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Potential of V2G in a Rural Low-Voltage Grid on Gotland for Voltage and Power Capacity Control

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Abstract

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The Swedish transportation sector needs to undergo major changes in order to achieve the established goals for climate and environment. The largest change is the replacement of fossil-fuelled vehicles to vehicles propelled by renewable energy sources, such as biofuels and electricity. To account for an increase in local electric power consumption, the electric power infrastructure of Sweden needs to adapt through expansion and reconstruction of the electric power grid. However, changes in infrastructure are usually expensive. It is therefore suitable to also examine alternative solutions, which could potentially be more cost efficient. One of these solutions are vehicle-to-grid (V2G), where electric vehicles acts as local electric power control and provides auxiliary services to the electric power grid. This thesis is a case study of a part of a low-voltage electric power grid on Gotland, with the goal of analysing the potential of V2G in the investigated area. The study focused on utilizing V2G for balancing electric power consumption and generation, and for adjusting voltage levels. Simulations of the area were executed in PSS®E for three different cases; one high-load case, low-load case and average-load case. It was found that by utilizing V2G a ramp up of electric power during mornings was delayed by approximately one hour, making the electric power grid potentially more compatible with photovoltaics (PV). However, the overall effects from V2G was fairly low. This outcome can partly be explained by the assumptions made in the report, and also due to some odd behaviour of the system model.

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Populärvetenskaplig sammanfattning

Skulle du ge tillbaka el till elnätet från din elbil vid ett stort elbehov på elnätet? Samhället och många av dess stora system är i en pågående förändring för att kunna klara uppsatta mål för miljö och klimat. I samband med denna förändring pågår även en ökad urbanisering, där fler invånare väljer att flytta från mindre orter till större städer och dess förorter. En ökning av invånare i en stad leder i sin tur till att elbehovet ökar. Samtidigt kan kablar och transmissionsledare bara som högst leverera den effekt de designats för, annars tar de skada och kan gå sönder. I samband med ökad urbanisering och en utbyggnad av energikällor med mycket varierande effektuttag, som vindkraft och solenergi, kan det uppstå flaskhalsar i det svenska elnätet. För att förebygga mot dessa flaskhalsar utvecklas elnätet med fler förbindelser eller förstärkningar av nuvarande elledare.

En plats som idag är sårbar för störningar i det svenska elnätet är Gotland. På Gotland finns förvisso en ansenlig mängd vindkraft installerad, dock förses Gotland i huvudsak utav el från fastlandet. Elen till Gotland transporteras via två kablar mellan fastlandet och ön. Detta gör Gotland sårbar i händelse av störningar på någon av dessa kablar, alternativt om ön kräver mer el än vad kablarna kan överföra. För att förbättra elnätets pålitlighet och stabilitet gentemot störningar skulle Gotland behöva fler förbindelser till fastlandet, alternativt en reglerande elförsörjning på ön. Dessa typer av investeringar är dock mycket kostsamma, och kan vara svåra att få ekonomiskt försvarbara.

Detta projekt har därför i samband med Vattenfall AB undersökt en alternativ lösning för hur elnätet skulle kunna stabiliseras, nämligen genom att använda outnyttjad kapacitet i batteridrivna elbilar. Konceptet att låta elbilar föra tillbaka el till elnätet brukar kallas för ”vehicle to grid” (V2G), på svenska ”fordon till nät”. Genom att låta elbilar ladda ur sig mot elnätet när det är ett stort tillfälligt elbehov, och sedan laddas upp igen när behovet minskat, skulle Gotland kunna få tillgång till en reglerande elkraft som potentiellt varken kräver stora ändringar av infrastruktur eller är kostsamt relativt andra lösningar. I dagsläget har Gotland bara har två elanslutningar till fastlandet, och kan därför ses som ett separat elnät, vilket gör ön utmärkt för att studera effekter från olika elnätsrelaterade lösningar. Detta projekt har därför handlat om att undersöka hur en del av Gotlands elnät skulle påverkas om V2G utnyttjades för att stabilisera elnätet.

I projektet skapades en modell av en del av Gotlands lågspänningsnät, den spänningsnivå på 400 V som alla hushåll är kopplade till, som användes för att simulera hur effekt och spänning förändrades i systemet. Simuleringarna utfördes i PSS®E, en programvara där elnätsmodeller kan skapas och simuleras. Totalt simulerades tre fall, som representerades av dygn då elbehovet var högt, lågt och normalt. För att effektivisera arbetet byggdes en kod via kodspråket Python.

Slutsatserna dragna från resultatet var att det fanns indikationer att V2G inte hade någon markant effekt på elnätet. Genom V2G kunde områdets elbehov under morgonen förskjutas fram någon timme, samt ge upphov till en jämnare lastprofil. Det gjordes dock vissa förenklingar under arbetets gång som förmodligen påverkat resultatet, och dessutom förekom vissa märkliga beteenden i modellen. Vidare saknades även material för att kunna validera resultaten. För att kunna säkerställa resultaten från studien skulle modellen behöva bearbetas ytterligare, samt jämföras noggrannare med det verkliga systemet.

Executive summary

This master thesis study has investigated the potential effects on voltage levels and strain, in terms of power capacity of conductors, on a low-voltage power grid of Gotland when V2G (Vehicle-to-grid) was implemented.

In the study the following assumptions were made:

- All EVs (Electric vehicles) in this study were BEVs (Battery electric vehicles)
- These BEVs did only charge or utilize V2G from an EVSE (Electric vehicle supply equipment) at their respective household.
- A smart grid on Gotland able to incorporate V2G functionality was available.
- All cars used the same type of charge station for V2G and charge services, which could deliver a power output of 3,6 kW.
- All chargers could only turn on or off for charge or V2G utilization.
- The residents would have the same power consumption during the following decades as presently.
- EV distribution was fairly evenly distributed on the island where each load in the system model had one BEV connected, unless it created simulations errors at certain loads.
- People mostly use their cars for getting to and from work (7:30-8:00 and 17:00-17:30).
- Everyone used their vehicles and were in need for charging simultaneously.

A model was created and simulated in PSS®E for three cases, where the cases represented days when the loads were high, low or on an average level respectively. The main findings of the report were that the voltage levels were barely changed due to V2G utilization, and that V2G was able to delay the power demand during mornings by approximately one hour. In addition, the load profile for each case became flatter when the BEVs were integrated and were allowed for V2G utilization.

The results lack validation and there are known errors in the system model. In order to verify the conclusions, these errors need to be solved, and the results need to be more accurately compared to the real system on Gotland.

Acknowledgements

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First I would like to thank my supervisors at Vattenfall AB, Colin Stewart and Ying He, for their expertise and help in planning the project, and for their trust in me during the duration of the project. In addition, a special thanks to Julio Gadea at Gotlands Energy AB for providing me with necessary data.

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1.Introduction

The modern society is changing to become a civilization with less negative impact on planet Earth. In 2015 the UNFCCC (United Nations Framework Convention on Climate Change) declared the Paris Climate Agreement, in which countries of the UNFCCC were to cooperate in order to limit the rise of the global temperature to below 2 degrees Celsius [1]. Presently nearly every nation has ratified the agreement, and the country of Sweden is no exception. In order to reach the asserted goals of not only the Paris Climate Agreement, but also from goals regarding climate change on a nation-wide level, the Swedish society and infrastructure needs to change. As an example, Sweden as a nation has declared its intention to become a net-zero emission society by 2045 [2]. Multiple actions are necessary in order to reach this goal.

One sector of the Swedish infrastructure which will have to undergo major changes, in order to reach these climate goals, is the transportation system. Fossil fuels such as petrol and diesel are presently the most dominant fuels for transportation, resulting in large amounts of carbon dioxide emissions from the transportation sector [3]. The domestic transportation alone stands for approximately one third of the total amount of the Swedish annual carbon dioxide emissions, where more than 90% are due to the use of fossil fuelled vehicles [4].

The need for transportation is apparent in the Swedish society. Between the years 2010 and 2017 the number of vehicles registered in Sweden increased from 4.3 million to 4.8 million private cars, an increase of approximately 12 percent [5]. In comparison, during the same time period the Swedish population increased by approximately 7.5 percent [6]. The number of private cars per capita has not decreased during the recent decade but rather increased. If the trend of an increase in private cars per capita continues in Sweden, and all these vehicles are propelled by fossil fuels, the goal set up regarding CO2-emissions will be unreachable. This highlights the importance of replacing fossil fuels in the transportation sector with more climate neutral fuels, such as biofuels or electricity generated through energy sources with low CO2 emissions.

Another sector that also must undergo major changes is the electric power system of Sweden. These changes are however not to reduce carbon emissions, as with the changes in the transportation sector, but rather due to a potential increase of electric power consumption. According to a report from 2016 by IVA, the electric power utilization of Sweden is estimated to be somewhat similar to present values [7]. The overall use of electric power in Sweden is expected to increase due to more power demanding technology such as electric vehicles, yet this increase is estimated to be somewhat cancelled out by energy efficient innovations [7]. However, most of the electric power of Sweden is generated in the northern parts of the country, while most of the power is consumed in the southern parts of the country [8]. That means large quantities of electric power needs to be transported in order to satisfy the demand for electric power. If the power consumption were to increase in the upcoming decades, some electric grid components may not be able to transport the required power. For example, conductors and transformers cannot transport more power than they are designed for, which would result in them overloading and become damaged. These limitations create bottlenecks in the electric power grid where alternative routes for power distribution are sparse.

One area which already is affected by bottle-neck effects is the Swedish island Gotland, since there are only two HVDC cables connecting Gotland and the mainland. Gotland also primarily produces energy from wind power, which results in quite a volatile power production. These conditions of bottle-necks in power distribution and volatile power generation may lead to an unbalanced power system, where electric power generation and consumption becomes harder to match. For the time being the only major way of balancing the grid of Gotland is by the power connection to the mainland. There are ongoing projects to increase the stability of the power grid of Gotland, there has for example been a project regarding adding an additional cable which connects Gotland to the mainland of Sweden. However, the project was stopped in 2017 due to financial reasons [9]. If no additional connection between the mainland and Gotland is established, other types of power control technology would be necessary to improve the power quality and stability of the electric power grid on Gotland. One alternative could be to buffer electricity through energy storage solutions.

Today there are mainly two technical solutions for storing large amount of electricity for long durations. The first most conventional method is by constructing water dams and utilizing hydro power, where the water is converted from potential energy into kinetic energy [10]. By installing a turbine in the flow of water, which in turn rotates a generator, the momentum will be converted into electrical power [10]. In 2015, approximately 47 percent of the annual electricity production in Sweden was generated through hydro power [11]. Hydropower is usually utilized where large amounts of water flows, such as rivers, but dams may also be built for reasons such as pumped hydro for later electric power utilization. One issue of building new dams are negative impacts on the environment of the site where it is constructed [12].

The second and more recent method for storing electrical power is through the usage of large battery banks. An electric battery can shortly be described as electrons being pushed into a state with higher potential, which is the charging process, and return to its initial phase during discharge. Battery banks usually has an efficiency of approximately 80% and 90% and is a storage system which does not require many additional components except the battery banks. However, batteries are today a quite expensive solution for storing electricity, and in many cases the benefits are not justifying the costs of investing in a large bank of batteries. Alternative electrical storage methods are tested in order to find more cost-efficient solutions. One of these new methods, which is currently in a piloting stage, is to store electricity in the batteries of electric vehicles (EVs) for later use.

When the grid is in need of more electrical power for stabilization, EVs which at that time are connected to the grid may support the demand of extra electric power. When the grid has re-stabilized, the EVs may utilize the grid for charging instead of providing the grid with power. The concept of allowing EVs to provide auxiliary services to an electric power grid, such as voltage regulation or for balancing power flows, is called vehicle-to-grid (V2G). Several large vehicle companies, for example Mitsubishi Motors, PSA Group and Nissan, have started pilot-tests for V2G, called the Parker Projects [13]. There have also been previous projects regarding V2G, such as the Edison project in Denmark [14] and a research project in California [15]. In addition, Vattenfall is involved in surveillance of V2G applications through developing communication signals and protocols for implementation, and industry research work together with the Swedish Electromobility Centre (SEC) in this area.

Since the society is pushing for a transportation system with vehicles that operate on renewable fuels, a significant share of all vehicles on Gotland will likely be EVs or bio fuelled vehicles in a few decades. If these EVs can be utilized for V2G, the grid of Gotland can look to acquire a level of power control without making major changes in infrastructure. The grid of Gotland will gain a decentralized battery bank that can handle immediate local grid issues. However, the potential benefits from using V2G are somewhat unclear. In addition, the utilization of EVs owned by the residents of Gotland may affect their flexibility for transportation. It is therefore necessary to examine the effects on the grid of Gotland in terms of strain and voltage levels when V2G is utilized, and to study how V2G may affect the transport flexibility of the residents of Gotland.

1.1. Purpose of the study

The purpose of this study is to examine and estimate the effects of utilizing V2G for stabilizing purposes on the low-voltage power grid of Gotland. The effects that are investigated are the strain on conductors in terms of their maximum power capacity and voltage levels in the system. This is done by simulating the power grid of a rural area on Gotland and observe any effects when V2G is utilized in the investigated area. In addition, an estimation of how EVs can be utilized during a day for either transportation or V2G is presented.

1.2. Discussion about source material

As with any scientific study, this study is based upon the work of earlier studies. The material deemed necessary for the project has primarily been collected by reading scientific articles and recent projects regarding relations and auxiliary services between EVs and an electric power grid.

The effects of how EVs and an electric power system may cooperate are presently not completely determined, and the topic can be considered controversial. The positive aspects are usually generally described, yet rarely quantified. There are also challenges in terms of power which are derived from a large amount of EVs in an area. To increase the transparency and objectivity for the reader, the project has tried to include reliable sources for both the positive and negative aspects of EVs and their use as auxiliary services for an electric power grid. However, it has been easier to obtain sources for projects supporting EVs for auxiliary services rather than questioning it’s potential. Therefore, the report also includes more sources which support V2G and smart grid solutions.

Due to this bias in sources, the results from earlier studies and projects have been handled with care. In general, the trends and general effects of the results can be considered reliable, while the magnitude of the effects can be doubtful. The earlier studies have also mostly been used for finding data and theory regarding electric power systems and information about technical components in a V2G power system, rather than the actual effects of the V2G in a system.

2. Background

To have a better understanding and rewarding reflection of the content in the report, the reader needs some general knowledge about EVs, V2G, Gotland and power grid design. For example, it is good to know the general difference between EVs and conventional cars, and the benefits and downsides EVs have today. The reader also needs some background information about Gotland to understand how the society on the island functions. Therefore, a brief explanation of these topics will be presented in this section. The first part will be a presentation of how electric power grids are designed and affected by several factors. There is also a brief explanation of how the quality of a power grid is measured and what defines a smart grid. Secondly, information regarding the definitions of EVs and their benefits and drawbacks are presented. Lastly, a short general description of Gotland, the investigated area, and the driving habits of people are presented.

2.1. Electric power systems basics

A basic power system consists of three components. The first component is the load, which demand a certain amount of power to be utilized for a designated purpose. The second component is the generator, the component that generates electric power. The third component is a branch conductor that connects the generator and load to each other, thus creating a basic electric power system. The electric power systems can either have an alternating current (AC) or direct current (DC), and the electric power transported in the system is calculated using equation 1.

$$S = U \cdot I^* \qquad (1)$$

S is the complex power, U the voltage over the conductor and I^* the conjugate of the current passing through the conductor. The components of a system would ideally transport electric power without any losses, yet in practice this is seldom the case. For instance, conductors have active power losses due to resistivity as seen in equation 2.

$$P_{loss} = R \cdot I^2 \qquad (2)$$

P_{loss} is the active power losses and R the resistance of the conductor. As can be seen in equation 2, the current I is squared, which means it has a significant impact on the active power losses. In order to reduce the power losses, it is desirable to minimize the current, especially during long transportation distances. However, lowering the current will according to equation 1 also reduce the delivered complex power. If the complex power is to remain the same the voltage must increase.

An increase in voltage is done by a fourth type of component called transformers. A transformer is usually placed close to power plants in order to increase the voltage, and thereby minimizing the active power losses. The electricity is transported along a high-voltage transmission grid until it reaches a high/medium-voltage transformer. There, the voltage is lowered and transported along the distribution grid. The voltage is usually lowered once more to 400 V when the power is close to the end loads, such as one or multiple household. The power flowing through these last-mentioned transformers are what the loads in the system model are representing, since every load can consist of multiple households. A diagram presenting how an electric power system with generators, conductors, loads and transformers are connected to one another is shown in Figure 1. The low-voltage transformer represented as loads in the system model have been marked in Figure 1 with a red circle.

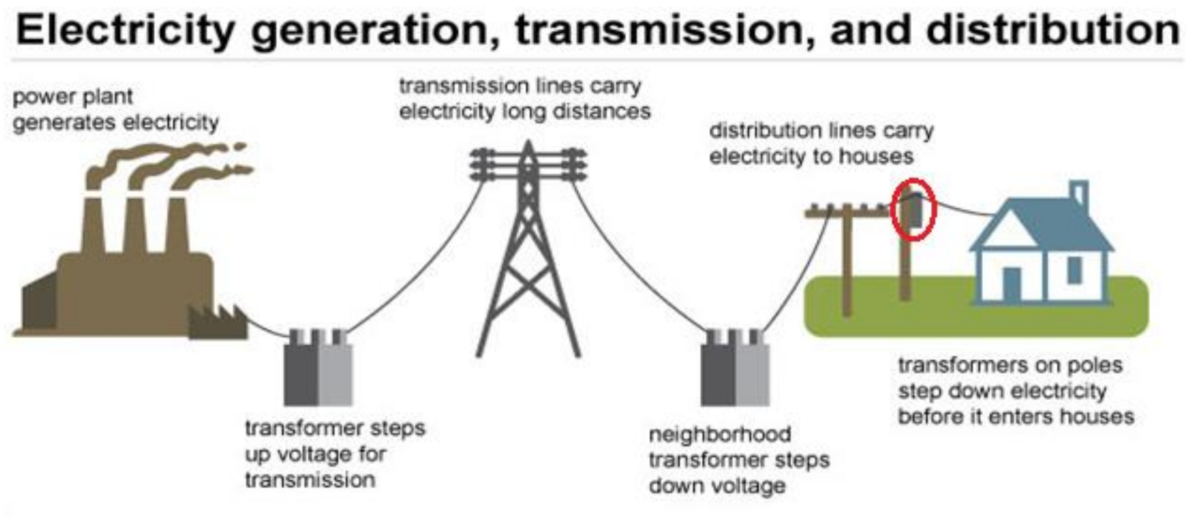

Figure 1. An illustrative diagram of how generators, conductors, loads and transformers are connected to each other in an electric power system. In addition, the low-voltage transformer which is represented by a load in the system has been marked with a circle. The diagram is a modified version of a diagram made by EIA (U.S. Energy Information Administration) [16].

2.2. System investigated on Gotland

Gotland is a Swedish island located approximately 100 km (kilometres) from the mainland of Sweden. The island has an area of 3000 km^2 (square kilometres). The distance between the northernmost and southernmost point of Gotland is approximately 176 km, and 50 km between its most eastern and western points. The total amount of private cars on Gotland at the end of 2017 was about 36 000 vehicles, which is approximately 600 cars for each 1000 citizen on Gotland [5].

The power system which was examined in the project was a rural area mainly consisting of household loads. All information regarding the system was obtained from GEAB, a daughter company of Vattenfall AB which owns the electric distribution grid on Gotland. The area was located in the eastern parts of Visby, the largest urban area of Gotland. The system consisted of a low voltage grid, 400 V, which was connected to the 11-kV distribution grid of Gotland through a transformer. A diagram of the system is presented in Appendix A. The system contained approximately 150 loads, yet most of these loads had a significantly larger average power consumption than a regular household has. A regular Swedish household has an annual electricity consumption of approximately 25 000 kWh [17,18], which corresponds to an average power consumption of approximately 3 kW. Most loads in the system had an average power consumption much larger than 3 kW. This indicated that multiple household were tied together into one load, meaning a load likely represented a local distribution feeder rather than an individual household. Based on mentioned average power consumption of a household, the number of households connected to the investigated system was estimated to approximately 600 households.

2.3. Definition of power quality in the electric power system.

In order to measure how well an electric power system performs it is important to first determine what defines a well-performing power system. The purpose of an electric distribution power system is to provide its consumers with the right amount of electric power, at the right time, without major losses and without compromising electrical components connected to the system. If a power system is performing perfectly, it will always balance the electric power supply and demand and keep the voltage level of the grid at nominal voltage. In practice this is a difficult task because the power system has undesirable behaviours and losses, for example the power losses explained in section 2.1. Therefore, regulation standards for different disturbances are used to ensure a sufficient level of grid stability. One of these regulations concerns voltage drops, and in Sweden any voltage levels in a the power grid should be between 90 and 110 percent of the nominal voltage [19].

2.4 Electric power consumption of a regular household in Sweden.

The electric consumption of a household can roughly be described by having a power peak in the morning after the residents wake up, and in the evening when they arrive home from work. During working hours most people are not at their homes, and the households will only utilize power for basic maintenance such as heating, ventilation and refrigerating. Even though the system is in a low power state during most of the day, the grid must be designed based on the peak load since the grid must be able to deliver the necessary peak power.

When examining the total power consumption of Gotland, it is observed that the daily power consumption trends are similar to a residential area. The load of the whole system increases during the morning and keep a nearly constant power consumption during work hours until late afternoon. The reason for this is because industries and offices with power demanding processes are mainly active during daytime, but then reduced or shut down when the workers end their work shifts.

A third perspective to look at the power consumption of Gotland is the annual trends; power loads based on weather and season. The power consumption of Gotland is at its peak during the winter season, since people utilize more electricity for heating and lighting, and at its lowest during the beginning of summer. In Figure 2, which presents the normalized values of Gotland power consumption during 2016 for each month, it may be observed that the power consumption is approximately one third less during the months of summer compared to consumption during winter.

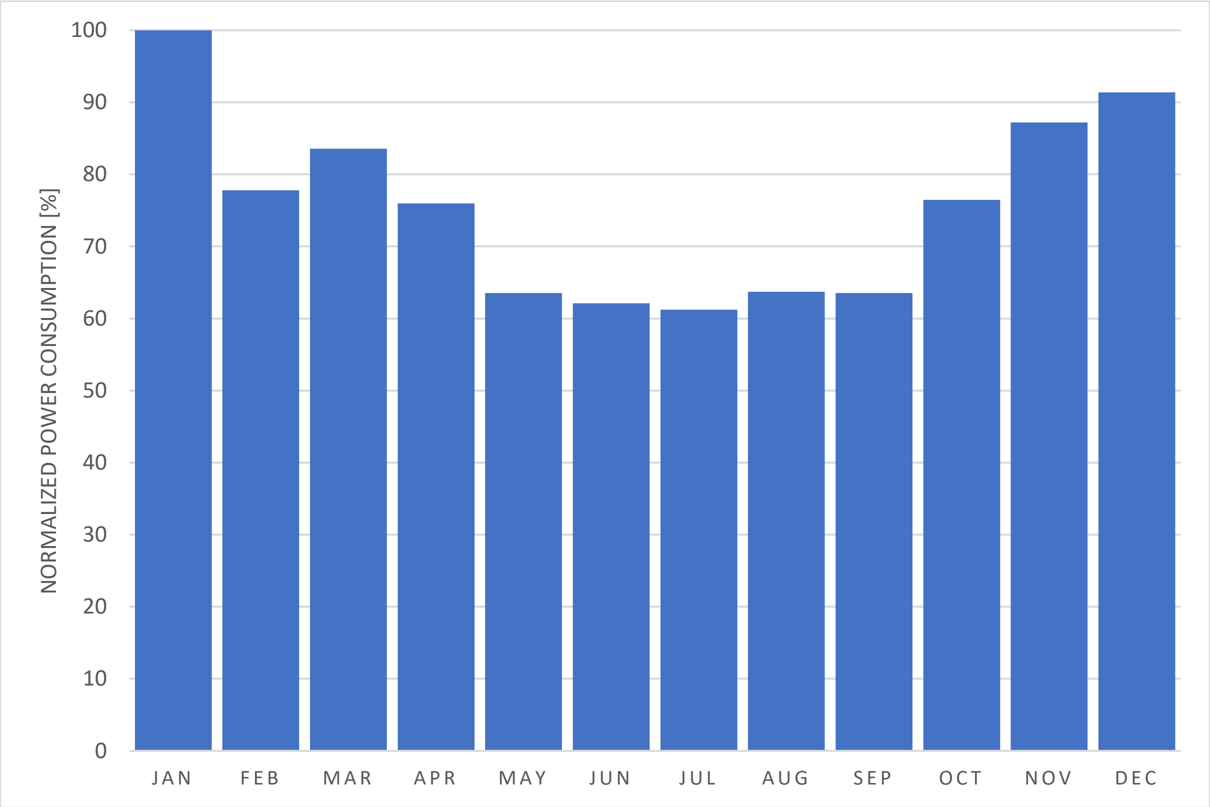

Figure 2. Total electric energy consumption during each month of 2016. The values are normalized, where the energy consumption of January, which was the month with the largest electrical energy consumption, was used as a normalizing factor. The power consumption is based on data obtained by GEAB, presented in Appendix D.

2.5. Load profiles of household loads on Gotland

Three load curves of the investigated system, where data were provided from GEAB, is shown in Figure 3. The data is also presented in Appendix B. The curves represent the hourly mean power consumption for three different days during the year 2016. The different days were chosen to capture as much of the data variance as possible. For instance, the load curve of January represents a very cold day, while the day in May represents a warm day where the residents don’t use much electric power. The day in October represents a mean day. The y-axis on Figure 3 is normalized based on the mean load in October.

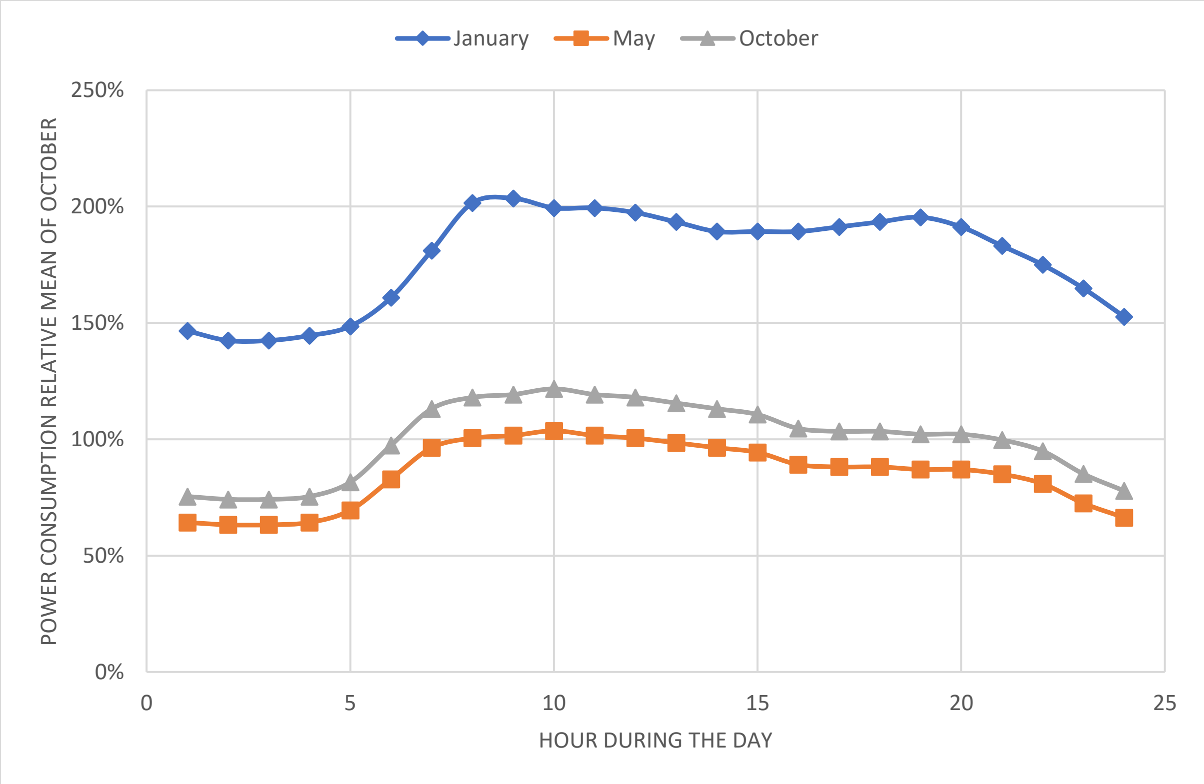

Figure 3. The load profiles of the three different days representing the cases of high, low and mean load. All values have been normalized with the mean value for the load profile of October.

2.6. Electric vehicles (EVs)

Electric Vehicles (EVs) are vehicles which propel by using an electric powertrain. EVs are in turn classified into three types; hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). The major differences between the three types are how they propel themselves. HEVs consists of both an electric power engine and an internal combustion engine (ICE) [20]. These engines can either be connected in a parallel or serial drivetrain. In a serial powertrain, the ICE propels a generator, providing power to the electric engine which propels the vehicle. In a parallel powertrain, the engines are coupled and utilized at different driving conditions [20]. PHEVs also have an electrical engine and a combustion engine which are coupled, such as a hybrid vehicle. However, the electric engine in a PHEV is powered by a small battery bank in the vehicle [20]. In 2018, the battery banks installed in PHEVs commonly had a size between 10 and 20 kWh [21–24]. It is possible to charge these batteries externally by connecting the PHEVs to an electric power grid [20]. The last type is called battery electric vehicles (BEVs). BEVs are vehicles which only propels using an electric power engine. The engine is powered by a battery bank which is recharged by connecting the BEV to an external power source, such as an electric power grid. The battery bank in BEVs are usually much larger than in PHEVs. In 2018, the storage in the battery bank of conventional BEVs ranged between 40 kWh and 70 kWh [25–27]. A summary of how the different types of EVs differ from each other is presented in Table 1.

Table 1. Summary of some differences between the three presented EV types.

Type of EV	ICE	Plug-in battery bank	Battery capacity [kWh]
HEV	Yes	No	-
PHEV	Yes	Yes	10 - 20
BEV	No	Yes	40 - 70

The vehicles used for the V2G services in this study were all BEVs, since they had potential to store larger amounts of electrical power compared to the other types of EVs. The reason for only choosing one type of EV was due to simplicity, as it made it easier to set up a standardized battery capacity of the EVs in the system. PHEVs could also have been chosen instead for BEVs since they also interact with an electric power grid. However, BEVs had a higher battery capacity compared to PHEVs and thus allowed more V2G utilization in the system. Therefore, BEVs were regarded as more interesting for this study compared to PHEVs.

2.7. V2G and BEV charging

The definition of V2G is simply that the charging of EVs has a bidirectional charging station, the electric car also has the possibility to feed power back to the grid. This differs from conventional electrical vehicle supply equipment (EVSE) which most commonly are unidirectional; they can only charge the EV. The concept of V2G is quite simple; when the grid is unstable and in need of extra power, the batteries in the EVs discharge to a threshold limit and provide power at locations where it’s required locally. The EVSE would become bidirectional instead of unidirectional. However, doing this practically is complex and demands a fast response controlling unit at each charge station. Just imagine how a system with a few large generators in a couple of years adds thousands of small generators distributed around the whole system. An illustrative diagram of how V2G works is presented in Figure 4.

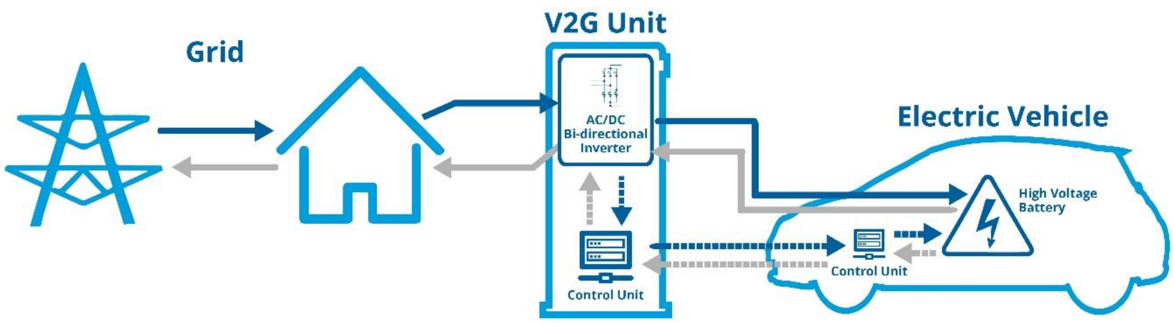

Figure 4. Diagram of how the BEV and power grid interacts with each other using a bi-directional EVSE [28].

There are additional challenges and issues which concerns the implementation of V2G. One of these challenges is the need for a bidirectional communicational electric power grid, which is one characteristic of a smart grid [29]. The concept of a smart grid can generally be described as an electrical power system which has a number of characteristics which the traditional grid is lacking [29]. A few examples of these characteristics are digital devices, condition monitoring, self-healing, two-way communication and distributed power generation [29]. An increase in information rate and bidirectional communication between components in the system will allow much faster regulations of power, making it possible for the grid to handle more complex power systems.

An increase in the grid's ability to handle distributed power generation is important since V2G would provide local auxiliary services, which requires fine regulation in order to operate. The power grid of Gotland does not presently have the characteristics of a smart grid, however for the sake of this study it is assumed to be developed for V2G to function properly.

2.8. Why electro-mobility?

As mentioned in the introduction of the report, society must change in order to achieve the goals for sustainability and climate. The transportation sector is no exception from these changes. The possibility of transporting goods and services is crucial for the modern society to function. At the same time, transportations were estimated to contribute approximately 20 percent of all annual global CO2-emissions during 2014 [30]. BEVs are an alternative that releases less CO2-emissions compared to fossil fuelled vehicles [31]. In a study from 2012 it was estimated that light-duty BEVs, and a European energy mix, had 10 to 24 percent less global warming potential (GWP) compared to their fossil fuelled counterparts [31].

In addition to lowering CO2- emissions from transportations, EVs have a few more benefits compared to fossil fuelled vehicles. These benefits are reduced noise and better air quality, since EVs are quiet and emit no tailpipe emissions [32]. These benefits are especially beneficial at locations with high traffic density, such as city centres.

2.9. Challenges brought by electro-mobility

Even though BEVs are considered to have less environmental impact compared to fossil fuelled cars, there are some downsides and problems with BEVs which need to be addressed. There are in general four major challenges BEVs must deal with, in order to compete with conventional cars.

Two of these challenges are cost and driving distance before recharging, which are factors that directly affect people's general opinion about BEVs. The general driving distance of commercial BEVs are today around 270 to 400 km [25,26]. Range anxiety and cost are challenges which are handled on an individual level, where a person is deciding what alternative that mostly fulfils a specific need. In this case, a person chooses between having an EV or a purely fossil propelled vehicle. In 2017 the EVs were still more expensive than cars with a combustion engine, yet studies have found that EVs are expected to be cheaper than similar fossil fuelled cars by 2025 [33]. The main argument for the reduction of price is a continued decrease for cost of material used in the batteries of BEVs [33]. As for range anxiety, there are multiple projects undergoing to install large quantities of publicly available charge stations with short distances between them. One example of these projects are InCharge, a project performed by Vattenfall AB, which have worked with expanding the charge infrastructure in the Nordics, Germany and the Netherlands [34].

The third and fourth challenges are challenges on a scale much larger than the daily life of a person. The third challenge is to balance a large increase in local power consumption. The power output from an EVSE connected to a household, which is connected by one phase and limited to 16 amperes (A), is approximately 3.7 kW. In comparison, a regular household usually has a mean power consumption of about 2.8 kW if it has an annual power consumption of 25 000 kWh [18]**.** This means the load from a household may instantly more than double when the BEVs starts charging. This lead to large power peaks, especially if the cars are charging immediately when people get home in the evening, which in turn may result in lack of electric power due to bottle-necks in the distribution grid. If the EV penetration in the Swedish vehicle fleet will increase, this may become a serious issue in rural areas where the grid can't handle these power quantities. This shows the importance of creating smart grid solutions and reinforcing a power system for an upcoming increase in power consumption.

Lastly, the fourth challenge is the lack of materials for creating the necessary batteries. Most of the common BEVs uses Li^+ batteries. The use of large quantities of lithium itself isn't major problem, however the batteries use other metals in their cathodes as well as lithium. One of these materials is cobalt, which is scarce [35]. This lack of cobalt could result in very high prices, which means there might not be enough cobalt to satisfy the whole world's need of BEVs. The manufacturing of cobalt also has issues in terms of social sustainability. Today a majority of the cobalt used in batteries are affiliated with cases of child labour and poor working conditions [36]. This is of course if BEVs will use the exact same technology in the future as in the present. The battery industry and the research on batteries is a highly developing area and it is therefore likely that future batteries of BEVs will consist of a different material composition than present batteries.

2.10. Driving habits

In modern society the car plays an important role for rural households. It creates easy and flexible transportation of goods and services for a household family, such as driving to work, shopping for groceries, dropping off children for school or visiting friends in other towns. However, even though the car grants a lot of flexibility, it has a low level of daily utilization. The driving habits of a Swedish citizen is to make 0.7 main trips every day, drive about 25 km each day for approximately 44 minutes [37]. If an assumption is made that people generally drive their cars between 8:00 in the morning and 20:00 in the evening, the car will be parked about 94 percent of the time where cars usually are utilized. If one also considers that the car can be utilized for V2G or charging the whole day, the total time during a day in this case is estimated to 97 percent of each day in average.

3. Method

To study how V2G can affect the grid capacity of Gotland, simulations were executed in PSS®E (Power System Simulator for Engineering). PSS®E is a program which is commonly used to analyse large electric power systems. Other simulation programs were also considered during the project, such as a MATLAB add-on called Simulink, yet in the end PSS®E was considered as the most suitable option.

There were two main reasons why the simulations were done in PSS®E. The first reason was because Vattenfall AB had used this program during earlier studies regarding the electric power system of Gotland, and therefore it was also deemed suitable for this project. In addition, if the models of the power grid of Gotland were built in the same program, then it may be easier to combine them for further studies. The second reason was because PSS®E is a common tool in power engineering for load flow analyses. It is easy to set up load flow analyses and the program is compatible with Microsoft Excel, which enables import of large data sets from Microsoft Excel directly to PSS®E for simulation. The simulation model was set up to simulate a part of the low-voltage grid of Gotland that has, or will have, issues in the future regarding grid capacity.

3.1. Scope and assumptions

An electric power grid consists primarily of generators, transformers, loads and branches, but the complexity increases as the power systems becomes larger. Multiple generators can support multiple loads. The branches can also be connected to each other, to prevent large power losses during short circuits. When V2G as a function is added the system becomes even more complex. Through V2G the system obtains a much larger amount of available power sources, yet these can only be utilized to a certain amount depending on for instance the battery capacity of every EV. In addition, other indirect factors will have a larger impact on the power system after V2G is utilized. One example is the driving habits of the residents that are connected to the electric power grid. The complexity and all indirect factors are hard to account for, and in this study some simplifications have been made to keep the scope of the study at an appropriate size. These simplifications were mostly focused on setting initial or steady-state conditions on factors that were considered having large uncertainties, such as the driving habits of the residents or how many EVs on Gotland that can utilize V2G. All these simplifications are based upon assumptions which are motivated in this section. These simplifications were expected to have an impact on the results obtained from simulations in this study, and the potential effects are presented later in the report along with an analysis of the simulation results.

The first and foremost assumption in this study was that the resident in the area primarily charged at home. V2G could possibly have the potential to be more centralized, with multiple charge stations placed at tactical locations connected to the distribution grid of 11 kV on Gotland, but for the scope of the study the charging was mainly considered to be at the homes of the EV owners. In addition, Surveys regarding the charge habits of EVs have shown that most of the charging occurs at low-voltage level, 400 V, at the households of the EV owners [38]. Therefore, the area to investigate should be a low-voltage power system on Gotland.

After the voltage levels was set to 400 V followed the process of choosing an area to investigate of appropriate size. To create a model of the whole low-voltage grid was considered too time consuming during the study, and there was no preconstructed model available at Vattenfall AB. Therefore, a second assumption was made that the low-voltage grid on Gotland could be separated into smaller segments with similar system properties. The results obtained from investigating one of these segments could then also be applied for the rest of the low voltage grid on Gotland.

The investigated area does include residents, where a portion of the residents have BEVs which utilizes V2G. The number of BEVs installed in the system was set to 120, which means 20 percent of all 600 estimated households in the area had a BEV utilizing V2G. The value was based on predictions of how the selling of EVs was expected to progress during the upcoming decades. A report by Bloomberg estimated that by 2040 approximately a third of the global car fleet would consist of EVs [39]. Since the definition of EVs not only includes BEVs but also HEVs and PHEVs, it is not possible to assume that a third of all private vehicles on Gotland would be BEVs. After evaluations it was assumed that 20 percent of all households in the area would have one BEV and a EVSE which supported V2G services, thus 120 V2G systems was added to the system.

The BEVs were assumed to be fairly evenly distributed among the households of the system, and also evenly distributed on the three phases of the electric power grid. The advantage of distributing the BEVs evenly was that the results from the simulations would yield more general changes in performance of the power grid. In practice it could be possible that certain parts of the neighborhood area have a higher concentration of BEVs compared to others, due to for instance socio-economic factors, yet this was considered to reach beyond the scope of this master thesis study. The reason for the BEVs not being completely evenly distributed was due to two reasons. The first reason was that the loads in the system model was measured from transformers, which could be connected to multiple households on their secondary sides. In the model just one BEV and V2G subsystem was connected at each of these transformers, thus the number of households connected would differ between the V2G subsystems. The second reason for not having the BEVs being completely evenly distributed among the households was due to unpredicted behaviour of the model. When V2G subsystems were added to certain parts of the system model no converging solutions was found. In order to yield converging solutions during simulations, no V2G subsystems were installed at those locations in the model. During the project duration no reasonable explanation was found for this behaviour of the model.

For simplicity, all BEVs were assumed to charge and utilize V2G at the same time. This assumption did also include that all residents left and returned to their respective household at the same time, which in practice seldom was the case. In order to make an accurate estimation of when the cars can be used for V2G or are charging, detailed knowledge of the behaviours of the resident on Gotland is required. This information was considered to lie beyond the scope of this study, as the aim of the study is to determine the potential and effects from utilizing V2G on Gotland. Setting all BEVs to operate simultaneously yields the maximum effects for the investigated cases. If the case would be implemented practically, the effects would probably be smaller than shown in the results from this report.

Some additional assumptions were made regarding when the BEVs would charge or utilize V2G, and regarding the charge and discharge rates of the EVSEs. As mentioned earlier in this section, the BEVs were assumed to charge at home using a one-phase EVSE. The charge rate was therefore set to 3.6 kW, which is approximately the power supplied by a one-phase charger station at households [40].The power supplied during charge or V2G was also assumed to be static. The time when the BEVs would utilize V2G or charge was set by observing potential power peaks or durations with low power utilization in the load profiles in Figure 3. In addition, times when the BEVs would be used by their respective owners were also considered and regarded as time when the BEVs would neither charge nor utilize V2G. After simulating the model with different time intervals for charge and V2G utilization, one final time interval was chosen. The BEVs were decided to charge during the evening and night between 21.00 and 05.00 At 05.00 the BEVs would be utilized for V2G until approximately 08.00, at which the BEVs would be used for transportation services. Since the BEVs would not be stationed at the households during the day, they would not affect the system neither by charging or be used for V2G services. Therefore, the BEVs were regarded as inactive during the day, except for a small loss of energy capacity by driving the BEV between households and workplaces for approximately half an hour for each trip. The BEVs would return at their respective household between 17.00 and 18.00, and then utilize V2G between 18.00 and 20.00. The BEVs were neither charging or being utilized for V2G between 20.00 and 21.00, and the cycle would repeat once again with the BEVs charging at 21.00. These time intervals for charging and V2G utilization was regarded suitable since they created a flatter load profile; a more constant power supply to the system in terms of amplitude, while also resulting in only a small impact on the driving habits of the BEV owners.

The BEVs were assumed to only provide active power to the grid. V2G has the potential to also supply the grid with reactive power for other auxiliary services. However, when the BEVs were set to support the grid using reactive power, the model had difficulties in balancing the power flows in the system grid.

The assumptions presented have so far only handled issues and conditions for how the BEVs were assumed to behave in the system, yet it is also important to note that integration of V2G services drastically increases the complexity of an electric power system. In order to fully utilize V2G a smart grid is needed with a two-way communication between the electric power grid and the EVSE. This type of power grid was not present on Gotland during the time of this thesis project. Having a smart grid on Gotland is crucial for determining if V2G even can be utilized on the island. However, as the scope of the project was to determine the potential of utilizing V2G services in a power grid, it was just assumed that the grid was considered “smart”. As mentioned earlier, V2G is currently only in a piloting stage, and large-scale implementations are probably not likely during the upcoming decade. This means that technically it could be possible to have a smart grid on Gotland by the time V2G services could be implemented on in large scale systems.

Since V2G was not considered to be implemented on large scale projects until future decades, it was also necessary to estimate how the power consumption of the investigated area would change in the upcoming decades. This estimation was no easy task due to large uncertainties in forecasting key factors. A scenario from a study by IVA estimated that the power consumption from the household sector would be between 20 and 25 TWh in 2050 [7]. The present power consumption of the household sector is approximately 21 TWh [7], indicating that the power consumption in the future decades might only slightly change in the household sector. Therefore, it was assumed that the power consumption of the investigated area on Gotland would have a similar power consumption as today when V2G would be implemented.

This section included the assumptions made during the study. These assumptions are important to bear in mind when continuing reading this report, as they would have an impact on the results. A brief presentation of all assumptions is therefore summarized in a bulleted list.

- All EVs in this study were BEVs
- These BEVs did only charge or utilize V2G from an EVSE at their respective household.
- A smart grid on Gotland able to incorporate V2G functionality was available.
- All cars used the same type of charge station for V2G and charge services, which could deliver a power output of 3,6 kW.
- All chargers could only turn on or off for charge or V2G utilization.
- The residents would have the same power consumption during the following decades as presently.
- EV distribution was fairly evenly distributed on the island where each load in the system model had one BEV connected, unless it created simulations errors at certain loads.
- People mostly use their cars for getting to and from work (7:30-8:00 and 17:00-17:30).
- Everyone used their vehicles and were in need for charging simultaneously.

All these assumptions had most likely an effect on the results of the study, and some of them are probably rather weak or questionable if they properly reflect the system in practice. For example, it is highly unlikely that all owner of the BEVs would live their daily lives exactly the same and have the same needs for transportation. It is also possible that certain areas of the system are more likely to have a larger density of BEVs compared to other parts of the system. At the same time, these assumptions were necessary to create a scope for the study which was more easily comprehended and would still yield results which presented the potential of utilizing V2G on Gotland.

3.2 Setting up cases

To define suitable cases to examine, it was important to first determine what questions the case will handle. One thing which needed to be examined was how the power system will react to V2G in the worst case based on available data; when the load was at maximum. By examining this point in time, one would obtain the maximum effects from the V2G solution. The second case which was interesting for examination was the opposite of the first case; when the system load was at minimum . At times when the power consumption is low V2G wouldn't need to be utilized, however the BEVs could be able to handle potential overproduction from intermittent power generation e.g. wind power. In this case, the BEVs will act as additional loads instead of small DC generators. The minimum load case might have a small relevance to this study. The results from this could however be of potential interest as for future studies if the system model was integrated with large power generation source, such as a wind power park. These results from simulating these two cases were expected to show how the power system would react when the system load was very high or very low, yet in most of the time the load would be somewhere in between. The third and last case to simulate was therefore when the system had a regular load.

One challenge in designing these cases was to determine a suitable time period for each case. Since an assumption was made that the annual load curve looked similar between years, the time period could be set to one year. Then, the three days representing each case was found by creating a Python-script consisting of multiple built-in functions in MS Excel and Python. The maximum and minimum cases were found by first summing up the load for a whole day, and then by finding the maximum and minimum value of these summed values. To find the case with the average load curve the load was summed up hourly instead of daily. The values would then represent the mean value of power for each hour. The squared error from how much each hour of each day was different from the mean load curve was calculated, and the day with the smallest total squared error was chosen. The entire code used in this script can be found in Appendix C. The three days found to be interesting for the study were a day in January, May and October respectively, the days with the highest, lowest and most average power consumption.

3.3. Input data to PSS®E simulation model

The data necessary for simulation was obtained from Gotlands Energi AB (GEAB), a daughter company of Vattenfall AB. GEAB is the owner of the power grid of Gotland, and stored information about the investigated low-voltage power grid used in this study. The input data required for the system model included active and reactive power, ratings and impedance of the components which built up the system. The values of this data were measured at a certain time, and data were chosen to match the cases presented in the previous section 3.2. In addition, data of the power consumption for the whole island was used to determine which time of the year they could represent in each case, as corresponding data of the investigated area was not available at the time of the project. A sample of the data is shown in Appendix D to give a better understanding of the data structure.

The data obtained from GEAB needed in some cases to be altered or combined in order to fit the model. For instance, the model required the power consumption for each load in the system for every hour. This data was obtained by combining two other sets of data obtained from GEAB; the average annual power consumption of each load, and hourly data of the power consumption of the whole system. An illustrative diagram of the process of estimating this data is presented in Figure 5.

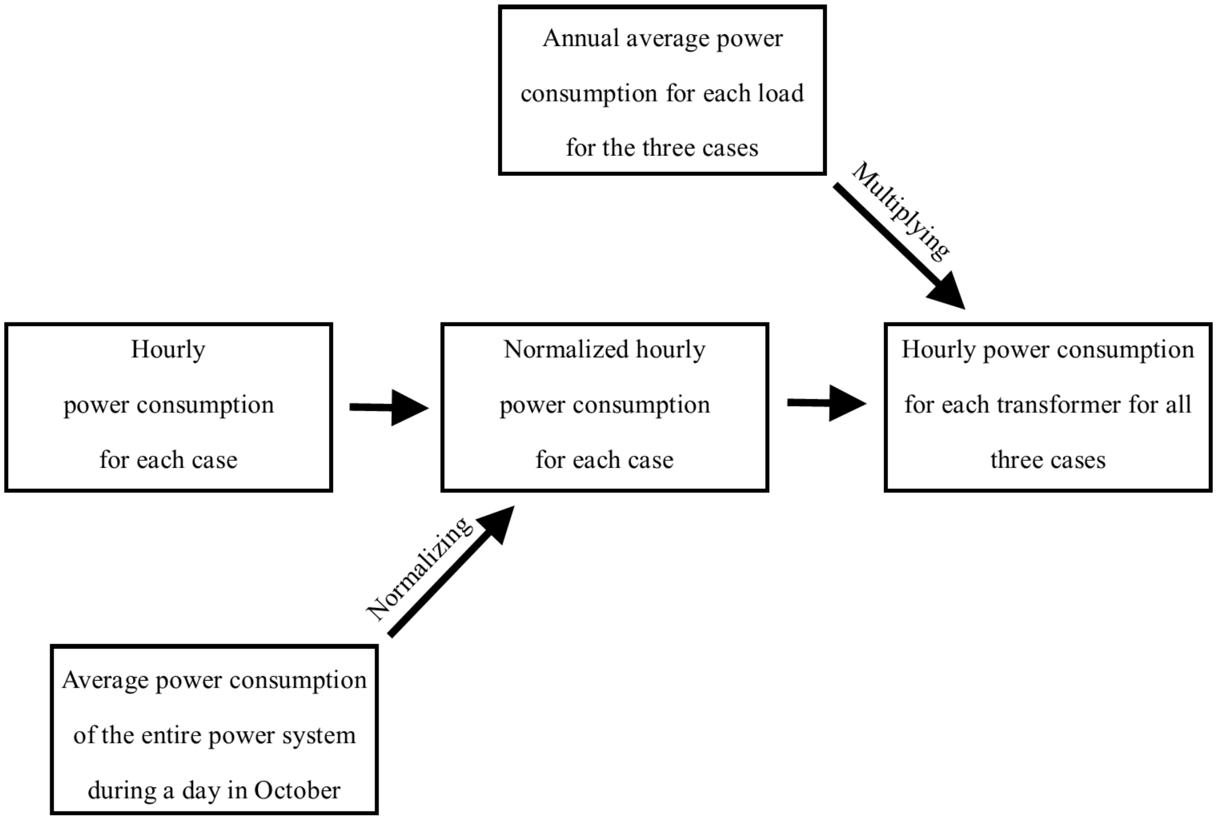

Figure 5. Process of estimating the power consumption for each transformer in the investigated system.

Every data point of the hourly power consumption of the whole system was normalized using the mean power consumption of the day with average power consumption. These normalized values were then multiplied with the annual average power consumption of each load, the mean power consumption of the day in October, which yielded a data set of power consumption of each load for every hour for the three days. The resulting data was presented earlier in the report in Figure 3. The reasoning behind this methodology was to assume that the annual average of every load was calculated by summing up the whole annual power consumption and dividing it by 365 (the amount of days during a year). That value would then also represent the mean power consumption of the day with an average power consumption. A drawback from creating data in this manner is that every load increase or decrease at the same time, which is certainly not the case in the real system. However, this was an effective way to create the necessary data points without knowing the exact value for every load for each hour of the investigated days.

The next estimated data set was the power limitations of the conductors. Data regarding cable types and electrical characteristics of the conductors was obtained from GEAB. However, there were difficulties in obtaining exact values for the power ratings of the conductors. The reason behind this was that the power limitations varied due to multiple factors, such as conductor material and installation type. The only information provided regarding the power ratings of the conductors was that they generally transport power corresponding to 40 - 50 percent of their maximum capacity during normal operating conditions, and 70 - 80 percent during high load conditions. With knowledge of levels for maximum capacity, the power ratings of all conductor types were estimated by simulating the model without any V2G subsystems. These simulations did also use the power consumption of an average day, but in this case it was to estimate power ratings instead of normalizing power loads. After each simulation the power ratings of the conductors were changed, and the goal of the simulations was to yield an output where a large amount of the conductors had a power flow between 40 and 50 percent of the power rating. The system consisted of many conductors, and to individually control every conductor was in this project considered to demand too much time. Since the conductors was categorized into different types, a simplification was made that every type of conductor had the same power rating. This simplification made the estimations of all power rating more time efficient, but it did also result in a variance between conductors of the same cable type. In some cases, the strain of the conductors could differ between 80 or below 10 percent of their maximum power capacity. The values chosen for the power rating can be found in Appendix E.

In summary, two input data sets to the simulation model was created using data and information obtained from GEAB. The first one was hourly data for every load during the three days for investigation, and the second was the power ratings of the cables. This data processing based on the data available creates some uncertainties which could not be validated in the work, however the input data created were deemed necessary for the purpose of the project.

3.4. Creating a complementary python-script.

When the cases were set up, the system models were finished and all necessary data was obtained, all that remained was to execute the simulations in PSS®E. The simulations executed were load flow analyses, where PSS®E would calculate the power flow in the conductors to meet load demands.

The investigated power system contained multiple buses and loads. To make the data inputs and simulations easier a Python-script was created. This script had four major functions. The first function was to import lists of input data from a starting file using Microsoft Excel. One example of this process was the import of bus names, which would be used to locate where the V2G subsystem would be connected. Secondly, the script started a predetermined case file in PSS®E and added a generator and load at these V2G buses. The generators represented the utilization of V2G, while the loads represented the BEVs charging. Thirdly, the script made simulations according to the case conditions. Lastly, the Python-script saved output data in new files for further examination. Using the Python-script instead of manually inserting each input data made the simulation setups much quicker, and reduced the risk of incorrect inputs due to human error. The whole script with brief comments of the code can be found in Appendix F.

In the Python script, the charge and discharge hours of the BEVs were set to different times during a day, in accordance with the assumptions in section 3.1.. The BEVs were set to utilize V2G during the morning and in the evening, more precisely between 5:00 and 8.00 and between 18:00 and 20:00. At 21:00, the BEVs would start charging until 5:00, when they once again started to utilize V2G. Since the BEVs were assumed to be stationed at the workplaces of the BEV owners during daytime, the BEVs were set to neither charge or discharge between 8:00 and 18:00. The reason was that these workplaces possibly were located outside the investigated system, thus resulting in that they would not have any impact on the system between these hours.

3.5. Output data

The output from the simulations consisted primarily of two sets of data; voltages in p.u. (per unit) of every bus, and the strain in terms of capacity in percent of every branch of the system. Since the system had more than 150 buses connected by branches, the number of output data points just from one simulation became very large. The total number of output data points obtained from all simulations, from simulating every hour of the three cases considering whether the system utilized V2G or not, were approximately 59 000 data points. This amount of data is too much to present in the report and is also very hard to interpret for the reader. The output data was therefore compiled, and the mean value of the voltage levels and capacity strain from every simulation was calculated and presented instead of showing the whole output data set. Using the mean value makes it easier for the reader to understand the overall change in the system in terms of voltage levels and strain. However, one major drawback of only presenting the mean value is that the variance in output data becomes unknown. Therefore, it's also important to express the change in variance in an easily interpretable way for the reader. This was solved by also presenting the highest and lowest values from each simulation.

3.6. Simulation models

The reference model created in PSS®E consisted of 152 buses, where every bus was connected to at least another bus by one or two branches (conductors). Loads were added to the system and placed at their corresponding buses, according to information provided by GEAB, which created a reference model electric power system without V2G. When the reference model was created, more components were added to it which would represent the V2G utilization model. V2G was modelled by using a generator and an additional load. Diagrams of how inputs, outputs, and additional data used in the study was integrated into the reference model without V2G is presented in Figure 6. The modified version of the reference system, where the V2G subsystems were added, is presented similarly in Figure 7.

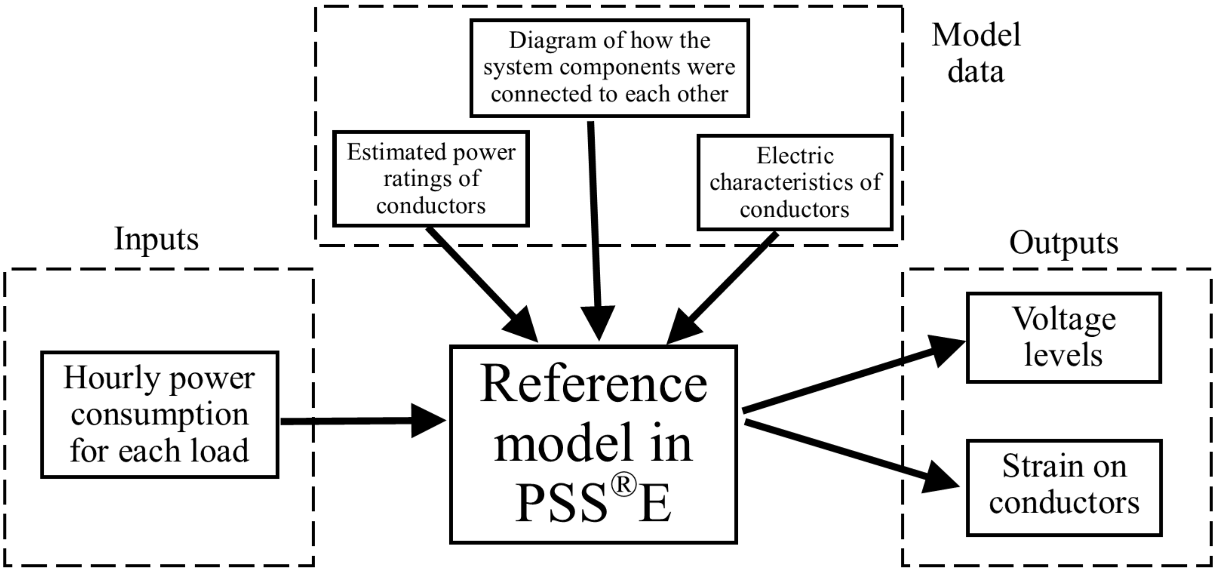

Figure 6. Diagram of the how different types of data was integrated and constructing the reference model, which represented the examined electric power grid on Gotland.

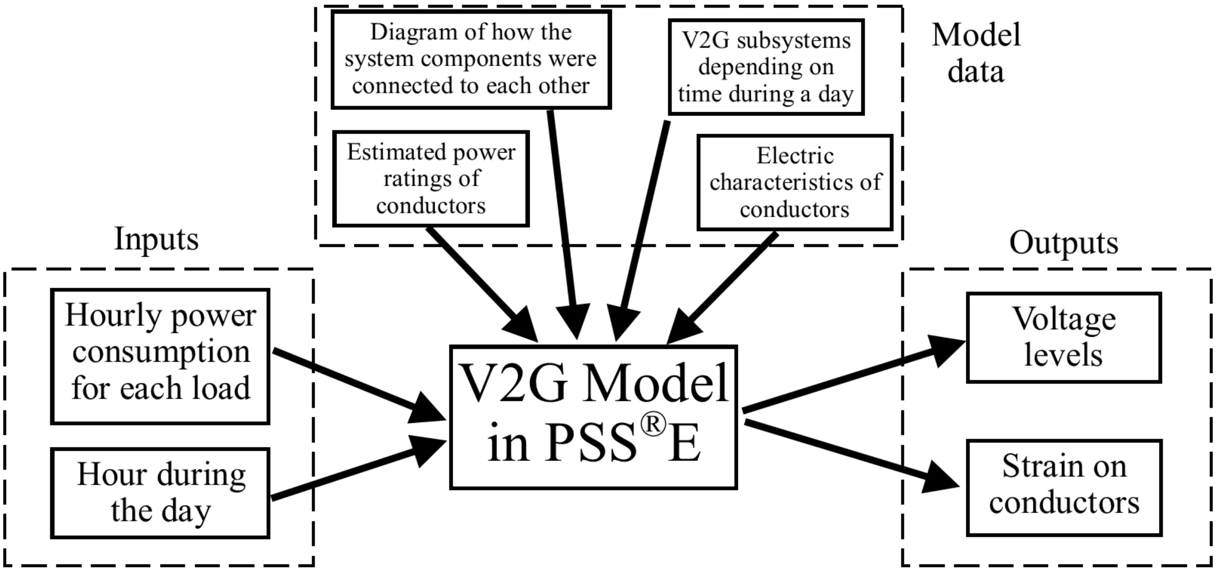

Figure 7. Diagram of the how different types of data was integrated and constructed the system model with V2G integration.

The V2G loads were connected to buses containing a household load and the V2G generators were connected to new buses, which in turn were connected to the buses with a household load. The buses with a V2G generator and buses with a V2G load were connected by branches representing lossless conductors. These conductors were regarded lossless since they are much shorter than other conductors in the system, and therefore these losses were considered small enough to be neglected in this study. If one would want to add these losses to the model, an alternative method could be to slightly increase the V2G loads and decrease the power output of the V2G generators. Also, the reason why the V2G generators are connected to a separate bus other than the same as the V2G loads is because PSS®E is not designed to have generators and loads connected to the same bus.

An illustrative example of how all components were connected to each other is presented in Figure 8, which is one bus in the system with all components described in this section. Please note that not all buses look exactly as the one in Figure 8. For instance, some buses may have more branches, while other buses did not have any V2G component.

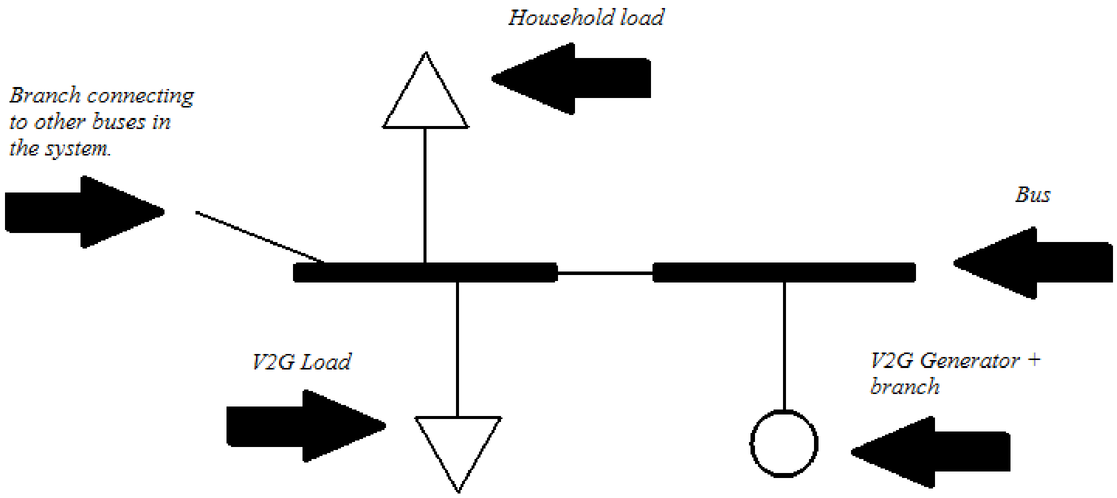

Figure 8. Illustrative example of a bus including every different component in the system directly connected to it. Please note that not all buses had all component as represented in the figure.

4. Results and Discussion

In this project the effects of V2G on voltage levels and strain, in terms of power capacity, of a part of the electric power system of Gotland have been investigated. Three different load cases were simulated which represented operating conditions during a day in January, May and October respectively. Also, how the transporting flexibility of the BEV owners would change due to these changes was estimated. In this chapter the results from the simulations are presented. Since the strain, voltage levels and transport flexibility are three different issues, the issues are presented in sections separately from each other. The discussion of the results regarding each issue is included in each section after the presented results. First the results for how the battery capacity in the BEVs would change during a day is presented, followed by a discussion of how this affected transportation flexibility of the BEV owners. Secondly the results for how the strain were affected by V2G are presented and discussed. The third section presents and analyses the impact on the overall voltage levels of the system when V2G was integrated. Lastly, the fourth section discusses the results and project through more general perspectives. Topics which are discussed in the last section are for instance potential errors in simulations, credibility of the results and future development.

4.1. Utilization of EVs during a day

If the BEVs were utilized as described in the section 3.1, the available capacity and possible driving distances for each BEV at a certain time is presented in Figure 9. Note that each data point represents the capacity and driving distance at that exact moment, and depends on if the BEV was charging, driving or utilizing V2G. For example, an increase in battery capacity corresponds to the BEV charging, while a decrease that the BEV was either used for V2G or transportation. The starting point at hour 0 is an initial value and was set to 20 kWh, which symbolized a BEV with approximately 50 percent of its maximum battery capacity remaining. The value of 40 kWh was set as the maximum battery capacity as modern BEVs have an capacity of between 40 and 70 kWh, and is expected to increase in the near future [25–27]. Another initial value could also have been used, but using a BEV whose batteries were neither fully charged nor depleted was expected to yield a better approximation for the variance of available battery capacity in a continuous system. The net charging during the whole day was approximately 0.6 kWh, meaning the BEV would generally start at a slightly higher initial state for every new day. The calculations for these points were based on the simulations made and the assumptions mentioned in section 3.1. For instance, the cars were estimated to require 17 kWh to drive 100 km and that the cars were used for V2G, a value estimated by dividing the battery capacity of BEVs with their respective range capacity [25–27]. Also, the V2G were active from 05:00-08:00, and from 18:00-20:00. Since the model only investigates a rural area and not where the residents are during work hours, between 09:00-17:00, the calculation was made with the assumption that the cars are not charged at the workplaces. It was also assumed that the residents have approximately 30 km to their workplaces, which takes approximately 22 min if one would travel at a mean speed of 80 km/h. The residents are travelling to their workplaces between 08:00-09:00 and travel home between 17:00-18:00. Between 20:00-21:00 the BEV would neither charge nor be used for V2G. During that time of day the load seemed to be low enough for not having to utilize V2G. At the same time, if the BEVs would charge the load would result in a new power peaks, and therefore it was deemed suitable that the BEVs were passive during 20:00-21:00.

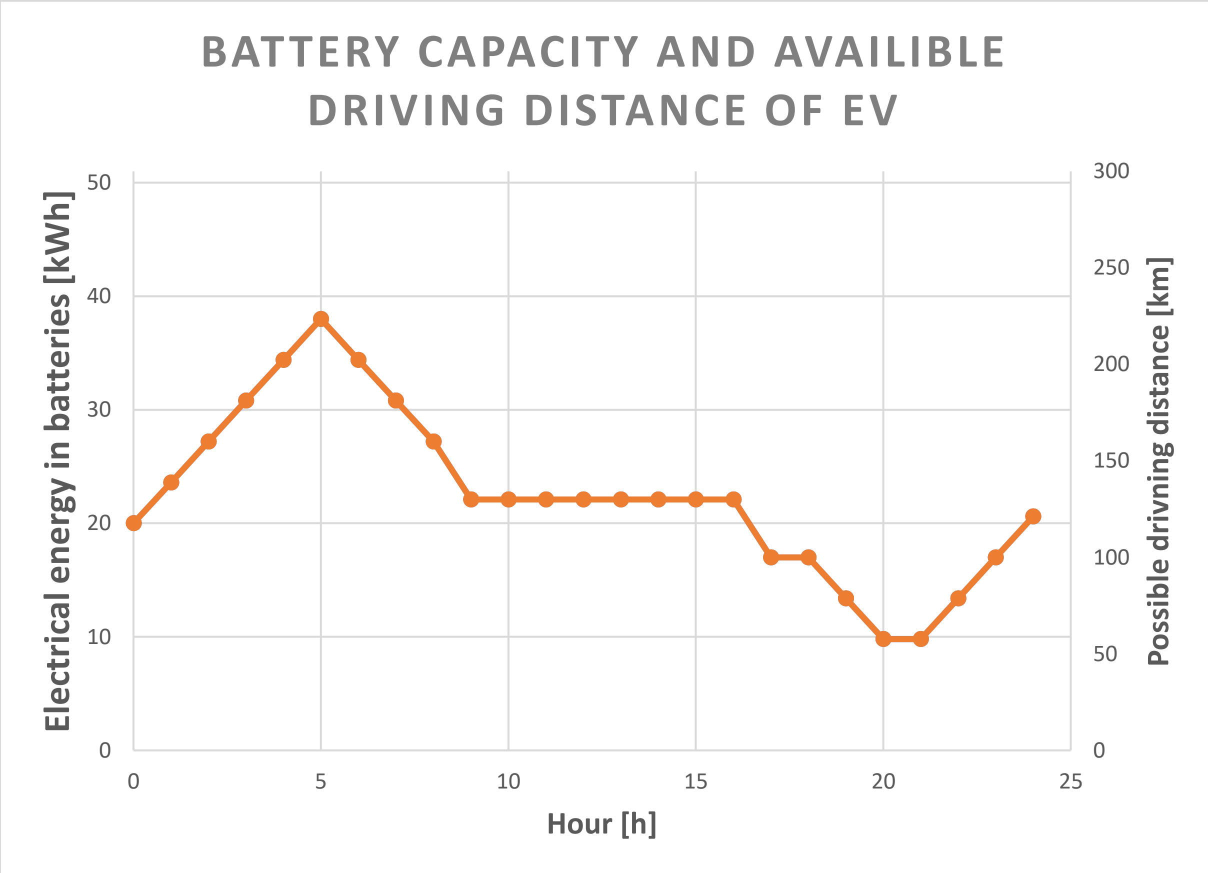

Figure 9. The electric energy stored in the batteries and corresponding driving distance of a BEV, during a day when V2G is utilized as in the simulations. Note that the efficiency of the BEV in terms of driving distance is estimated to 17 kWh per 100 km, and the maximum battery capacity to 40 kWh.

As can be seen in Figure 9, the BEVs are nearly fully charged during the morning if they're considered to have a battery capacity of 40 kWh. The residents can go to their workplaces without worrying about not being able to reach their workplaces before the batteries run out. There should neither be any troubles when they are travelling home from work in the evening. However, the available battery capacity and driving distance becomes quite low during the evening, approximately 58 km. This small amount of battery capacity may not be an issue in most cases, but it might if the residents for instance were to travel to evening activities such sport practices or cultural events. Therefore, the V2G solution could have a negative impact on the travel flexibility of the residents in the investigated rural area. At the same time, there are possible solutions to increase the available driving distance during the evening. For example, one solution could be to let the BEVs charged at the workplaces. Perhaps the BEVs will be used for V2G at the workplaces, but if the BEVs are charged more than they are discharged there will be more capacity available during the evening. Another solution is to have a predetermined schedule for when each BEV would be available for V2G. The compensation given to each BEV owner could then be based on how many hours they allow their BEV to be used for V2G.

The net charge during a day for a BEV is approximately 0.6 kWh, which means that the BEV becomes slightly more charged every day until they reach a maximum equilibrium point. However, this is only possible if the EVs are travelling a total distance of 60 km each day and V2G is utilized for 5 hours each day. If any of these parameters are increased, then the BEV would have a negative daily net charge. If for example the travelling distance is increased to 80 km each day, the daily net charge becomes -2.8 kWh. In that case, the BEVs would need to get charged for a longer time or with EVSEs with a higher electrical power output.

The estimation of how the BEVs would operate and interact with the electric power grid during a day has some uncertainties due to assumptions and estimated input values. The values for the battery capacity of a BEV and how much energy it requires to travel 100 km are based on present technology and forecasting, yet it is possible that these values are over- or underestimated by the time V2G can be implemented on a large scale. The estimation of how the BEVs would interact with the electric power grid indicate that a transportation issue for the BEV owners which utilizes their vehicles to V2G could occur during the evening. However, this problem regarding transport arise mainly due to the assumptions and rules set up on the BEVs and EVSE. If for instance the BEVs could charge a few hours during the day, or the EVSEs had a quicker charge rate, a larger battery capacity would be available during the evening. It was also observable in Figure 3 that the peak during the evenings on a regular basis are quite low, indicating that V2G might only be necessary during the power ramp-up during the morning.

4.2. Strain relative maximum capacity of the conductors

In Figure 10, Figure 11 and Figure 12 the mean strain on each conductor relative to maximum power capacity is presented, for each investigated case. Figure 10 shows the results from simulating a day in January, while Figure 11 and Figure 12 presents the simulations for May and October respectively. Additional values and data of the results regarding the capacity strain of the system are presented in Appendix G.

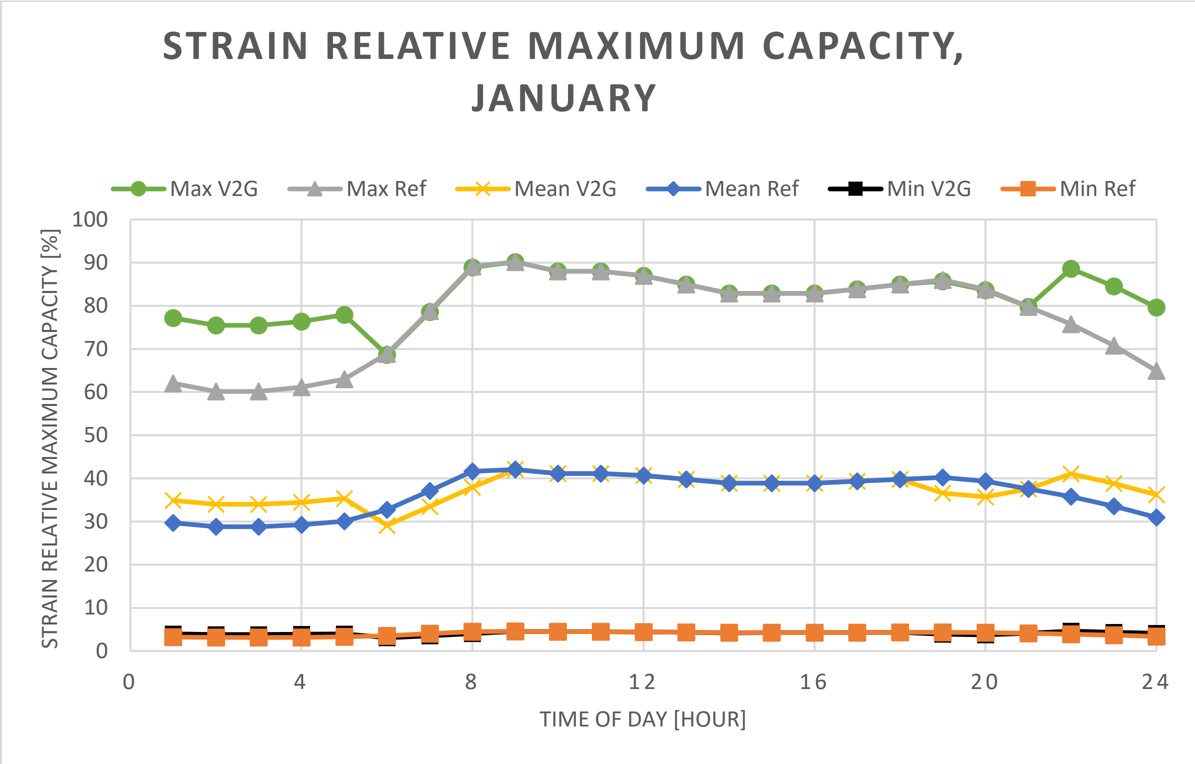

Figure 10. The strain relative the maximum capacity of the conductors for each hour during the case representing a day in January, when the system had a high power consumption.

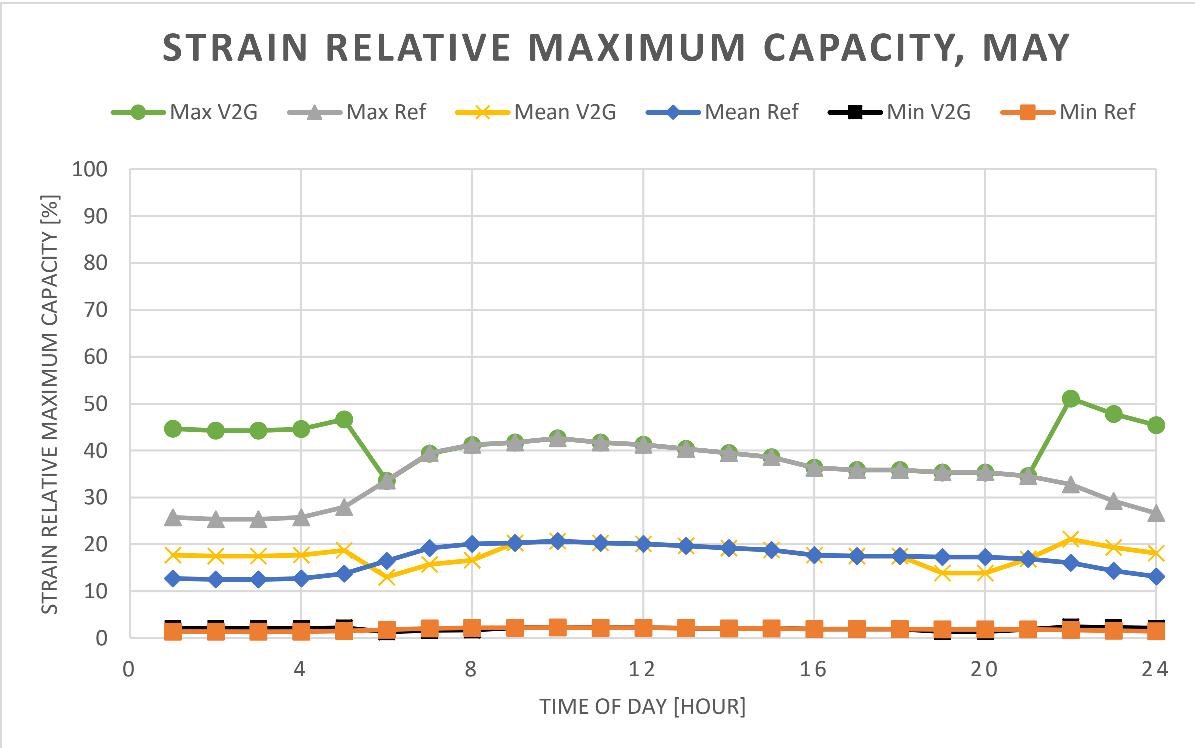

Figure 11. The strain relative the maximum capacity of the conductors for each hour during the case representing a day in May, when the system had low power consumption.

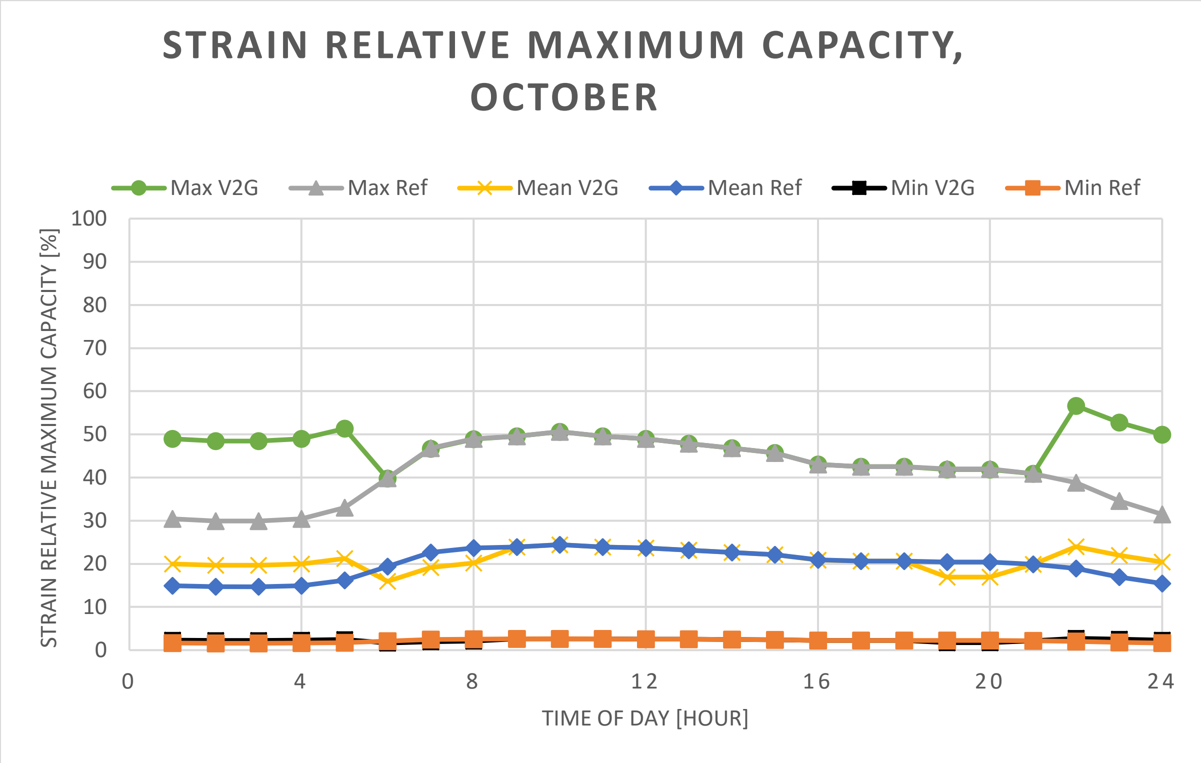

Figure 12. The strain relative the maximum capacity of the conductors for each hour during the case representing a day in October, when the system had an power consumption close to an average day in terms of power consumption.

The results from the simulations indicated that the overall strain on the system, in terms of electric power capacity, increased when the BEVs were connected and utilized V2G for 5 hours during each day to the grid. The overall strain during the whole day was increased by approximately 23.4 percentage units for the day in January and 22.8 percentage units for the days in May and October. If divided by the number of hours for each day, which is 24 hours, the increase was between 0.9 and 1 percentage units for each hour. At the same time, the strain was not always higher for the V2G systems compared to the reference systems. During hours when the V2G was active, the strain was decreased by approximately 4 percentage units, while the strain was increased by about 5 percentage units during charge hours. As one may observe in Figure 10, Figure 11 and Figure 12, the V2G utilization does not reduce any power peaks or fill any power valleys. The main reason for this was because the load profile of the system did not have any of these significant characteristics, power peaks or valleys, to begin with. Although, there are some other conclusions that can be drawn. For instance, while V2G was unable to decrease any power peaks, it was able to shift the time for when the power ramps up by about one hour. If a system for example has a lot of power generation from photovoltaics (PV), this shift might allow for a better matching between intermittent power generation and consumption during mornings. The BEVs did not only interact with the power grid through V2G, they also needed charging. If the BEVs only charged during night-time between 21:00 and 05:00, as they were set during the simulations, the load during night and day became similar to one another. The load profile during the whole day became flatter compared to when no BEVs were connected. The daily power consumption of the system would increase, but at the same time less regulating power would be necessary when the BEVs were integrated. However, a new power peak would occur at 21:00 in the evening. One way to solve this could be to not allow BEVs to start charging until 22:00. This would in turn decreases the total amount of hours that the BEVs would charge during a day, thus affecting the transport flexibly of the BEV owners. There are a few ways to compensate for this loss of charge time. One way could be to decrease the number of hours that the BEVs support the grid with V2G. In this case, it could be reasonable to remove the V2G function during evenings. By doing so the load profile would become flatter, which indicates that there is not any major need to account for power peaks in the investigated area during evenings. Another way could be to increase the charge rate of the EVSEs, which in turn decreases the charge time.

The overall impact of V2G on the whole system was low, however there were some local points where V2G utilization provided a large strain on the system. This can be observed due to the large difference between the maximum strain for the reference system and the V2G system in Figure 10, Figure 11 and Figure 12. The difference in strain was in some cases up to 19 percentage units, an increase of approximately two thirds from the reference system. These occurrences seemed however to be quite few, since the mean values at each point between the reference system and V2G system were one percentage unit. In addition, a few buses could not be provided with an V2G bus since it resulted in simulation errors. The maximum point in all three cases are possibly one of these buses which could not support a V2G in the simulations, since otherwise a trend would be shown where the strain is decreased when V2G was active. The same increase of strain was not observed for the minimum values. The difference between the systems were quite small, and the trends for the minimum values were similar to the curves representing the mean values for each system.

Even though the trends for how the strain changes between the reference system and V2G system seemed reasonable, the strain increased during charge hours and decreased during V2G hours, there was one factor that potentially had a major impact on the amplitude of the results. This factor was the estimations made for the power ratings of the conductors. The main information used for these estimations was that most conductors had a strain of between 40 and 50 percent, in terms of relative maximum power capacity, during normal operating conditions. For simplification, all conductors of the same type had the same power rating. The information by itself was not necessarily insufficient, but it was observed that there was a large variance of power flowing through a few conductors with the same type. This also resulted in a large variance of strain when a certain power rating was set. If the mean of all conductors of a certain type was set to a strain of 40 percent, some of the conductors with the largest power flows ended up with strains above 100 percent. This implied that the system had few overloaded conductors, which clearly was not a plausible scenario since the real reference power system on Gotland was in operating condition. The problem with overloaded conductors was solved by reducing the overall mean strain on a few conductor types to less than 40 percent. At the same time, it might be more plausible that the assumption regarding the connection between conductor type and power rating was insufficient. The trends for how the strain changes during the day would probably be somewhat similar regardless if the assumption is used or not, however the amplitudes will change if for example every conductor was set to have a mean strain of 40 percent. However, these values are also uncertain since there is currently no information to validate the results with. A more accurate solution could be achievable if the true power rating for each conductor was obtained and implemented in the model. This would also be a good measure for validation of the model combined with the information that every conductor usually has a strain between 40 and 50 percent.

In summary, the V2G system had an overall small effect on the strain of the grid and was able to shift the ramp up of the load profile to one hour later during the day. Allowing the BEVs to only charge during night-time resulted in a flatter daily load profile, meaning the system would have less need for regulating power. A small peak occurred during the evening due to the charging of BEVs, which can be reduced by delaying EV charging by one hour. This means the BEVs will have less time to charge, yet this can be compensated by not utilizing V2G during the evening because it did not improve the stability of the system in terms of strain. The factor which has the biggest impact on the results are the estimations for the power ratings of the conductors, and the assumptions regarding the estimations. In the following section the results regarding the voltage levels of the systems is presented, followed by a discussion about the results.

4.3. Impact on Voltage

The mean, maximum and minimum voltage levels for the cases January, May and October are represented in Figure 13, Figure 14 and Figure 15 respectively. One thing to observe about the axis, of voltage levels, is that it starts at 0.85 but not 0. The reason behind this is to better illustrate the differences in the graphs, which are harder to observe if the axis had a width starting at 0. A p.u. value of 1 represents the nominal voltage of the conductor, for example 0.95 p.u. means the voltage is 95 percent of the nominal voltage. It is desirable for all buses to have a voltage level equal to the nominal voltage, a p.u. value equal to 1. The exact values for the data point in Figure 13, Figure 14 and Figure 15 can be found in Appendix G.

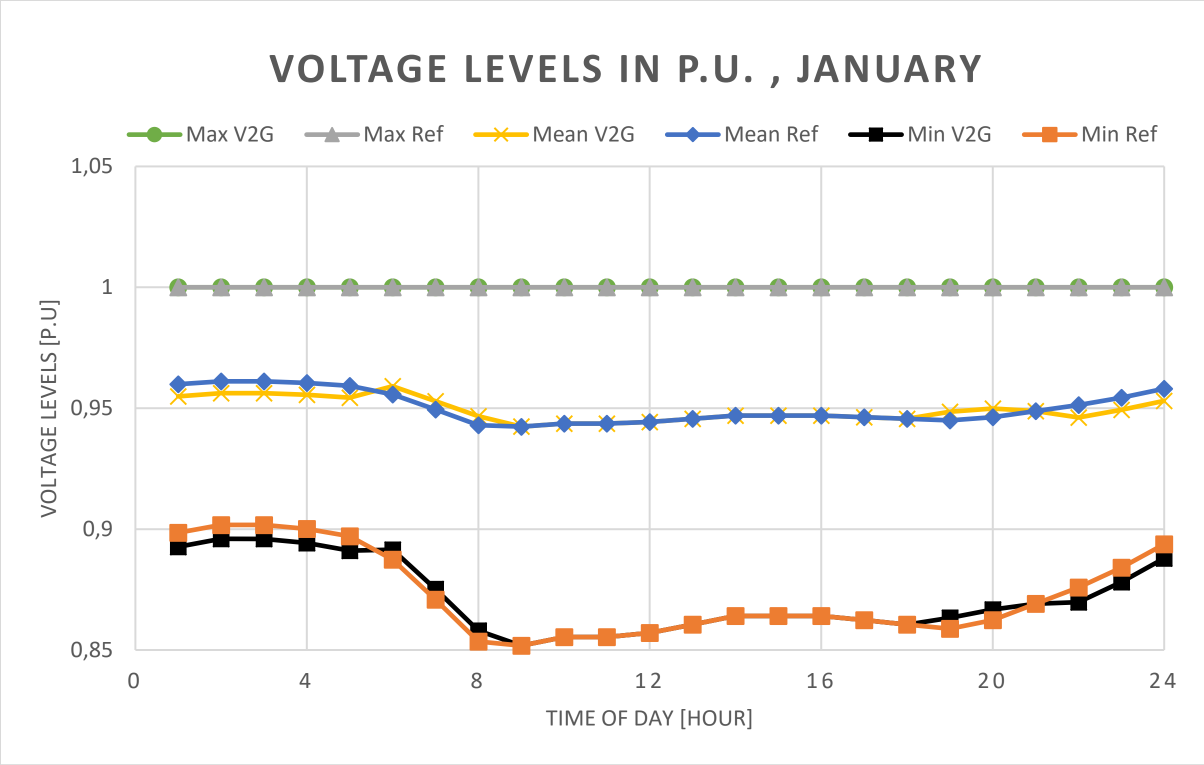

Figure 13. Voltage levels in p.u. of the system for each hour during the case representing a day in January, when the system has a high power consumption.

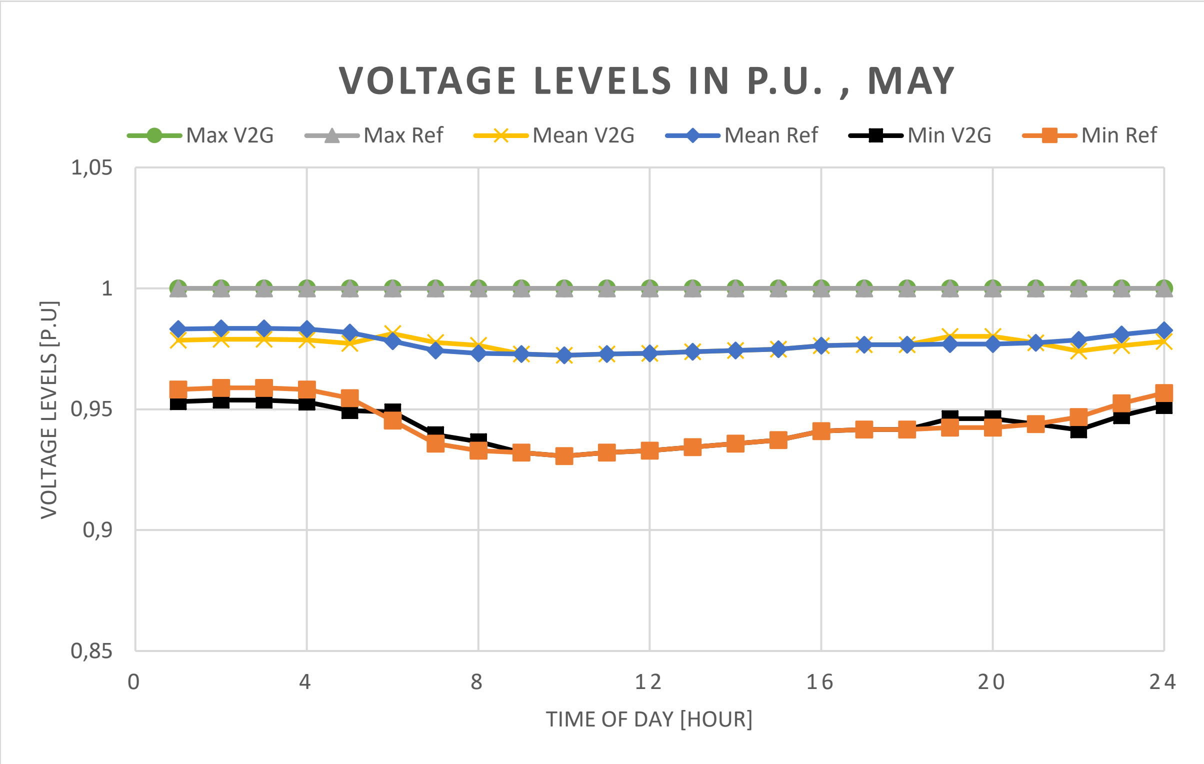

Figure 14. Voltage levels in p.u. of the system for each hour during the cases representing a day in May, when the system has a low power consumption.

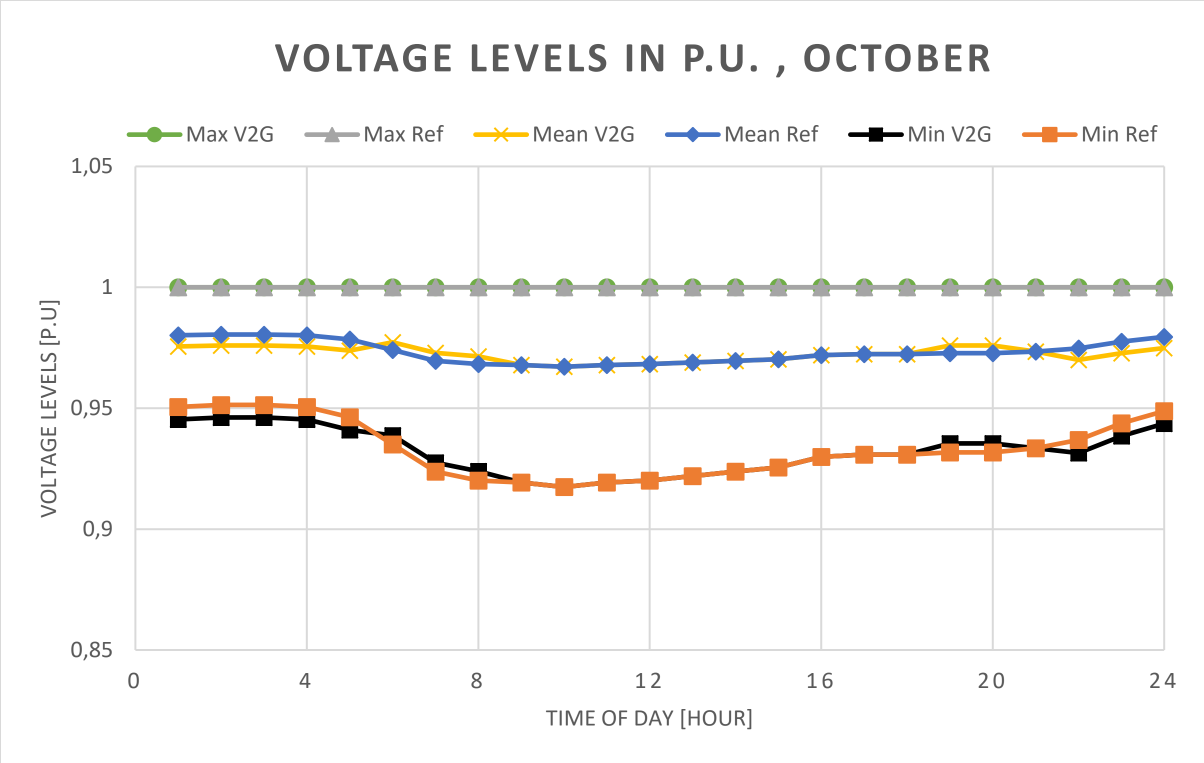

Figure 15. Voltage levels in p.u. of the system for each hour during the case representing a day in October, when the system has an average power consumption.

The net change of voltage levels between the reference system and V2G system during the whole day was approximately 0.02 p.u. for each case. If divided by the number of hours during a day, the net change is less than 0.001 p.u. per hour, which means the overall impact from the BEVs was quite small. During charging hours, the voltage level decrease by approximately 0.005 p.u. and increased by about 0.04 p.u. during V2G active hours. If the trend for the voltage levels was compared with the trend for the power strain, it was observed that they react the opposite of each other, where the overall voltage level increased as the overall strain of the system decreased.

The maximum values were unchanged when the V2G was integrated. Since the voltage levels of a power system are more related to the reactive power flow rather than the active power flow, and the V2G in this case only provide active power, there was not any large differences in voltage levels. In addition, since no large generators are connected to the system except the generator connected to the swing bus, no other buses than the swing bus were expected to have voltage level equal to the rated voltage. Therefore, the maximum voltage level was the same for both systems, which was the voltage of the swing bus. The minimum voltage level followed the same trend as that of the mean voltage levels, and with about the same differences for charged and V2G active hours.

If one examines the results and compares them to the limitations of set up for voltage stability, that the voltage levels needs to be higher than 0.9 p.u. of the rated voltage. This is achieved during the days in May and October. However, during the day in January the voltage level drops to approximately 0.85 p.u. of rated voltage, which exceeds the limitation. This was also the case when V2G was integrated into the system, as the differences between the systems were small. One factor why V2G has almost no effect on the voltage level is, as mentioned earlier, because the V2G in the simulations only provided the system with active power. If one would try to affect the voltage levels, the effect would be larger if the V2G was set to also provide reactive power. During test runs for the simulations, when the V2G generators were set to also provide reactive power, large mismatches in power flows occurred in the simulations. Therefore, the results from the simulations were regarded very uncertain, and would probably not shed any new information than could be obtained from the simulations with only active power. Even when the V2G system was set to only supply the grid with reactive power, the changes in p.u. was still small. This indicated that V2G was not suitable to balance voltage drops but, as with the results concerning the strain of the system, there are simplifications which probably had an impact on the results. It is possible that the bus with the lowest voltage level is closely connected with the buses that could not support a V2G subsystem, which in turn reduces the V2G effect at those buses. This could be an explanation for why the values for the voltage levels are quite similar between the reference system and V2G system, because the V2G might not be applied in the most critical areas of the model. It is necessary to solve why the solution of the simulation diverged when V2G subsystems are integrated at certain buses in the investigated system. This would yield more trustworthy results from the simulations.

The results regarding the change of voltage levels in the system showed that V2G seemed to not have a major impact on the voltage levels of a rural electrical power grid, thus indicating that V2G is non-suitable for voltage regulation. However, there were issues in the simulation model which probably affected the results. One of these issues could be the loss of a few V2G subsystems at desired buses, as these resulted in simulation errors if they were integrated in the model. Another problem with the system model was the issue with non-converging results when the V2G subsystems were set to also supply the grid with reactive power. These issues need to be solved before a more definite conclusion can be presented.

4.4. How well does the model fit the true system?

As seen in Figure 12, the mean strain differs between 15 and 25 percent during the day in October. Considering that the strain in the real system of Gotland should be, according to GEAB, between 40 and 50 percent, the estimated power limits of the conductors are generally set to high. In addition, the results in Figure 13 seem to indicate that a few conductors in the system have a voltage level below the regulated limitations. Since there seem to be some odd results from simulating the reference system model, it could be argued that the model does not represent the real examined electrical low-voltage power grid on Gotland. This does of course not imply that the whole model is incorrect. For example, the trends for how the system reacts when the V2G is integrated into the system seem plausible, where the strain increases during charge hours and decreases during hours when the BEVs are used for V2G. The issue does not lie in how the model behaves, but rather in how the credibility of the results can be validated. Since the system aims to replicate an already functioning electric power system, the best way would be to compare the simulated output data; the power flows and voltage levels, with the real time data from the real power system. Though the comparison would be possible to more specifically identify local errors in the system model. Unfortunately, this output data were not obtainable during the project and therefore a comparison was not possible. However, validating the credibility of the model and to solve the diverging issues when the V2G sub system is added to certain buses are probably the two most important activities in order to improve the model further.

4.5. Future potential projects and model improvements

The model, with complementary python-script, has potential to simulate complex estimations of how the power flows in an electric power system are modified due to large integration of BEVs or PHEVs. The python-script was designed with focus on making it possible to change both the inputs and grid systems without any major changes in the script, as long as the format of the inputs are ordered in a similar manner as the input data used in this project. However, there are known errors in the model and script that requires attention in order to improve the model performance. The two errors which first should be solved were addressed in the previous section, the lack of validating data and the addition of V2G subsystems at buses that currently cannot support them. Solving these problems will clarify the credibility of the model and make it more applicable for estimation of other power grid systems.

After these issues have been handled, there are a few other aspects which could be interesting to examine. The model of this study could for instance be integrated into system models which also includes voltage levels above 1 kV. Also, an ongoing discussion on Gotland is if wind power or PV could be installed. These are intermittent energy sources, which on a local scale do not always match with the demanded power consumption. In this study it was possible to displace the power ramp-up in the morning, indicating that an intercommunion between BEVs for example PVs could be possible. It could be of interest to study if V2G utilizing BEVs would be able to balance out the volatile and intermittent aspects of wind power and PVs.

Another improvement to the model would be to take more consideration for the needs and behaviour of the residents in terms of transportation. In the current model it was just assumed that all cars were charging or available for V2G during the same hours of the day, a simplification which most certainly only is applicable to a small number of residents. For example, statistical methods such as Monte-Carlo-simulations, or proportional weighting for different hours could be used to better handle the needs and variance of the resident transportation. Also, data regarding the driving habits of people are probably very useful in other projects regarding transportations, for example the infrastructure of public charge stations along roads and highways.

5. Conclusions

In this project an electric power grid of a rural area on Gotland has been modelled, and the effects on the power capacity strain of the conductors and voltage levels of the grid when V2G was utilized have been investigated.

The integration of V2G into the investigated power system generally resulted in small changes for both voltage levels and strain of the grid. The overall strain increased while voltage levels decreased when the BEVs were charging, and there was a decrease in strain and an increase in voltage levels when V2G was active. Integrating V2G resulted in a delay of the power consumption ramp-up during mornings and created a flatter load profile during the whole day. Since the BEVs are charging during night-time the everyday transportation needs of the residents in the area investigated were not disturbed. However, transporting problems could arise if the residents were to travel longer distances during the evening.

The investigation was made under several assumptions regarding the operation and performance of the V2G charge stations. The V2G utilization was modelled as switches, which operated during mornings and a few hours during the evening. All EVs in the study was assumed to be BEVs, where approximately 20 percent of all households were assumed to include a BEV, which could only charge during night-time at the household. In addition, all BEVs was assumed to be utilized at the same time during the day. All the mentioned assumptions were made in order to simplify the complexity of the system, which needed to balance a demand of both electric power and transportation. The assumptions were justified by the project being a case study with focus on estimating the potential effects V2G utilization could have on a low-voltage grid, in this case located on Gotland. However, these assumptions do certainly have an impact on the simulation results. Some of the assumptions do probably not represent reality well, especially the simultaneous use of BEVs and when the BEVs are able to charge.

One important factor regarding the system was that most power ratings in the system were approximately estimated to between 40 and 50 in the reference system. In addition, the load profile of the system did not seem to have any distinct power peaks or valleys. This could indicate that the investigated area did not have any major issues in the first place, thus V2G could potentially only have small effects on the voltage levels and strain of the system.

The model has potential of being accurate, due to almost non-existent mismatch of the power flows. However, due to a lack of validating material it is not possible to truly confirm how well the model fits the real system. In addition, solutions to the model during simulations diverge when V2G is integrated to certain buses. By solving these issues and by having more consideration for the driving habits of people, the model with complementary scripts might be able to accurately estimate the impact and potential effect of V2G for any electric power system.

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Appendix A – Diagram of the investigated low-voltage power grid

To construct and set up the model it was necessary to know how all components in the model would be connected to each other. This was handled by examining a diagram sent from GEAB, which presented how buses, loads and conductors were connected. The same figure is presented in Figure A1.

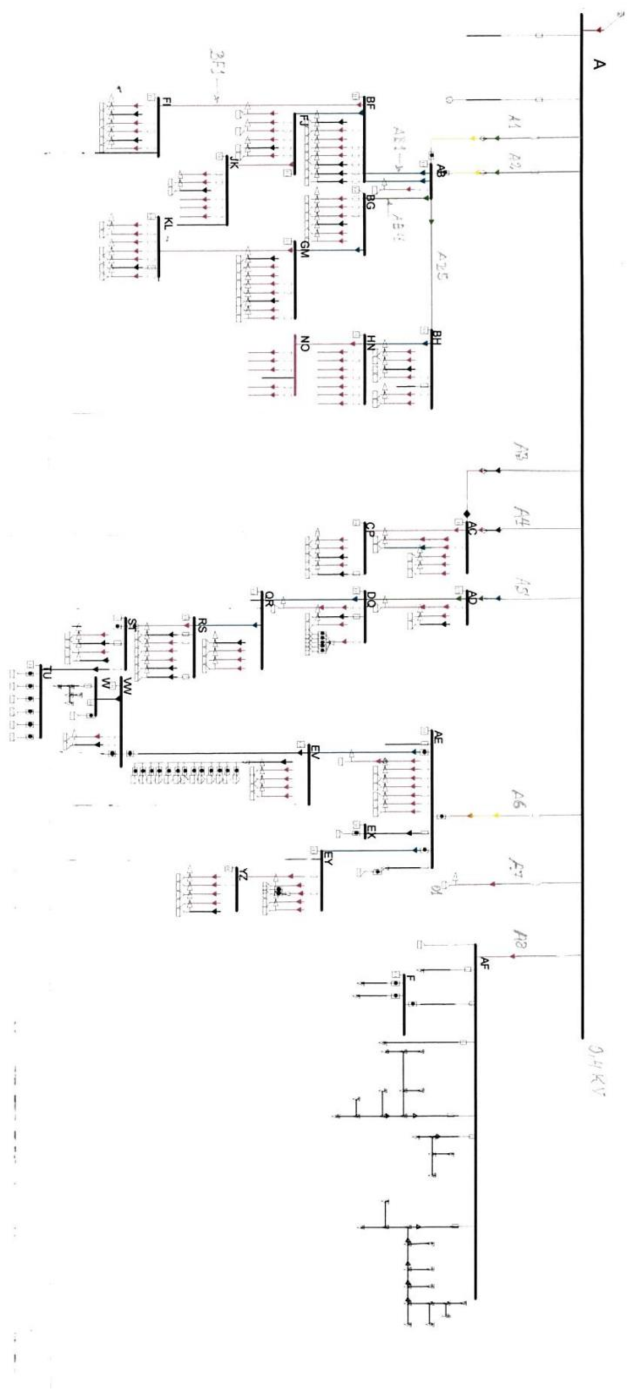

Figure A1. Diagram of the investigated system.

Appendix B – Active power consumption for a day in January, May and October for the investigated area on Gotland.

In Table B1 the active power values used for the whole investigated system are presented. The power was measured in 2016 and are presented in MW (Megawatts). These values are also shown in Figure 3, yet in that diagram the values have been normalized by the mean value of the day in October. The data were provided by GEAB.

Table B1. Active power consumption of the investigated low- voltage power system on Gotland for one day in January, May and October.

Hour	January [MW]	May [MW]	October [MW]
1	1,314	0,576	0,676
2	1,277	0,567	0,665
3	1,277	0,567	0,665
4	1,296	0,576	0,676
5	1,332	0,623	0,731
6	1,442	0,743	0,873
7	1,624	0,864	1,014
8	1,807	0,901	1,058
9	1,825	0,911	1,069
10	1,788	0,929	1,091
11	1,788	0,911	1,069
12	1,77	0,901	1,058
13	1,734	0,883	1,036
14	1,697	0,864	1,014
15	1,697	0,846	0,992
16	1,697	0,799	0,938
17	1,715	0,79	0,927
18	1,734	0,79	0,927
19	1,752	0,78	0,916
20	1,715	0,78	0,916
21	1,642	0,762	0,894
22	1,569	0,725	0,851
23	1,478	0,65	0,763
24	1,369	0,595	0,698
Total	**38,339**	**18,333**	**21,517**

Appendix C – Script for finding days that would represent each case

This appendix presents the code used to determine which days of the year that best represents days where the system has a high load, low load and average load.

```
#-*- coding: latin-1 -*-
# Function that imports values from a cell in a .xlsx-sheet.
def XLread(XL_file,XL_sheet,cell,row,col): #x,y - offset from cell
   Value=xlApp.Workbooks(XL_file).Worksheets(XL_sheet).Range(cell).Offset(row+1,col+1).Value
   return Value

#Imports necessary functions used in the script.
import sys
from os import getcwd, path
from win32com.client import Dispatch

#Code for opening the .xlsx-file.
xlApp = Dispatch("Excel.Application")
XL='GotlandDailyConsume.xlsx' #Name of the .xlsx file to read data from
cwd=getcwd()
XL_path=path.join(cwd,XL)      #Creates the full xlsx-file
xlApp.DisplayAlerts= False
xlApp.Workbooks.Open(XL_path)

# Reads and imports data from MS Excel to Python.
N_Cells=17544 # Number of cells to import.
CheckSim=N_Cells/8 #Variable to check the progress of the data import.
ConsumeHour=[]

#Loop that imports the  hourly power data.
for j in range(N_Cells):
   ConsumeHour.append(XLread(XL,'Blad1','C3',j,0)/1000)
   if len(ConsumeHour) % CheckSim == 0: #If-statement that prints out the progress on the data
import process.
      print str(len(ConsumeHour)*100/N_Cells) + " % have been imported to Python."
   elif len(ConsumeHour) == len(range(N_Cells)):
      print "\nAll values have been imported from MS Excel. \n"

#Calculate the average power counsumption for the whole data set.
MeanConsumeHour=sum(ConsumeHour)/len(ConsumeHour)
RelMeanConsumeHour=MeanConsumeHour/max(ConsumeHour)

#Creates a loop which sums up the hourly data to days, and tag them with the correct day.
Loop=1
k=0
CD={}
Days=[]
while Loop==1:
   start=0 + 24*k
   end= 24 + 24*k
   Day=str((XLread(XL,'Blad1','A3',start,0)))
```

```
    Days.append(Day)
    CD[Day]=(sum(ConsumeHour[start:end]))
    k=k+1

    if end>= len(range(N_Cells)):
        Loop=0

#Find the day which has the highest power consumption, and obtain the day and value.
#Also runs a quick check to see if more than one day has the maximum value.
MaxDay=max(CD,key=CD.get)
MaxV=CD.pop(MaxDay) #Extracts the maxiumum Value.

if MaxV==CD[max(CD,key=CD.get)]:
    print "More than one day has the maximum value. \n"

else:
    print "There's just one day with the maximum value. \n"
    print "The day with the highest power consumption is " + MaxDay + ",\nwith a power consumption
of " + str(MaxV) + " MWh."
CD[MaxDay]=MaxV

#Find the day which has the lowest power consumption, and obtain the day and value.
#Also runs a quick check to see if more than one day has the minimum value.
MinDay=min(CD,key=CD.get)
MinV=CD.pop(MinDay)
MinDay2=min(CD,key=CD.get) #Upon investigation, the day with the lowest power counsumption
had an odd value.
                            #Therefore the second value was considered better for simulations.
MinV2=CD.pop(MinDay2)
if MinV==MinV2:
    print "More than one day has the minimum value. \n"

else:
    print "\nThere's just one day with the minimum value. \n"
    print "The day with the lowest power consumption is " + MinDay2 + ",\nwith a power consumption
of " + str(MinV2) + " MWh."
CD[MinDay]=MinV

#Creates an average for each hour based on every hourly data.
AverageDay=[0] * 24
HourDay=[0]*(len(ConsumeHour)/24)
ErrorDay=[0]*(len(ConsumeHour)/24)
for i in range(24): #Loop for every hour of a day.
    for m in range(len(ConsumeHour)/24): #Loop for every day investigated.
        HourDay[m]=(ConsumeHour[i+m*24])
        HourMean=sum(HourDay)/len(HourDay) #Calculate the average power conusmption for every
hour.
        ErrorDay[m]+=(HourMean-HourDay[m])**2 #Calculate the total sqared error for every day.

    AverageDay[i]=HourMean
```

```
AverageDayConsume=sum(AverageDay) #Calculate the total power consumption during the whole
average day.

#If-statement that make sure that the grouping into days are the same as the total amount of days in the
imported data.
if len(ErrorDay)==len(Days):
   Day2Error={}
   for n in range(len(Days)): #Matches the error with its corresponding day.
      Day2Error[Days[n]]=ErrorDay[n]
else:
   print "The amount of days and errors do NOT match!"

#Find the days with the smallest error, and also extracts the corresponding error-value.
#In addition
ClosestAverageDay=min(Day2Error,key=Day2Error.get)
MinError=Day2Error.pop(ClosestAverageDay)
if MinError==Day2Error[min(Day2Error,key=Day2Error.get)]:
   print "More than one day is closest to the average day. \n"

else:
   print "\nThere's just one day with the minimum value. \n"
   print "The day with the lowest squared error is " + ClosestAverageDay + ",\nwith a total squared
error of " + str(MinError)+"."

#Calculates values used for presenting the findings from the script.
Day2Error[ClosestAverageDay]=MinError
PowerDiff=CD[ClosestAverageDay]-AverageDayConsume
PowerDiffRel=PowerDiff/AverageDayConsume
print "The total error in MWh between the average day and " + ClosestAverageDay + " is " +
str(PowerDiff) + " MWh,"
print "which is equal to " + str(PowerDiffRel*100) + " % of the power consumption of an average day.
(" + str(AverageDayConsume) +" MWh.)"

print "The mean power for Gotland during a year is approximately " + str(RelMeanConsumeHour) + "
% of the maximum annual power."

xlApp.Quit() #Closes MS Excel-application.
print '\nDone!'
```

Appendix D – Hourly energy consumption of Gotland 2015/2016

This appendix presents the data of the hourly energy consumption for all of Gotland during the years 2015 and 2016. However, these data consist of more than 17 000 data point, and to present all of them and still make it readable requires more than 100 pages. Therefore, only a fragment of the data will be presented in order to visualize how the data were structured. The fragment of the consumption data of Gotland during 2015 and 2016 is presented in Table D1. These data were mainly used for determining what days that could best would represent cases when the load was very low, very high or close to a regular load profile for the power grid of Gotland. For the full set of data, it is recommended to contact Vattenfall AB or GEAB.

Table D1. A small part of the data for the power consumption for Gotland. The values are in kWh.

Time and Date	Energy Consumption [kWh]
01/01 2015	110628,3
Hour 02	109181,42
Hour 03	108222,72
Hour 04	109138,28
Hour 05	109441,09
Hour 06	112438,93
Hour 07	116211,35
Hour 08	119206,52
Hour 09	119147,89
Hour 10	122347,1
Hour 11	121842,14
Hour 12	123477,15
Hour 13	122973,18
Hour 14	121693,88
Hour 15	122767,52
Hour 16	127101,12
Hour 17	129203,73
Hour 18	131093,38
Hour 19	128295,23
Hour 20	125817,93
Hour 21	122332,4
Hour 22	118845,03
Hour 23	113948,09
Hour 24	111673,94
02/01 2015	108951,02
Hour 02	108314,89
Hour 03	107458,72
Hour 04	107914,32
Hour 05	109317,91
Hour 06	112135,71
Hour 07	118781,19
Hour 08	123451,73
Hour 09	127933,55

Appendix E – Estimated power ratings of cable types

This appendix presents the rating set for the conductors in the system. In this study an assumption was made that all conductors of the same cable type also had the same power rating. The values for the power rating were based on the knowledge that, according to GEAB, most conductors usually had a strain between 40 and 50 percent of their maximum capacity during normal operating conditions. The power rating values for all cable types were estimated by first doing a simulation where all power rating was set to 1. The calculated strains from the simulations were then sorted by cable type and examined further. The power ratings were than manipulated by two rules. If any of the strain was close to 100 percent, close to overloading, the power rating was increased with a factor that created strain levels closer to 50 percent. Also, if a large share of the strains of a cable type was much lower than 50, the power rating was decreased to an appropriate level. In some cases, these two rules interfered with each other. For instance, some cable types had a large variance in how much power they were distributing in the system. This resulted in either a few very large power strains or many unreasonably low power strains on the conductors, depending if the power ratings were set low or high. Since it was unreasonable that the power system would have a strain close to 100 % for a few cables, the first rule to dampen high power strains was favoured over the second rule during interference. The estimated values used for the power ratings are presented in Table E1.

Table E1. Power ratings for all conductors used in the simulations. The values are presented for each cable type.

Cable Type	Power rating [MVA]
AKKJ 3X120/50	0,78423850
AKKJ 3X240/72	0,29489650
AKKJ 4X50/16	0,01804100
AKKJ 4X95/29	0,08618838
AXQJ 4X50/29	0,04001650
ECJJ3X10/10	0,03059300
EKKJ 3X10/10	0,06193961
FKJJ 3X35/16	0,02257117
FKKJ 3X16/16	0,07539600
FKKJ 3X35/25	0,15628640
FKKJ 3X70/35	1,16500500
N1XV-R4G16	0,09386088

Appendix F- Script for simulations and PSSE/ Excel interactions

In this appendix the code used for importing data from .xlsx-file and run them in a PSSE-model is presented.

```
#-*- coding: latin-1 -*-

#IMPORTANT NOTE! In order for the script to function properly,
#please put all PSSE-files(.raw,.sav and so on...) and .xlsx-files in the same folder as this script!

#Adds the psspy and excelpy functions. This function shows which library to search for the functions.
#The redirect.psse2py just let's you see everything that happends in the python-code instead of pop
ups, which is nice.
def PSSEpaths():
    from sys import path
    from os import environ

    _PSSBINPATH = r"C:\Program Files (x86)\PTI\PSSE33\PSSBIN"
    environ['PATH'] = _PSSBINPATH + ';' + environ['PATH']
    path.insert(0,_PSSBINPATH) #sys.path, not os.path
    import redirect, psspy, excelpy
    redirect.psse2py()
    return psspy, excelpy

#Function that starts PSSE and sets _i,_f and _s as defult variables.
def startpsse33():
    psspy.psseinit(buses=80000)
    _i = psspy.getdefaultint()
    _f = psspy.getdefaultreal()
    _s = psspy.getdefaultchar()

    return _i, _f, _s

#Function that opens a .case-file in PSSE.
def Work_Case(PSSE_case):
    Case=path.join(cwd,PSSE_case) #PSSE-case you want to open.
    psspy.case(Case)
    print "The current PSSE case: " + PSSE_case + "\n with path: \n" + Case


#Sets up global parameters.
def lfsetup():
    global _i, _f, _s

#Function that simulates the PSSE-model.
def doLF():
    ierr = psspy.fnsl([1,0,0,1,1,0,99,0]) #With Tap Changers och VAR-limitations
    return ierr

#Sets up the set up the V2G in the system.
```

```
def V2G(V2GBuses, hour,CountBus):
    #If-statements that decides at which hours the electric vehicles are charging or utilizing V2G.
    #The values for Rate are stated in MW.
    Rate=0.0036 #In MW
    if 0<hour<=5 or 21<hour<=24:
        Charge_rate= Rate
    else:
        Charge_rate=0

    if 5<hour<=8 or 18<hour<=20: # V2G will be active during 5to8 and 18to20, a total of 5 hours. The point is when an hour has ended.
        Discharge_rate= Rate*0.7
    else:
        Discharge_rate=0

    if hour==21:
        Discharge_rate=0 #Neither charge or V2G at 21.

    #Currenlty some buses are unable to be integrated with a V2G subsystem without finding a convering solution.
    #Therefore, these buses needs to be filtered out to create a vector that only includes buses with a V2G subsystem connected to them.
    FilterBus=[]
    for key in CountBus:
        if CountBus[key]>1:
            FilterBus.append(key)

    Extrafilter=[1402, 1403, 1404, 4172, 4173, 4174,17182,17183,17184,17185,18192,18193,18194,18195,18196,18197]
    FilterBus+=Extrafilter
    for bus in FilterBus:
        V2GBuses=filter(lambda w: w!=bus, V2GBuses)

    #Changes the V2G subsystem to either act as a load or a generator.
    Generators=[]
    GeneratorBus=30000
    hCheck=[]
    hCheck.append(hour)
    #Adds a load and generator representing EVs at the bus. It also adds a generator bus (with busnumber +1000) and branch.
    for x in V2GBuses:
        GeneratorBus=GeneratorBus+1 #Creates a bus for the generator which is has the same busnumber as the original bus and a zero added afterwards
        Generators.append(GeneratorBus)
        psspy.load_chng_4(x,'C',[_i,_i,_i,_i,_i,_i],[ Charge_rate,_f,_f,_f,_f,_f])
        psspy.machine_chng_2(GeneratorBus,'D',[_i,_i,_i,_i,_i,_i],[ Discharge_rate,_f, 0, 0,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f])

    return Generators, Charge_rate,Discharge_rate
#Sets up the names for the .xlsx files used for import and export of data.
```

```
# Lastly it adds paths for the functions which acually import and export data between MS Excel and PSSE.
def GetXLfiles(XL_input,XL_output, XLV_output, XLC_output, DoV2G):
    from win32com.client import Dispatch
    from os import getcwd

    xlApp = Dispatch("Excel.Application")
    cwd=getcwd()
    cwd_output=path.join(cwd,'OutputData')
    print cwd +'\n'
    XL_input_path=path.join(cwd,XL_input)               #Start xlsx-file.
    XL_output_path=path.join(cwd_output,XL_output)       #Target xlsx-file.
    XLV_output_path=path.join(cwd_output,XLV_output)
    XLC_output_path=path.join(cwd_output,XLC_output)
    print "Data will be imported from " + XL_input_path + '\n'
    print "Outputs will be written to file " + XL_output_path + '\n'
    xlApp.DisplayAlerts= False #MS Excel will now not show any warnings, for example if you want to save before quitting the program.
    xlr=excelpy.workbook(XL_input_path, mode='r')

    #If-statement for the name of the sheet in the .xlsx-file, depending if the system tested with V2G or not.
    if DoV2G==1:
        xlw=excelpy.workbook(XL_output_path, sheet='V2G Hour '+ str(hour),overwritesheet= False, mode='w')
        xlwV=excelpy.workbook(XLV_output_path, sheet='V2G Voltages', overwritesheet=True, mode='w')
        xlwC=excelpy.workbook(XLC_output_path, sheet='V2G Capacity', overwritesheet=True, mode='w')
    else:
        xlw=excelpy.workbook(XL_output_path, sheet='NoV2G Hour '+ str(hour),overwritesheet= False, mode='w')
        xlwV=excelpy.workbook(XLV_output_path, sheet='NoV2G Voltages', overwritesheet=True, mode='w')
        xlwC=excelpy.workbook(XLC_output_path, sheet='NoV2G Capacity', overwritesheet=True, mode='w')
    return xlr, xlw, cwd, xlApp, xlwV, xlwC


#Sets up headning and strucutre for the .xlsx file you want to export the PSSE-data to.
def XL_Export():
    xlw.set_cell('a1','Buses')
    xlw.set_cell('b1', 'Voltages in PU')
    xlw.set_cell('d1', 'Load Buses')
    xlw.set_cell('e1', 'ID')
    xlw.set_cell('i1', 'Branch Buses (FROM)')
    xlw.set_cell('j1', 'Branch Buses (TO)')
    xlw.set_cell('k1',' Branch Buses Name')
    xlw.set_cell('l1', 'Branch Active Power Flow [MW]')
    xlw.set_cell('m1', 'Branch Reactive Power Flow [MVAr]')
    xlw.set_cell('n1', 'Branch Complex Power Flow [MVA]')
```

```
    xlw.set_cell('o1', 'Percentage of Rated power limit [%]')

    #Finds and reads the data from PSSE.
    ierrA, buses = psspy.abusint(-1, string="NUMBER")
    ierrB, volts = psspy.abusreal(-1, string="PU")
    ierrC, loadbuses= psspy.aloadint(-1, string="NUMBER")
    ierrD, ID_load=psspy.aloadchar(-1, string="ID")
    ierrG, branch_from=psspy.abrnint(-1, string= "FROMNUMBER")
    ierrH, branch_to=psspy.abrnint(-1, string= "TONUMBER")
    ierrI, branch_name=psspy.abrnchar(-1, string="TONAME")
    ierrJ, active_power_branch= psspy.abrnreal(-1, string ="P")
    ierrK, reactive_power_branch= psspy.abrnreal(-1, string ="Q")
    ierrL, complex_power_branch= psspy.abrnreal(-1, string ="MVA")
    ierrM, pctrating=psspy.abrnreal(-1,string="PCTRATE")

    # Exports the data from PSSE to MS Excel.
    xlw.set_range(2,'a',zip(*buses))
    xlw.set_range(2,'b',zip(*volts))
    xlw.set_range(2,'d',zip(*loadbuses))
    xlw.set_range(2,'e',zip(*ID_load))
    xlw.set_range(2,'i',zip(*branch_from))
    xlw.set_range(2,'j',zip(*branch_to))
    xlw.set_range(2,'k',zip(*branch_name))
    xlw.set_range(2,'l',zip(*active_power_branch))
    xlw.set_range(2,'m',zip(*reactive_power_branch))
    xlw.set_range(2,'n',zip(*complex_power_branch))
    xlw.set_range(2,'o',zip(*pctrating))

    xlw.save() #Saves the data in the .xlsx-file.

    print "New data has been saved in: " + XL_out
    return buses, volts, loadbuses, pctrating, branch_to

#This function does also export data to an .xlsx-file just like EL_Export.
#The difference is that XL_Export sorts the data by hour, while CollectData stores the data by catagory.
#Sorting by category, such as voltage levels or strain, made it simple to analyze the data.
#In addition, this cuntion also calculates the mean, maximum and minimum values for every hour and export them to an .xlsx-file.
def CollectData(alphabet, hour, VOLTS, PCTRATING, branch_to, volts, pctrating, steps,buses, Generators):
    if hour==1:
        Extras=['','Hour','Mean','Min','2nd Min',' 3rd Min','Max','2nd Max', '3rd Max']
        VOLTS.append(buses)
        VOLTS[0][0] +=Extras
        PCTRATING.append(branch_to)
        PCTRATING[0][0] +=Extras

    #Compile all outputs for strain in one list of multiple lists.
    PCTRATING.append(pctrating)
    ModRate=sorted(filter(lambda M: M!=0, PCTRATING[hour][0]))
```

```
    OutRate=['',hour,sum(ModRate)/len(ModRate), ModRate[0], ModRate[1], ModRate[2], ModRate[-
1], ModRate[-2], ModRate[-3]]
    PCTRATING[hour][0] += OutRate

    #Compile all outputs for voltage levels in one list of multiple lists.
    VOLTS.append(volts)
    if Generators!=0: #Only have to do this when V2G is tested, which is the same as Generators not
being equal to 0.
        CutGen=VOLTS[hour][0][:len(VOLTS[hour][0])-len(Generators)-1) #Removes the generator
buses, only the original buses are included.
        CutGen.append(VOLTS[hour][0][-1])
        ModVolt=sorted(CutGen)

    else:
        ModVolt=sorted(VOLTS[hour][0])

    OutVolt=['', hour,sum(ModVolt)/len(ModVolt), ModVolt[0], ModVolt[1], ModVolt[2], ModVolt[-
1], ModVolt[-2], ModVolt[-3]]
    VOLTS[hour][0]+= OutVolt

    #If-statment that export the data to an .xlsx-file when all simulations are finished.
    if hour==steps:
        print '\n Collecting data...   \n'
        for key in range(hour+1):
            xlwC.set_range(2,alphabet[key],zip(*PCTRATING[key]))
            xlwV.set_range(2,alphabet[key],zip(*VOLTS[key]))

            xlwC.save()
            xlwV.save()

    return VOLTS, PCTRATING


#Closes Excel and the .xlsx- files, otherwise otherwise these will be active after the simulations are
finished.
def Close_XL():
    xlw.close()
    xlr.close()
    xlwV.close()
    xlwC.close()
    xlApp.Quit()

#Changes the values for the loads.
def Insert_Load(Buses,ID,P,Q):
    for index in range(len(Buses)):
        psspy.load_chng_4(Buses[index],str(ID[index]),[_i,_i,_i,_i,_i,_i],[P[index],Q[index],_f,_f,_f,_f])


#THE SCRIPT STARTS HERE.
#Imports time and date to see how long the simulation take, and also for creating the name for the
.xlsx-files for the output data.
```

```
import time
from datetime import datetime
start_time = time.time()

#Additional text which are added in the name .xlsx-files for the output data.
AddInfoFile=raw_input('Please write any extra data for output file here, for example
TEST/V2G/noV2G etc: ')
'
Runs=[0,1] #List where 1 means V2G is active, while 0 means it the original system.

#For- loop that states which load case is investigated.
for Scenario in ['January','May','October']:
    Date=datetime.now().strftime('%Y-%m-%d %H-%M-%S') #Import the current data in a certain
format. Used in names for .xlsx-files of output data.

    #If-statement that what input data will be used, based on which load case that are investigated.
    if Scenario=='January':
        print 'The simulations will be based on the data for ' + Scenario
        SheetP=3
        SheetQ=4
        ChooseScenario=1
    elif Scenario == 'May':
        print 'The simulations will be based on the data for ' + Scenario
        SheetP=5
        SheetQ=6
        ChooseScenario=1
    elif Scenario == 'October':
        print 'The simulations will be based on the data for ' + Scenario
        SheetP=7
        SheetQ=8
        ChooseScenario=1
    else:
        print 'Wrong input of scenario, please choose between January/May/October.'
        Scenario=raw_input('Please choose scenario (January/May/October): ')

    #Simulates with and without V2G.
    for DoV2G in Runs:
    #Input strings for the simulations.
        XL_in='LoadInData'+'.xlsx'       # Name of .xlsx file you want to import data from.
        XL_out= str(Date)+ ' All OutData '+ Scenario +' '+AddInfoFile+ '.xlsx'        # Name of .xlsx file
you want to export data from PSSE to.
        XLV_out= str(Date)+ ' OutData Voltages '+ Scenario +' '+AddInfoFile+ '.xlsx'
        XLC_out= str(Date)+ ' OutData Capacity '+ Scenario +' '+AddInfoFile+ '.xlsx'

        #Defines what PSSE-model that should be used, depending on if V2G is tested or not.
        if DoV2G==1:

            PSSE_case='InPSSE'+'.sav'
            print 'The file used is ' + PSSE_case

        else:
```

```
            PSSE_case='InPSSE_noV2G'+'.sav'
            print 'The file used is ' + PSSE_case

        #Creates lists where data will be stored for the CollectData-function.
        VOLTS=[]
        PCTRATING=[]

        #Sets up PSSE and simulation conditions.
        psspy, excelpy = PSSEpaths()
        from os import path
        _i,_f,_s = startpsse33()
        lfsetup()
        first=0 #Index that starts some extra code during the first simulation.
        steps=24 #Number of times the simulatons should be done for each load case, in this case 24
since its for 24 hours.

        from collections import Counter #Used to identify buses with multiple loads. These could not
handle the V2G subsystem being integrated to them.

        #Loop that runs all simulations defined earlier.
        for hour in range (steps):
            hour+=1 #Range(steps) starts at 0 and ends at 23, so 1 is added as a correction.
            xlr, xlw, cwd, xlApp, xlwV, xlwC = GetXLfiles(XL_in,XL_out,XLV_out,XLC_out, DoV2G)
#Returns functions used for data import/export.

            #Import data of identification, active power and reactive power for all loads in the original
system.
            LoadBus=xlr.get_range((3,3,151,3), transpose=True, sheet=SheetP)
            PowerP=xlr.get_range((3,hour+3,151,hour+3), transpose=True, sheet=SheetP)
            PowerQ=xlr.get_range((3,hour+3,151,hour+3), transpose=True, sheet=SheetQ)
            print ('Data imported')

            #Scales and format the data to fit the PSSE-model
            for i in range(len(LoadBus)):
                LoadBus[i]=int(LoadBus[i]) #Float into an integer.
                PowerP[i]=PowerP[i]/1000 #From kW to MW
                PowerQ[i]=PowerQ[i]/1000 #From kW to MW.

            # If-statement that filters out buses that had multiple loads connected to them.
            if first==0:
                IDLoad=[1]*len(LoadBus)
                CountLoad=Counter(LoadBus)
                for key in CountLoad:
                    if CountLoad[key]>1:
                        for b in range(CountLoad[key]):
                            IDLoad[LoadBus.index(key)+b]=b+1


            Work_Case(PSSE_case) #Opens a PSSE model.
            Insert_Load(LoadBus,IDLoad,PowerP,PowerQ) #insert new values for the loads at their
corresponding buses.
```

```
        #If-statment that includes the V2G-function if V2G is tested.
        if DoV2G==1:
            Generators,Charge, Discharge =V2G(LoadBus, hour,CountLoad) #Changes the values of the generators and loads in the V2G subsystems.

        else:
            Generators=0

        doLF() #Simulates the model
        psspy.save(PSSE_case) #Saves the current simulation

        import string
        alph=list(string.ascii_lowercase)
        buses, volts, loadbuses, pctrating, branch_to= XL_Export() #Export data sorted by hour.
        print "\nSimulations for Hour: " + str(hour)+ " Completed.\n"
        VOLTS, PCTRATING = CollectData(alph,hour,VOLTS,PCTRATING, branch_to, volts, pctrating, steps,buses, Generators) #Exports data by category.
        Close_XL() #Closes Excel-applications, otherwise these will be active after the simulations are finsihed.
        first=1 #Changes so only code that only should run first time are not repeated.

#The simulation is finished!
print ('\n THE SIMULATION IS FINISHED!')
elapsed_time = time.time() - start_time
print time.strftime("%H:%M:%S", time.gmtime(elapsed_time))

raw_input('\nPress Enter to continue.')


### Code that might be useful, but are not in the simulations ###
#This code was used to add the V2G subsystems. If one wants to add it to an system that do not currenlt have V2G, this can be inserted into the V2G-function.
#However, make sure to only make one V2G-simulation (for example: Runs=1, Steps=1 and Scenario=October)
##      psspy.load_data_4(x,'C',[_i,_i,_i,_i,_i,_i],[ Charge_rate,_f,_f,_f,_f,_f])
##      psspy.bus_data_3(GeneratorBus,[2,_i,_i,_i],[0.4,_f,_f,_f,_f,_f,_f],_s) #Used to add a generator bus for each load bus first time to build the grid.
##
psspy.branch_data(x,GeneratorBus,r"""1""",[_i,_i,_i,_i,_i,_i],[_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f])# Same as above, just used the first time for setup.
##      psspy.plant_data(GeneratorBus,0,[ 1.0, 100.0])
##
psspy.machine_data_2(GeneratorBus,'D',[_i,_i,_i,_i,_i,_i],[_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f])
```

Appendix G – Output values from simulations

This appendix presents the values used in the figures for strain and voltage levels, which was obtained from simulating the system models. Here are the exact values used in the graphs presented in the results section of the report. Every table is presented with two sets of data, one data set from simulating the reference model and one from simulating the V2G-integrated model. The data sets are separated with a black line in each table. The data on the left side of the black line are values from simulations using the reference system, while the right side are values from simulations when the V2G system was used. The values are presented in Table G1, Table G2, Table G3, Table G4, Table G5 and Table G6.

Table G1. Mean, maximum and minimum strain on the conductors in the reference system (left of black line) and V2G system (right of black line) during January. The values are also illustrated in Figure 10.

Hour	Mean	Min	Max		Hour	Mean	Min	Max
1	29,675	3,217	62,073		1	34,867	3,924	77,159
2	28,803	3,127	60,149		2	33,981	3,831	75,487
3	28,803	3,126	60,149		3	33,981	3,831	75,490
4	29,252	3,175	61,137		4	34,436	3,881	76,339
5	30,104	3,267	63,020		5	35,299	3,975	77,949
6	32,726	3,552	68,848		6	29,130	3,064	68,667
7	37,118	4,027	78,767		7	33,480	3,532	78,546
8	41,609	4,513	89,123		8	37,921	4,012	88,855
9	42,055	4,561	90,164		9	42,054	4,559	90,164
10	41,139	4,462	88,028		10	41,140	4,462	88,028
11	41,140	4,462	88,028		11	41,140	4,462	88,028
12	40,695	4,414	86,996		12	40,695	4,414	86,996
13	39,809	4,318	84,943		13	39,809	4,318	84,943
14	38,901	4,220	82,850		14	38,901	4,220	82,850
15	38,901	4,220	82,850		15	38,901	4,220	82,850
16	38,901	4,220	82,850		16	38,901	4,220	82,850
17	39,342	4,268	83,866		17	39,342	4,268	83,866
18	39,809	4,318	84,943		18	39,809	4,318	84,943
19	40,252	4,366	85,967		19	36,583	3,868	85,715
20	39,342	4,268	83,866		20	35,681	3,769	83,623
21	37,557	4,075	79,768		21	37,555	4,075	79,768
22	35,784	3,883	75,732		22	41,055	4,602	88,602
23	33,589	3,645	70,782		23	38,831	4,360	84,500
24	30,984	3,363	64,967		24	36,192	4,072	79,606

Table G2. Mean, maximum and minimum strain on the conductors in the reference system (left of black line) and V2G system (right of black line) during May. The values are also illustrated in Figure 11.

Hour	Mean	Min	Max	Hour	Mean	Min	Max
1	12,686	1,381	25,754	1	34,867	3,924	44,673
2	12,479	1,355	25,348	2	33,981	3,831	44,212
3	12,479	1,355	25,348	3	33,981	3,831	44,212
4	12,681	1,376	25,766	4	34,436	3,881	44,603
5	13,737	1,491	27,958	5	35,299	3,975	46,646
6	16,447	1,786	33,622	6	29,130	3,064	33,550
7	19,204	2,085	39,436	7	33,480	3,532	39,349
8	20,052	2,177	41,236	8	37,921	4,012	41,143
9	20,282	2,202	41,724	9	42,054	4,559	41,724
10	20,695	2,247	42,604	10	41,140	4,462	42,604
11	20,282	2,202	41,724	11	41,140	4,462	41,724
12	20,052	2,177	41,236	12	40,695	4,414	41,236
13	19,640	2,132	40,359	13	39,809	4,318	40,359
14	19,204	2,085	39,436	14	38,901	4,220	39,436
15	18,793	2,040	38,564	15	38,901	4,220	38,564
16	17,721	1,924	36,300	16	38,901	4,220	36,300
17	17,516	1,901	35,868	17	39,342	4,268	35,868
18	17,516	1,901	35,868	18	39,809	4,318	35,868
19	17,288	1,877	35,389	19	36,583	3,868	35,312
20	17,288	1,877	35,389	20	35,681	3,769	35,312
21	16,879	1,832	34,528	21	37,555	4,075	34,528
22	16,040	1,741	32,766	22	41,055	4,602	51,101
23	14,345	1,557	29,224	23	38,831	4,360	47,822
24	13,107	1,423	26,651	24	36,192	4,072	45,429

Table G3. Mean, maximum and minimum strain on the conductors in the reference system (left of black line) and V2G system (right of black line) during October. The values are also illustrated in Figure 12.

Hour	Mean	Min	Max		Hour	Mean	Min	Max
1	14,931	1,621	30,447		1	19,949	2,299	48,956
2	14,683	1,594	29,929		2	19,699	2,272	48,477
3	14,683	1,594	29,929		3	19,699	2,272	48,477
4	14,931	1,621	30,447		4	19,949	2,299	48,956
5	16,176	1,756	33,051		5	21,207	2,437	51,360
6	19,411	2,107	39,873		6	15,940	1,639	39,784
7	22,656	2,460	46,797		7	19,155	1,986	46,689
8	23,675	2,570	48,990		8	20,165	2,095	48,875
9	23,931	2,598	49,540		9	23,932	2,601	49,540
10	24,442	2,653	50,645		10	24,442	2,653	50,645
11	23,931	2,598	49,540		11	23,930	2,598	49,540
12	23,675	2,570	48,990		12	23,675	2,570	48,990
13	23,165	2,515	47,891		13	23,165	2,515	47,891
14	22,656	2,459	46,797		14	22,656	2,459	46,797
15	22,147	2,404	45,706		15	22,147	2,404	45,706
16	20,902	2,269	43,045		16	20,902	2,269	43,045
17	20,649	2,242	42,506		17	20,649	2,242	42,506
18	20,649	2,242	42,506		18	20,649	2,242	42,506
19	20,397	2,214	41,968		19	16,917	1,744	41,874
20	20,397	2,214	41,968		20	16,917	1,744	41,874
21	19,892	2,159	40,894		21	19,891	2,160	40,894
22	18,907	2,053	38,806		22	23,968	2,738	56,618
23	16,902	1,835	34,576		23	21,940	2,517	52,757
24	15,429	1,675	31,486		24	20,452	2,354	49,917

Table G4. Mean, maximum and minimum voltage levels of the original buses in the reference system (left of black line) and V2G system (right of black line) during January. The values are also illustrated in Figure 13.

Hour	Mean	Min	Max		Hour	Mean	Min	Max
1	0,960	0,899	1,000		1	0,955	0,893	1,000
2	0,961	0,902	1,000		2	0,956	0,896	1,000
3	0,961	0,902	1,000		3	0,956	0,896	1,000
4	0,960	0,900	1,000		4	0,956	0,894	1,000
5	0,959	0,897	1,000		5	0,954	0,891	1,000
6	0,956	0,887	1,000		6	0,959	0,891	1,000
7	0,949	0,871	1,000		7	0,953	0,875	1,000
8	0,943	0,854	1,000		8	0,947	0,858	1,000
9	0,942	0,852	1,000		9	0,942	0,852	1,000
10	0,944	0,855	1,000		10	0,944	0,855	1,000
11	0,944	0,855	1,000		11	0,944	0,855	1,000
12	0,944	0,857	1,000		12	0,944	0,857	1,000
13	0,946	0,861	1,000		13	0,946	0,861	1,000
14	0,947	0,864	1,000		14	0,947	0,864	1,000
15	0,947	0,864	1,000		15	0,947	0,864	1,000
16	0,947	0,864	1,000		16	0,947	0,864	1,000
17	0,946	0,862	1,000		17	0,946	0,862	1,000
18	0,946	0,861	1,000		18	0,946	0,861	1,000
19	0,945	0,859	1,000		19	0,949	0,863	1,000
20	0,946	0,862	1,000		20	0,950	0,867	1,000
21	0,949	0,869	1,000		21	0,949	0,869	1,000
22	0,951	0,876	1,000		22	0,946	0,870	1,000
23	0,954	0,884	1,000		23	0,949	0,878	1,000
24	0,958	0,894	1,000		24	0,953	0,888	1,000

Table G5. Mean, maximum and minimum voltage levels of the original buses in the reference system (left of black line) and V2G system (right of black line) during May. The values are also illustrated in Figure 14.

Hour	Mean	Min	Max		Hour	Mean	Min	Max
1	0,983	0,958	1,000		1	0,979	0,953	1,000
2	0,983	0,959	1,000		2	0,979	0,954	1,000
3	0,983	0,959	1,000		3	0,979	0,954	1,000
4	0,983	0,958	1,000		4	0,979	0,953	1,000
5	0,982	0,955	1,000		5	0,977	0,949	1,000
6	0,978	0,945	1,000		6	0,981	0,949	1,000
7	0,974	0,936	1,000		7	0,978	0,940	1,000
8	0,973	0,933	1,000		8	0,976	0,937	1,000
9	0,973	0,932	1,000		9	0,973	0,932	1,000
10	0,972	0,931	1,000		10	0,972	0,931	1,000
11	0,973	0,932	1,000		11	0,973	0,932	1,000
12	0,973	0,933	1,000		12	0,973	0,933	1,000
13	0,974	0,934	1,000		13	0,974	0,934	1,000
14	0,974	0,936	1,000		14	0,974	0,936	1,000
15	0,975	0,937	1,000		15	0,975	0,937	1,000
16	0,976	0,941	1,000		16	0,976	0,941	1,000
17	0,977	0,942	1,000		17	0,977	0,942	1,000
18	0,977	0,942	1,000		18	0,977	0,942	1,000
19	0,977	0,942	1,000		19	0,980	0,946	1,000
20	0,977	0,942	1,000		20	0,980	0,946	1,000
21	0,977	0,944	1,000		21	0,977	0,944	1,000
22	0,979	0,947	1,000		22	0,974	0,941	1,000
23	0,981	0,953	1,000		23	0,976	0,947	1,000
24	0,983	0,957	1,000		24	0,978	0,952	1,000

Table G6. Mean, maximum and minimum voltage levels of the original buses in the reference system (left of black line) and V2G system (right of black line) during October. The values are also illustrated in Figure 15.

Hour	Mean	Min	Max	Hour	Mean	Min	Max
1	0,980	0,951	1,000	1	0,976	0,945	1,000
2	0,980	0,951	1,000	2	0,976	0,946	1,000
3	0,980	0,951	1,000	3	0,976	0,946	1,000
4	0,980	0,951	1,000	4	0,976	0,945	1,000
5	0,978	0,946	1,000	5	0,974	0,941	1,000
6	0,974	0,935	1,000	6	0,977	0,939	1,000
7	0,970	0,924	1,000	7	0,973	0,928	1,000
8	0,968	0,920	1,000	8	0,971	0,924	1,000
9	0,968	0,919	1,000	9	0,968	0,919	1,000
10	0,967	0,917	1,000	10	0,967	0,917	1,000
11	0,968	0,919	1,000	11	0,968	0,919	1,000
12	0,968	0,920	1,000	12	0,968	0,920	1,000
13	0,969	0,922	1,000	13	0,969	0,922	1,000
14	0,970	0,924	1,000	14	0,970	0,924	1,000
15	0,970	0,926	1,000	15	0,970	0,926	1,000
16	0,972	0,930	1,000	16	0,972	0,930	1,000
17	0,972	0,931	1,000	17	0,972	0,931	1,000
18	0,972	0,931	1,000	18	0,972	0,931	1,000
19	0,973	0,932	1,000	19	0,976	0,935	1,000
20	0,973	0,932	1,000	20	0,976	0,935	1,000
21	0,973	0,933	1,000	21	0,973	0,933	1,000
22	0,975	0,937	1,000	22	0,970	0,931	1,000
23	0,977	0,944	1,000	23	0,973	0,939	1,000
24	0,979	0,949	1,000	24	0,975	0,944	1,000