17,318%	18,278%	21,094%
Generated Power [kW]	1105	1105	1105
Consumed Power [kW]	7765,96	8133,02	9211,07
Critical Line Load	39,67%	41,37%	43,42%

Figure B3.3: MS Clusternetz 1 Worst Case Scenario

MS Clusternetz 3

1. January 15th at 19:00

MS Clusternetz 3	Without EM	1 Mio. Scenario	6 Mio. Scenario
Exchanged Power [kW]	11754,77	12135,74	13571,71
Transformer Load	15,18%	15,64%	17,4%
Generated Power [kW]	11893,37	11893,37	11893,37
Consumed Power [kW]	23513,39	23890,62	25313,3
Critical Line Load	23,64%	23,7%	23,43%

Figure B3.4: MS Clusternetz 3 Jan. Power Flow Sim.

2. July 15th at 13:00

MS Clusternetz 3	Without EM	1 Mio. Scenario	6 Mio. Scenario
Exchanged Power [kW]	4786,41	4939,29	5192,32
Transformer Load	6,69%	6,85%	7,12%
Generated Power [kW]	18206,37	18206,37	18206,37
Consumed Power [kW]	22881,83	23034,31	23286,28
Critical Line Load	21,24%	20,8%	21,11%

Figure B3.5: MS Clusternetz 3 Jul. Power Flow Sim.

3. January Saturday at 19:00

MS Clusternetz 3	Without EM	1 Mio. Scenario	6 Mio. Scenario
Exchanged Power [kW]	14420,5	14870,07	16185,51
Transformer Load	18,52%	19,07%	20,69%
Generated Power [kW]	11043,37	11043,37	11043,37
Consumed Power [kW]	25293,61	25739,9	27041,01
Critical Line Load	27,16%	27,25%	27,83%

Figure B3.6: MS Clusternetz 3 Worst Case Scenario

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