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The Impact on The Power System of Grid-Connected Electric Vehicles

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Abstract

Two ways of decreasing greenhouse gas emissions are using electric vehicles and renewable energy sources. The electrification of the transport sector will lead to a higher electricity demand and could amplify existing peaks in the distribution grid. A larger share of intermittent energy sources can cause a mismatch between consumption and production, which then requires back-up power which can increase the electricity price and greenhouse gas emissions. In recent years, a new concept called vehicle-to-grid has been developed. The idea is that the battery of electric vehicles can be used to supply the grid with power when needed. An ancillary service vehicle-to-grid can be used for is peak shaving by supplying power at times of high power demand, and therefore decreasing the strain on the electric grid. The electric vehicle owners in turn can earn money by allowing their vehicle to be used in vehicle-to-grid by selling electricity when the electricity prices are high. With the increasing number of electric vehicles in the world, and more intermittent renewable energy sources, the potential of vehicle-to-grid becomes larger. In this thesis vehicle-to-grid is modeled and evaluated for 24 hours using 2 cases, the first case is with one household load and one EV, and the second case is with 10 households loads and 10 EVs. Two different driving profiles were used to determine how vehicle-to-grid is dependent on usage patterns. One profile represented a person working from 8 am to 4 pm, and the other profile worked from 9 pm to 5 am. The results showed that the peak shaving potential was high for both types of user profiles in the single load case and the 10 household case. The optimal combination would be to utilize both user profiles at the same time, as one can peak shave while the other one is unavailable and vice versa. The economic revenue from vehicle-to-grid is highly dependent on the electricity price. To maximize the revenue, working from 8 am to 4 pm was the best for the chosen load data, since most peak shaving occurred during the evening. When 24 hours passed, there was still sufficient state of charge for further usage of the electric vehicle.

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Populärvetenskaplig sammanfattning

Samhället står idag inför svåra utmaningar. En av dessa är klimatet, som kontinuerligt påverkas av människornas vanor. Utsläpp av växthusgaser bidrar till uppvärmning av jorden, vilket i sin tur kan leda till stora problem för mänskligheten. Dessa konsekvenser är till exempel torka, skogsbränder, tillgång till sötvatten, och förändringar i biodiversitet. För att motverka dessa konsekvenser så krävs det i första hand att mängden växthusgasutsläpp minskar. Flera länder, bland annat länderna i Norden, har åtagit sig att på olika sätt minska deras utsläpp för att uppnå uppsatta klimatmål. En del av dessa klimatmål kan skilja sig smått mellan länderna, men i det stora hela så är målen likadana. Det finns flera sätt att minska växthusgasutsläppen, men det är framförallt två som är relevanta för det här projektet. Det första sättet är att öka mängden förnybar energi och minska energislag som använder sig utav fossila bränslen, som släpper ut växthusgaser vid förbränning. Det kan göras genom att använda mer vindkraft, vattenkraft, och solkraft. Det andra sättet handlar också om att minska förbränning av fossila bränslen, men i ett annat sammanhang, nämligen bilar. De senaste åren så har antalet elbilar ökat, och förväntas fortsätta öka framöver. Bilar med förbränningsmotorer förväntas att fasas ut i Europa vilket ytterligare kan öka mängden elbilar i framtiden.

Problemet med den första lösningen är att vissa förnybara energislag är väderberoende vilket gör det svårt att förutse när de kan producera el. Till exempel, det behöver vara en viss vindhastighet för att vindkraftverk ska producera el, eller sol för att solceller ska göra det. Detta är problematiskt eftersom den el som konsumeras av hushåll, fabriker, skolor och så vidare, måste produceras och finnas tillgänglig vid samma tillfälle. Om det inte finns tillräckligt med el, så kan det leda till, till exempel, strömavbrott, vilket man vill undvika. Att använda väderberoende energikällor kan även leda till osäkerheter i elpriser, som i övrigt har varit höga de senaste åren. Vid Ukrainakrigets start så skenade elpriserna på grund av brist av naturgas, och Europakommissionen vill undvika detta genom att introducera användning av andra energikällor istället.

Den andra lösningen är problematisk eftersom även om den löser ett viktigt problem så finns det möjligheten att den förvärrar ett annat. Elbilar drivs av ett batteri som behöver laddas, precis som att en fossildriven bil behöver tankas. Batteriet laddas med el, och kan göras antingen i hemmet med en speciell laddare, eller utomhus vid dedikerade laddare. Vårt samhälle blir allt mer elektrifierat, det vill säga att vi konsumerar mer och mer el. Elanvändningen förväntas fortsätta att öka kommande årtionden. Problemet med det är att elledningar och kablar bara kan överföra en viss mängd el, vilket innebär att det behöver byggas ut och förnya gamla komponenter. Det kan ta lång tid, och samtidigt vara väldigt dyrt. Elanvändningen är som störst tre gånger under dagen, första är på morgonen när många går upp och startar kaffebryggare, brödrostar och liknande.

Andra är runt lunch när många blir lediga under en kortare period, och den tredje och sista är på kvällen när folk kommer hem från jobbet för att laga mat, ståda, diska, tvätta och så vidare. Vid dessa tillfällen är elnätet särskilt belastat, vilket helst ska undvikas för att inte riskera att skada till exempel en kabel som kan överhettas vid för hög belastning. Det optimala hade varit att ha en jämn och konstant elanvändning under hela dagen för att undvika dessa toppar"i elnätet. Tillbaka till elbilar, om alla som äger en elbil kommer hem vid 17.00 och börjar ladda samtidigt så kan det förvärra redan existerande toppar och skapa fler problem.

Det här projektet handlar om hur elbilar, istället för att bidra till problemen, kan användas för att lösa problemen med stigande elpriser och elektrifieringen som leder till toppar i elnätet. Konceptet heter "vehicle-to-grid" eller på svenska "fordon till elnät", principen med vehicle-to-grid är att använda elbilars batterier för att tillförse elnätet med el. Batteriet laddas alltså ur till elnätet, och laddas inte upp som det vanligtvis gör. Batteriet fungerar därmed som lagring, och kan stötta elnätet vid behov och minska topparna, vilket kallas för "peak shaving" eller på svenska "toppkapning". För att undersöka koncepetet så har en modell skapats, som består av ett elnät, batterier, och hushåll. Data för elanvändning i hushåll har tagits från en studie som gjorts i Norge, och elbilen som har valts är Renault 5 E-tech. Två scenarion undersöktes, det ena med bara ett hushåll och en elbil. Det andra med 10 hushåll och samma antal elbilar. Två användningsprofiler användes, den ena jobbade mellan 08:00 och 16:00 och den andra mellan 21:00 och 05:00. Bägge har en timmes pendling till och från jobbet. Under tiden personen är på jobbet så kan elbilen inte användas för vehicle-to-grid. Modellen fungerar genom att först mäta elanvändningen för hushållet, och om det överstiger en viss gräns så används batteriet för att tillförse el, vilket hade minskat topparna. Eftersom elen från batteriet kostar pengar så behöver elbilsägaren kompenseras för det, och det görs genom att använda elpriser. Alltså om batteriet laddas ut med en viss mängd el så kan ägaren få pengar för det. Detta är viktigt, då det måste finnas någon fördel för ägaren att tillåta sin elbil att användas, då hen inte kan använda elbilen samtidigt.

Resultatet visade att elanvändningen när den är som störst kunde minskas med upp till 50 %. Elanvändning för både det enstaka hushållet, och kvarteret med 10 hushåll, var störst under kvällen. Det innebar att elbilsägarna som jobbade under dagen hade störst potential både för att minska topparna men också för att tjäna pengar. Det optimala hade varit en blandning av användningsprofilerna, då resultatet visar att de kompletterar varandra. Om flera elbilar hade börjat ladda samtidigt med maximal effekt, så hade det kunnat skapa problem för elnätet då belastning blir mycket större än utan elbilar som laddar.

Executive summary

In this project, the concept called vehicle-to-grid (V2G) is investigated, where the idea is that power can be supplied to the grid using the energy stored in electric vehicle (EV) batteries. The main focus is to investigate how V2G can contribute to, and decrease power peaks in the electric grid and if there are any economical benefits.

The potential of V2G was investigated by firstly conducting a literature review, secondly by creating a model of a V2G system, and lastly by running simulations of the created model. The model used two cases with different user profiles and loads to see how they would affect the potential of V2G.

The results showed that V2G can be used for peak shaving when the demand for electricity is high, and were able to reduce the demand by up to 50 % with the potential to reduce it even further. The potential of V2G was dependent on the user profile patterns, and the optimal case found was to have a mix of people working day and night shifts as they have their EV available at opposite times. If the EVs started charging at maximum capacity at the same time, the existing peaks could be amplified by up to 493 % in the worst scenario, which highlighted the importance of smart charging. There were economic benefits for supplying V2G according to the results. However, a deeper analysis of costs related to battery degradation is needed to confirm them, and to determine if any incentives are needed.

Acknowledgement

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Contents

1 Introduction

Human activities that result in greenhouse gases (GHG's) are the single largest reason for Earth's climate change. Between 1990 and 2015, net GHG increased by 44 %. Of total emissions, carbon-dioxide accounts for 75 %, and is emitted primarily by burning fossil fuels such as coal, natural gas, and oil. GHG in the atmosphere results in a warmer climate, which in turn leads to several different changes on our planet [1].

In 2019, the global average temperature reached 1.1°C and 2011 to 2020 was the warmest decade ever recorded. With global warming continuously increasing, there is a fear of what consequences it might bring. An increase of 2°C could result in catastrophic events for the global environment, which is the reason why efforts are being made to limit the global average temperature to 1.5°C [2]. Examples of natural consequences of climate change are more frequent drought and wildfires, availability of fresh water, sea-level rise, floods, changes in biodiversity, and changes in marine environment. There are also social threats, threats to businesses, and territorial threats. These are consequences that are already happening and will only intensify unless climate action is taken [3]. One of the climate actions taken is the Paris Agreement, which is an international treaty in which all European countries have agreed to participate. The main goal of the Paris Agreement is to keep global warming below 1.5°C, and presents a plan of action on how to achieve this [4].

By introducing renewable energy sources (RES) into our electricity mix, and phasing out traditional fossil-fueled power plants like coal and natural gas, which have high GHG emissions [5] the GHG emissions can be reduced. Additionally, since a large part of the GHG emissions come from the transport sector, electrification of the transport sector is becoming more common. For example, in the EU, commercial vans and passenger cars are responsible for 3 % and 16 % respectively of the total CO_2 emissions. The EU also has a goal that all new vans and cars after 2035 will have 0 g CO_2/km [6].

In the last couple of years, the number of electric vehicles (EVs) has increased substantially in the Nordics. By 2030, the number of EVs are expected to reach 4 million which is 15 times the current number of EVs [7]. In Sweden, for example, EVs stood for 32 % of all newly registered cars in 2022. Furthermore, the number of privately owned EVs have increased as well [8]. The EU goal will further increase the amount of EVs with traditional vehicles with combustion engines partially being phased out of production.

Intermittent energy sources, such as wind- and solar power, have played a large role in the transition from fossil fuels to renewable energy. They have almost doubled their share of global electricity generation between 2018 and 2023 [9]. Because wind and solar power is a non-dispatchable source of energy, which means that it can not simply be

turned on to meet any demand of electricity, it should be combined with a dispatchable source of capacity to ensure the stability of the power system, and to ensure that production meets consumption [10]. This is exemplified in the work [11], where the goal was to make solar electricity dispatchable by using, and evaluating, three different energy storage methods: electrochemical (referred to as battery energy storage system or BESS), thermal, and thermophotovoltaic. The results from the study showed that from a technical point of view, BESS has the best balance between dispatchability and yield due to its high round-trip efficiencies, simplicity, and stability. However, the downside is that even with the costs of Li-Ion and LFP (lithium ferrophosphate) having decreased by 97 % since 1991, the costs of electrochemical storage are the main hurdle for massive deployment of this technology [11]. An important aspect with Li-Ion batteries is the fact that producing them has high GHG emissions, because mining and refining the necessary materials requires large amounts of energy. In addition, if they are not properly disposed of, they can end up in landfills and release toxins such as heavy metals into the soil and groundwater [12].

EVs are often more expensive than combustion engine vehicles, and one of the reasons is because EVs are relatively new whereas combustion engine vehicles have been mass-produced for decades. Another reason is due to the costs of Li-ion batteries [13], which is the key obstacle for large-scale implementation according to [11].

In recent years, the concept of vehicle-to-grid (V2G) has emerged. V2G uses EV batteries to supply electricity to the grid when the vehicles are stationary and connected to the grid. Using the EVs as batteries and utilizing bidirectional charging, it is possible to provide electricity to the power grid when needed, thus mitigating the impact of intermittent energy sources [14]. This auxiliary service can be used for different services like peak shaving, voltage regulation, and intermittency reduction [10]. In addition, households can earn money by participating and allowing their EV to be connected to the grid, and selling electricity at times of high demand [15]. These kinds of services will become increasingly more important as the amount of RES in the electric grid increases.

The increase in EVs is not all positive for the power grid. The electrification of vehicles increases the demand for electricity, and if the EV owners have similar driving and/or charging patterns, it could result in peaks at already high load periods if all EVs are charged at the same time. Possible impacts of these peaks are power outages, reduced voltage, and overloaded electrical equipment. To solve this, additional power capacity and investments in the grid would be required to accommodate increasing peaks [10].

1.1 Contextualization

Utilizing V2G has several benefits. Firstly, it can improve the stability of the grid by using voltage and frequency control. Furthermore, it can discharge power during peak demand which decreases the chance of blackouts. Secondly, it can store surplus renewable energy that would otherwise be lost, and lastly it can be used for cost savings in residential homes and industries [16]. The work by Nagel et al. [17] investigated the grid benefits from V2G in Denmark and Norway. The result showed that V2G can decrease electricity price variability, operational costs, and help integrate higher shares of wind and solar power generation into the grid. As a consequence of utilizing V2G, the system emissions were reduced. In a study by Sagaria et al. [18] the potential of V2G was studied in Spain using the sustainability energy goals in 2030 and 2050. The research shows how V2G can be beneficial for large-scale integration of RES as an energy storage technology. The results indicate the importance of V2G, as large energy storage systems are needed if V2G is not utilized. Additionally, V2G can significantly reduce RES intermittency issues, and with lower V2G acceptance and battery availability, it can still provide noticeable support to the grid.

There have been several pilot projects that utilize V2G. In 2019, Renault started a pilot project in Utrecht, the Netherlands, using 15 EVs capable of V2G with plans to introduce more pilot projects in other countries [19]. In 2024, Renault expanded with a larger pilot project in Utrecht based on the increase of RES in the Netherlands [20]. The project idea was for Renault, We Drive Solar, and MyWheels to launch Europe's first V2G enabled car-sharing service. Renault provided 500 Renault 5 E-Tech electric capable of V2G, We Drive Solar provided bidirectional charging stations, and MyWheels operated the car fleet. Similarly, Polestar has in Gothenburg, Sweden, an ongoing V2G project with a large fleet of Polestar 3 cars [21]. Polestar is using a virtual power plant that links all available cars that are connected to the grid. It then calculates the collective capacity and starts charging or discharging based on grid demand.

2 Purpose, Aims and Motivation

The main purpose of this thesis is to investigate how EVs can impact and contribute to the electric grid by charging and discharging the EV battery. The main reasons for the underlying problem are the increase in RES, the increase in EVs, and the electrification of our society. The intermittency that follows RES can potentially be solved by using BESS, which in this case is the EV battery. With the increase of EVs, this potential also increases. Finally, the electrification of our society increases the stress on the electric grid, and more specifically the electrification of the transport sector could have a large impact on the grid as the number of charging EV increases.

The thesis will be limited to a geographical area, the Nordic countries, as part of an international collaboration project coordinated by Denmark's Technical University (DTU). The project aims to enable the widespread implementation of green transport and vehicle-to-everything technology [22].

The goal is to create a model of a V2G system, in which the amount of EVs and the size of the load can easily be changed in order to study different cases, and to determine the impact and contribution of EVs on the electric grid. Because the inputs can be changed with ease, the model can be used both in small-scale systems as a single household with one EV, but also in a smaller neighborhood with multiple loads and EVs. Using the model in this thesis, it will be investigated how V2G can be used for peak shaving and what economic benefits there are for the EV owners who participate in this ancillary service. Another important part of the thesis is to investigate how charging affects the grid and how it can amplify peaks instead of shaving them.

The main questions to be answered are as follows.

- How can electric vehicles be used for peak shaving?
- What are the economic benefits for the electric vehicle owners supplying the services?
- Will the increase in electric vehicles as a load contribute to grid stability problems?

3 Background

3.1 Climate goals, electricity generation, and number of EVs in the Nordic

The Nordic countries (Denmark, Finland, Iceland, Norway, and Sweden) have some of the world's most ambitious climate goals. The main goals for each country have different ways of being achieved with domestic and international actions. Net GHG emissions from Nordic countries have decreased from 203 million tonnes to 150 million tonnes of carbon dioxide between 1990 and 2021, which corresponds to a reduction of 26 % [23]. In this section, the climate goals for each country will be briefly presented as well as the effect that the transportation sector has on emissions. Additionally, the current and future sources of electricity production from the countries will be presented to correlate the increase in RES with the climate goals. This relates to what was mentioned in the introduction, where introducing more RES and electrification of the transport sector were presented as two solutions that reduce the amount of GHG emissions.

In order to get a better understanding of what the potential of V2G is, it is important to highlight the amount of EVs in the Nordic countries. In Figure 1, the share of EVs is presented. It is clear that Norway differentiates itself from the other four countries with a higher share of EVs. Not only is it higher, Norway has also had a much more rapid increase. In the other four countries, there has also been an increase, albeit a much slower one.

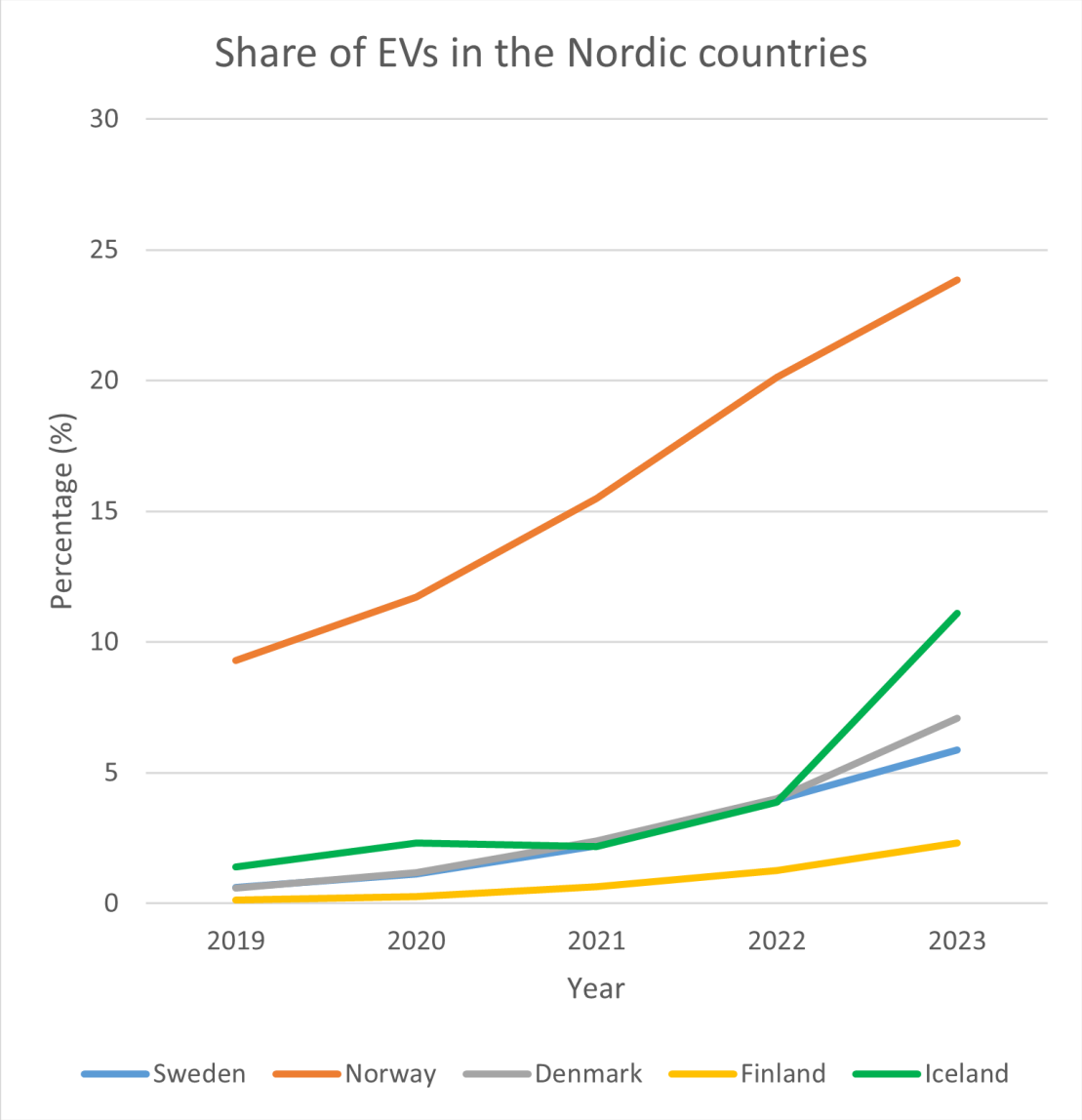

Figure 1 The share of electrically driven vehicles compared to the total amount. Data taken from [24].

3.1.1 Denmark

The goal of Denmark is to achieve climate neutrality by 2050, and to reduce GHG emissions by 70 % in 2030 compared to levels in 1990. The goal includes all GHG and LULUCF (land use, land-use change and forestry) emissions. In the transportation sector in Denmark, the share of total net emissions has increased from 15 % in 1990

and is expected to reach 35 % in 2025 [23]. However, with the electrification of road transport, emissions from the transportation sector are expected to decrease from 13.5 million tonnes of carbon dioxide in 2019 to 0.1 or 0.3 million tonnes of carbon dioxide in 2050. The emissions in 2050 are dependent on different scenarios that the Danish Energy Agency (DEA) has made [25].

The share of RES in Denmark's electricity production was in total 81.2 % in 2022. It is an increase of 424 % since 2000. One reason for this large increase is that the cost of wind turbines and solar panels has decreased substantially, and are now one of the cheapest sources of electricity generation in the world. The highest electricity production comes from wind, which stands for 85 % of the total generation from RES, and the second largest at 14.7 % comes from solar PV (photovoltaic) [26]. By 2030, Denmark's electricity generation will be independent of fossil fuels according to a goal set by the Danish parliament [27].

3.1.2 Finland

Finland aims to be climate neutral by 2035. The goal was set in 2019 and, like Denmark, includes all GHG and LULUCF emissions. By 2030, GHG emissions are to be reduced by 60 % compared to levels in 1990. There are uncertainties as to whether Finland will reach its goal by 2035 due to the development in the LULUCF sector. The sector has turned from a net sink into a source of emissions. In 2020, the LULUCF sector accounted for -17 million tonnes of carbon dioxide and 1 year later, in 2021, it accounted for +2 million tonnes. Emissions from the transport sector have decreased by 18 % since 1990, while the number of EVs has increased. However, the transition to EVs is slow, leaving a gap between emission targets and transport emissions [23].

In Finland, the increase in RES has not been as rapid as in Denmark, but it has increased by 60 % since 2000. In 2022 the share of RES in Finland's electricity production was 53.5 %, of which 50 % is from hydropower, 48 % wind, and roughly 2 % from solar PV [28]. The continued increase in RES is expected to come from offshore and onshore wind farms. Solar PVs have so far not had a large impact in Finland, but are also expected to increase according to a report by the IEA (International Energy Agency) [29] like it has in the rest of the Nordic countries [30]. By 2030, the goal is to have 3 times as much electricity produced electricity from PVs in Finland [31].

3.1.3 Iceland

Iceland's target was set in 2021, and aims to be both climate neutral by 2040 but also independent of fossil fuels by 2040. The target includes all GHG covered by the Paris Agreement and LULUCF emissions. Iceland along with the EU and Norway has committed to reduce net GHG emissions by 55 % by 2030 compared to 1990. In the transport sector, emissions have increased by 50 % since 1990 but are expected to peak as investments in EVs are made [23].

In 2022, 100 % of Iceland's electricity generation came from RES, they are one of the leading countries in Europe and the world when it comes to RES. Hydropower represents 70 %, and the remaining 30 % is geothermal. The electricity generation in Iceland has been 100 % renewable since the 2000's [32].

3.1.4 Norway

The Norwegian Parliament passed a climate neutrality target for 2050 in 2008, and has now changed the goal to be met in 2030 instead. Like Iceland, Norway has an international commitment to the Paris Agreement to reduce net GHG emissions by 55 % by 2030. The current policies and measures in Norway are inadequate to reach their climate goals. The transportation sector is a major GHG emitter, where reductions are challenging even with the electrification of transport [23].

Norway is another country with a high percentage of RES. In 2022, 98.5 % came from RES of which approximately 90 % was from hydro, 9 % from wind, and the rest from solar PV [33]. With wind, hydro and nuclear power requiring legal and licensing frameworks, it can have long building periods, which according to [30], is why solar PV is one of the few new power sources to add capacity in the coming years in Norway.

3.1.5 Sweden

Sweden aims to have net zero emissions by 2045, which is a reduction of 85 % compared to 1990. In Sweden's climate goal, emissions from LULUCF are not included, and in order to reach the goal of net zero emissions, other measures have to be taken such as capture and geological storage of carbon dioxide of biogenic origin (BECCS), bio-CCS and emission reductions through investments internationally. Efficient vehicles, increase in the amount of biofuels, and electrification in the transport sector have all contributed to a decrease in GHG emissions [23]. However, most of Sweden's GHG emissions are still from the transportation sector, which remains dependent on oil [34].

The electricity generation from RES in Sweden comes from three sources: Hydropower (64 %), wind (33 %) and solar PV (3 %). Of the total electricity generation, the share of RES was 68.3 % in 2022, which corresponds to an increase of 19 % since 2000 [34].

3.2 Electrification of our society

Electrification is characterized as a trend that will shape our society, global development, energy politics, and lastly our energy system. It can be used as a solution to the problems related to climate changes by accelerating the transition [35]. By replacing processes or technologies that are reliant on fossil fuels, such as internal combustion engines and gas boilers, with electric vehicles and heat pumps that are electrically powered. The electrical equivalent is usually more energy efficient and has lower emissions, as long as the electricity comes from RES, compared to the use of fossil fuels [36]. The increase in electricity has its downsides as well. Considering that the current electric grids can only handle a certain amount of transferred power, investments are expected by transmissions system operators (TSOs) to connect large decentralized power plants like off-shore wind. Additional, and larger investments than by the TSOs, are anticipated to be invested by the distribution system operators (DSOs) [35].

The investments are a necessity due to the increase in the demand for grid capacity which, as mentioned in [36], comes from electric heating and electrification of the transport sector. Furthermore, it is needed due to the increase in decentralized electricity generation from example solar panels on rooftops, which have increased in large numbers in the EU and are expected to increase further [31]. In a report by IEA [37] the increase in electricity consumption in the world is predicted to increase by 4 % each year through 2027. The generation of electricity from solar PV is expected to generate roughly half of this increase in global electricity demand. One of the main factors is the rapid electrification in which the transportation sector is leading.

3.3 V2G technology

The main principle of V2G is for the battery of a vehicle to supply electricity to the grid when it is needed. It can be used for ancillary services and to reduce electricity prices. The way V2G works, in simplified terms, is illustrated in Figure 2. Starting from the grid, it is connected to a bidirectional AC/DC converter which is needed because batteries are DC while the grid is AC. Then a bidirectional DC/DC is needed because it controls the battery charge and discharge currents and maintains the voltage at a correct level. Note that the arrows are going both ways, normally these components are unidi-

rectional, i.e. it is possible to charge the EV using the grid and not vice versa. Finally, there is the DC battery of the EV.

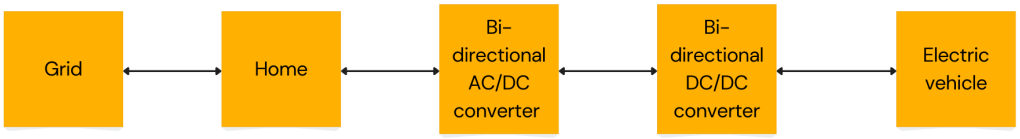

Figure 2 Illustration of how V2G is used.

3.4 Peak demand

According to Gyamfi et al. [38], peak demand is a major global issue. Peak demand is the highest demand over a specific period of time. It usually occurs when the end-use sectors, such as residential or industrial sectors, all have high usage at the same time creating a peak in power demand. When these peaks occur, it can reduce the stability of the power grid and if the demand is not reduced, it can lead to power outages. It can also lead to increased electricity prices [39], and like Gyamfi et al. [38] mentioned, peak load is often supplied by using fossil fuels, which results in high GHG emissions.

In Sweden, there is a new price model to use the power grid more efficiently, because with increasing electricity consumption, the power grid can become overloaded [40] and cause peaks. One solution according to Sweden's Energy Markets Inspectorate ("energimarknadsinspektionen") [40] is to expand the infrastructure of the power grid as Aalto et al. [35] also stated. However, this can take time, which is why another solution is proposed. By distributing the power consumption throughout the day, it can lead to more even consumption and thus help reduce peaks.

A technique for distributing consumption is load shifting, where the load demand is shifted from the peak hours to the off-peak hours. Another similar technique for optimizing energy consumption is peak shaving, which quickly reduces power consumption during high demand from on-site generation systems and batteries. Batteries can also be used for load shifting [41]. The main difference between the two methods is that the total power consumption is reduced when using peak shaving, whereas the total power consumption for load shifting is constant [42].

In a study by Lee et al. [43] it was investigated if V2G could be used for peak shaving, using preferences by the EV owners and under different compensation designs. The results showed that by using V2G, the net peak load could be shaved by 18.5 %. This

is supported in the research by Wallberg et al. [44], which used a peak shaving control algorithm and load prediction model to determine the impact of peak shaving in a parking garage in Sweden. Their results using the model showed that peak shaving could reduce peak load demand by 25.4 - 38.5 % while still having sufficient SOC (State Of Charge) at the end of the day.

3.5 Economic benefits of V2G

Electricity prices in Europe reached an all-time high in 2022 with 0.29 Euro/kWh (including taxes) which corresponds to 3.22 SEK/kWh. The electricity prices increased slowly and steadily from 2009 until 2020/2021, when a noticeable increase started [45]. One of the reasons for the so-called energy crisis is Russia's unjustified military aggression against Ukraine and with less gas exported from Russia to European countries, the electricity price continued to increase. To reduce the impact from this and any potential conflicts and supply cuts in the future, the EU took some key measures. An included measure was to reduce the demand of gas by, for example, incentivizing consumption reduction. Another measure was to diversify the supply of energy, and the last measure was to reduce bills for European households and businesses. To reduce costs, the EU has, for example, a target of reducing the electricity demand by 10 %, and furthermore an obligation to reduce demand by 5% during peak price hours [46].

The correlation between electricity price variability and the increase in RES is not entirely clear, and the studies that have been done vary in results. In a study [47] it was concluded that a combination of solar PV and wind power had a nonexistent or minimal impact on reducing electricity prices. Another study came to the conclusion that when the RES penetration is below a certain limit, its impact on the electricity price variability is insignificant, and when above the limit, the ability to reduce price variability was significantly increased [48]. Wind power can according to [49] reduce intraday variability while increasing the average daily prices in Denmark. In the work by Ketterer [50] the results showed that wind power increases the variability of electricity prices in Germany. Both [51] and [52] came to the conclusion that wind power and solar PV affect the price variability differently, which highlights the importance of balancing the electricity production accordingly.

As in previous studies [53], [54], and [55], V2G has the potential to be used to sell electricity when the electricity prices are high to compensate the EV owners for mainly the energy, but also for the battery degradation that occurs when the batteries charge/discharge. In a study by De Los Rios et al. [56] it was concluded that V2G can provide economical benefits and that further implementation is dependent on technological advancements. Additionally, V2G can potentially be a way of increasing the adoption

of EVs and to increase the cost-effectiveness through the revenue that the EV owners receive from participating in the ancillary services market.

A possibility is to use V2G in combination with peak shaving to reduce costs. In a recent report [55], it was concluded that V2G can be highly economically beneficial, particularly to people with low car usage and thus high availability. In addition, it can also be beneficial to people with higher car usage, but it is noted that the electricity price has a large impact on the outcome.

Another variant of this was performed in a study by Lee et al. [43] where the result was that it indeed can be used for cost savings compared to the use of energy storage, even when the degradation of the EV battery was taken into account. Another result of the study was the importance of incentives to increase participation in V2G, as their findings were that the willingness of EV owners was limited.

4 Method

In the following subsections, the method(s) used to create the V2G model is described in detail and illustrated to show the dynamics of the model. In short, the following parts will be covered:

- The simulation tool used to create the model.
- The delimitations and assumptions that have been made in the model.
- The EV user profiles used in the model.
- The data used as input for the model.
  - Load
  - Battery specifications
  - Electricity prices
- The model setup and the algorithm.

4.1 Simulation tool

In order to create the model and use it to evaluate how V2G can be used, a simulation tool was needed. In this thesis, the first of two simulation tools used is Matlab. It is a combination of programming, model design, and data analysis. The second simulation tool used is Simulink, which is a graphical editor that is integrated in Matlab. This means that Matlab code and variables can be used in the Simulink environment and the simulation results from Simulink can be exported to Matlab. In Matlab and Simulink there are add-ons that can be downloaded and used depending on the application. In the model, a toolbox called Simscape is used to model physical systems within Simulink.

There are also other options, such as PSS®E (Power System Simulator for Engineering) or Python. PSS®E is commonly used for load flow analysis and could have been a good option if a larger system were to be analyzed. Because the economic aspect was to be studied as well, Matlab/Simulink was a better choice because of its flexibility. Python has multiple relevant libraries on which the model could have been built. However, the simplicity, ease of use, prior knowledge, and the visual aspect of using Matlab/Simulink were the deciding factors in what tool to use.

4.2 Delimitations and assumptions

The electric grid is complex, and there are many things to consider. On a large scale, there are many loads and power sources connected to each other. The main components can be seen as loads, generators, transformers, and power lines/cables. The behavior of one component can affect multiple other components and can change the load flow. For example, the behavior of the load component could depend on energy consumption in a household. In turn, energy consumption depends on how household appliances are used by the consumer. The same appliance can be configured in multiple ways, and it can be different materials and designs which affect the efficiency and function.

In order to create a model within the given time frame, assumptions and delimitations are needed. The complexity of a real world V2G application is large, and would require a large amount of time to create a model of. The assumptions are made to simplify the model, because this thesis investigates V2G as a concept and how it can be used while leaving the in-depth modeling characteristics simplified. It is important to note that even with the simplifications made, the behavior of the model should still be as expected compared to other studies.

Each load in the model is assumed to have a single EV available for V2G. Adding multiple loads will create a smaller, custom neighborhood. This creates the opportunity to evaluate V2G on a varying scale.

V2G technology uses bidirectional converters. These converters use transistors such as IGBT'S (insulated-gate bipolar transistor) or MOSFET's (metal–oxide–semiconductor field-effect transistor) depending on the switching frequency. Using these components with a high switching frequency in Simulink/Simscape causes the simulation run-time to be slow. It can be used if shorter simulations are run, for example 1 second. However, the model needs to run for 24 hours, which is equal to 86 400 seconds. The initial model used power electronics, but the run time was much longer than the simulation time, which was not optimal. Furthermore, the data saved in the scopes and variables needed to be carefully selected, or the computer would run out of memory. Additionally, because the behavior of the converters is not studied in this thesis, it was deemed an important delimitation not to use power electronics.

One of the main purposes of the V2G model in this thesis is peak shaving. The model continuously measures the active power consumed, and a limit is needed for when the peak shaving algorithm should start. The limit is modeled as a constant that depends on the load. The limit for a single household is equal to 50 % of the peak active power consumed. This limit was chosen for two main reasons. Firstly, too much shaving would drain the battery too quickly and limit its function. Secondly, the amount of power the battery can provide is not unlimited, and depends on the specifications of the

bidirectional converters. The precise amount of active power the battery can provide is mentioned in the ”Data” subsection. Similarly, the limit for multiple households is equal to 70 % of the peak active power consumed. There needed to be a higher limit because otherwise the peak shaving would start whenever the EVs were available, i.e., the lowest power consumed for multiple households was greater than 50 % of the peak active power.

The load in the model is connected to an infinite grid that can supply an infinite amount of power. The active power demand by the load is therefore always met, with or without any power from the EV battery. Since the load is always connected to the infinite grid, the battery is connected directly to the load in the model. Technically, the battery does not supply electricity to the grid when modeled in such a way, but it makes it easy to either change the load or number of EVs without making any changes in the electric grid. This is a simplification made in order to focus on what V2G can be used for rather than how it is implemented. It is also possible to model it in such a way since no power electronics are used to connect the battery to the grid.

The driving patterns of the EV user are assumed to follow the same pattern daily. The daily patterns are presented in the ”User profiles” subsection. Based on the driving patterns, the SOC is affected. The distance traveled by the EV is assumed to be the same for all profiles, and is also presented in the next subsection. To simplify, and since electricity prices are in per hour, each trip taken with the EV is assumed to last for one hour.

The SOC drop from driving the EV, in the model is linear during each hour in use. In the real world the EV will not have the same speed the whole hour, and the SOC will not be linear, however, the importance lies in how much SOC is available. This results in the fact that the current drawn from the battery while the EV is in use is constant i.e. it is constant decharging.

The average distance per passenger vehicle per day in 2024, in Norway, was 30.7 km [57]. This is the distance used in the model. However, each trip (to and home from work) is assumed to be one hour, during which one would most likely get further than 15.35 km. It was deemed to be a necessary delimitation in order to make it easier to implement it in the model.

In order to maximize the benefits of using V2G during 24 hours, an assumption of the battery charge must be made. In the beginning of each day, the battery of the EV is assumed to be fully charged, i.e. the SOC is equal to one. Even though it might not be realistic for every case and EV owner, it is a necessity in order to create a best-case scenario.

An important delimitation made is that the aging or degradation of the battery is not

taken into account in the model. It is, however, an important aspect that can influence the V2G participation by EV owners. It also influences the performance of the battery, but in the model the battery performance is constant. Additionally, the EV battery is assumed to be Lithium-ion since it is the most common type of EV battery [58].

According to a study by Schram et al. [59], the round-trip efficiency of V2G ranges between 79.1% and 87.8%, when charging between SOC's 25 % and 75 %. This is the combined efficiency for the converter and battery for a full charge and discharge cycle. The efficiency in the model was chosen to be the mean, and it was assumed that the efficiency is the same for both charging and discharging. This results in $\eta = \sqrt{0.835} \approx 0.91 = 91\%$ which is the efficiency of one cycle. Also, due to the SOC limits in the study, the SOC of the battery in the model is minimum 25 %, and maximum 75 % when charging. It is limited to prevent excessive wear and increase battery performance [60].

4.3 User profiles

In order to make V2G viable in the real world it needs available EVs. Since EVs are not always stationary, the possibility to use V2G heavily depends on the charging/user pattern of the owner. If, for example, an EV should be used for a service such as peak shaving, it needs to be available at the time of high demand. There is no guarantee that this is the case because people want to be able to use their cars during the day. This was the case in the study by Lee et al. [43], where the likelihood of participation in V2G increased during the night when most of EVs are stationary and not in use.

Basically, EVs are suitable to provide ancillary services because they are only used part of the day. Privately owned vehicles are usually used at three peaks each day: in the morning, at noon, and in the evening [61]. In addition, the study concluded that the share of private vehicles used at the same time never exceeds 12 %, which means that there is always a majority of vehicles that are stationary throughout the day that could be available to provide services to the grid.

In a paper [62] that studies EV charging behavior in Australia, the results were that a large majority of total distance traveled (via EV) occurred between 7 am and 7 pm. Similarly, according to a report [63], the observed passenger vehicles on urban roads during workdays in Denmark peak twice during the day. The first peak is between 8-9 am and the second peak is between 4-5 pm.

Although a regular work day can be considered between 8 am and 5 pm, it is not the case for everyone, which is why it is important to also consider other usage patterns in order to evaluate V2G. This is illustrated in a previous work [53] where three custom profiles were made illustrating when the EVs are available and not. The three cases

consists of:

1. The EV is not available for three short periods, in the morning, at noon, and in the evening.
2. The EV is not available between 7 am and 5 pm.
3. The EV is not available between 5 pm and 5 am.

Like previously mentioned, there are problems related to EVs as well. The charging of EVs must be smart and distributed throughout the day to avoid amplifying already existing peaks or creating new peaks. In the research by Rotondo et al. [64], the potential increase in electricity demand that follows with electrification of the transport sector is evaluated on an hourly basis. The key findings from the study are that implementation of smart charging is crucial because of the electrification of the transport sector which could lead to an electricity demand increase of 28 %. In addition, without smart charging the peak demand of 652 MW that already exists could be amplified by 50 - 250 MW with more EVs.

In a study by Wang et al. [65] multiple EV charging scenarios were investigated. Their findings were that uncontrolled charging can increase household peaks by up to 181 %. By limiting the charging power, the charging time is longer. However, in doing so, the effect of EV charging on peaks is mitigated with minimal downsides with respect to SOC and EV usage.

In the model, 2 different profiles are used. The first user, user 1, is seen in Figure 3. This user represents a person who works 8 am to 4 pm and has a one-hour commute each way. While the user is at work, the EV is not available for V2G. These working hours, with minor differences are normal for most people, which is why they are considered to be the main user profile.

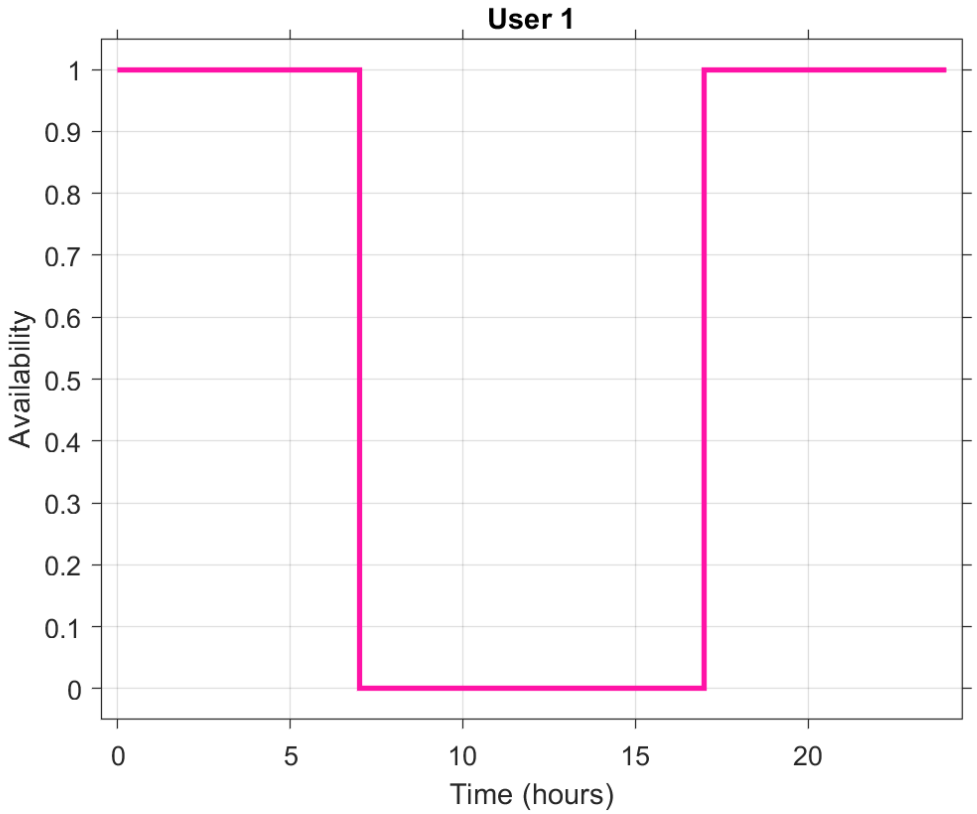

Figure 3 User profile 1. Binary representation of when the EV is available, where 1 means it is available and 0 means it is not available for V2G.

The second profile, user 2, is presented in Figure 4. This user represents a person who works 9 pm to 5 am, with the same commute time of 1 hour each way and the same number of working hours as user 1. The point of using these 2 profiles is that they complement each other. Although the EV is not available in one profile at a certain hour, it will be available in the other and vice versa. Another point is that not everyone works 8 am to 4 pm, and to include people who work opposite times to user 1, user 2 is utilized.

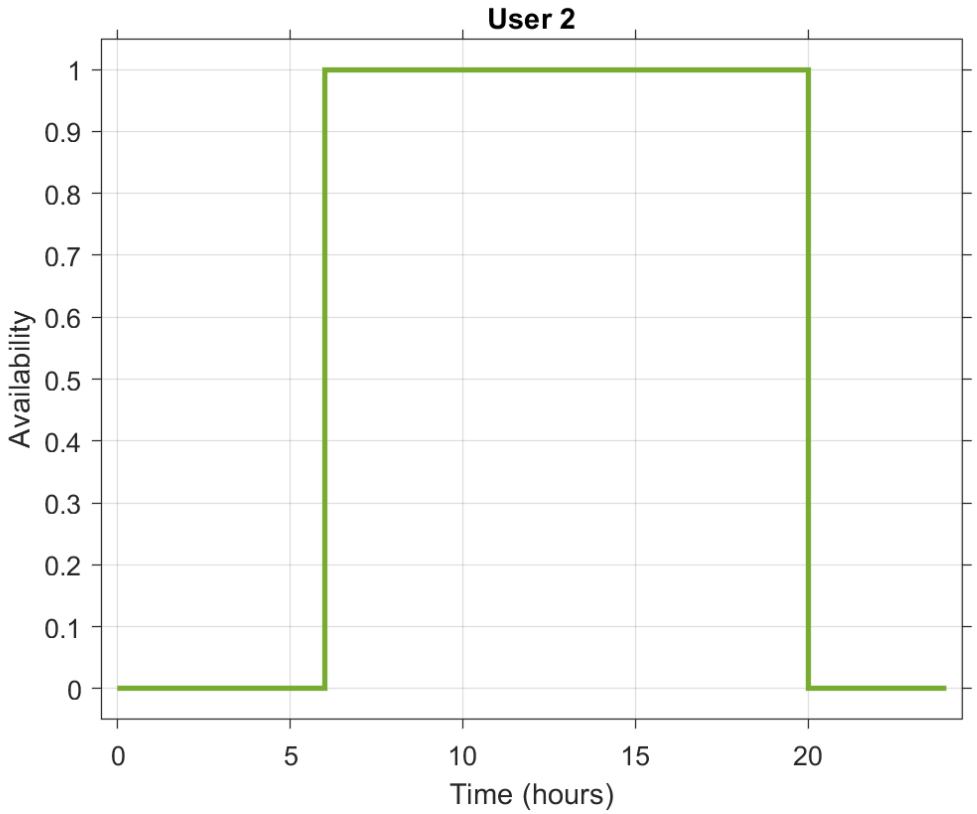

Figure 4 User profile 2. Binary representation of when the EV is available, where 1 means it is available and 0 means it is not available for V2G.

One of the questions that must be answered is whether the increase in EVs as a load can cause grid stability issues. To answer this question, a user profile for the charging of EVs has been made. The profile can be seen in Figure 5, where the idea is that the battery starts at its lowest SOC at 25 %, and starts charging at maximum power during peak hours until it reaches 75 %. As seen in the figure, the peak hours are between 5 pm and 8 pm. This time period is chosen for two reasons, firstly because user 1 arrives home at 5 pm after which the EV is available to be charged. Secondly, because that is the number of hours required to charge the EV from 25 % to 75 %, which will be described in detail in the ”Battery” section.

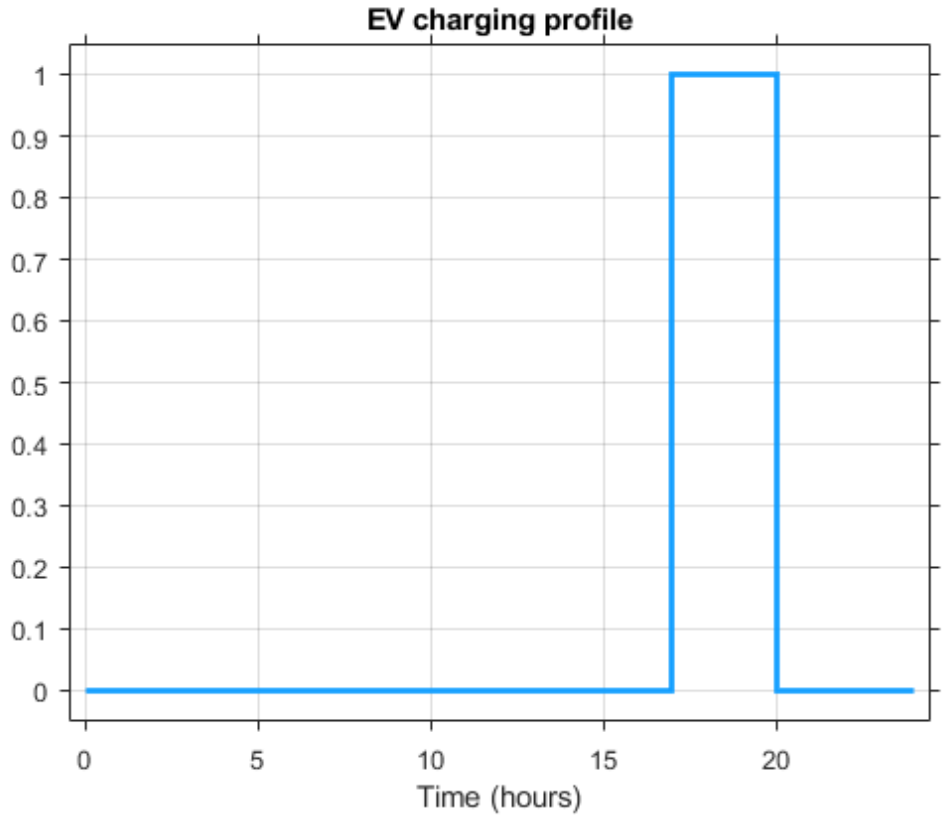

Figure 5 EV charging profile. Binary representation of when the EV is charging, where 1 means it is charging and 0 means it is not charging.

4.4 Data

In this section, the data and inputs used in the model will be presented. It consists mainly of 3 inputs: load data, battery specifications, and electricity prices. Other data used are the user profiles chosen which are presented in the previous section.

4.4.1 Load data

The chosen load data was based on two things. Firstly, it had to be in one of the Nordic countries because this is where the Best4Grid project is set. Secondly, it had to be in at least hourly resolution, but a higher resolution would give better and more accurate results. If more accurate data are found, it can be used in the model as well. The load data are from a study in Norway [66]. It consists of hourly electricity consumption in

4483 households in different regions, and is measured during two different phases.

The data chosen are from winter 2019-2020, more precisely, the 3rd of February, during the first phase of the study. The reason for using this period is mainly because of a higher electricity consumption during the winter, amplifying the peaks. Furthermore, the potential of V2G increases with, for example, higher electricity prices. The first data is presented in Figure 6 which shows the electricity consumption of a single, randomly chosen household. The demand is high during two periods for this household, first during the morning, and second during the evening.

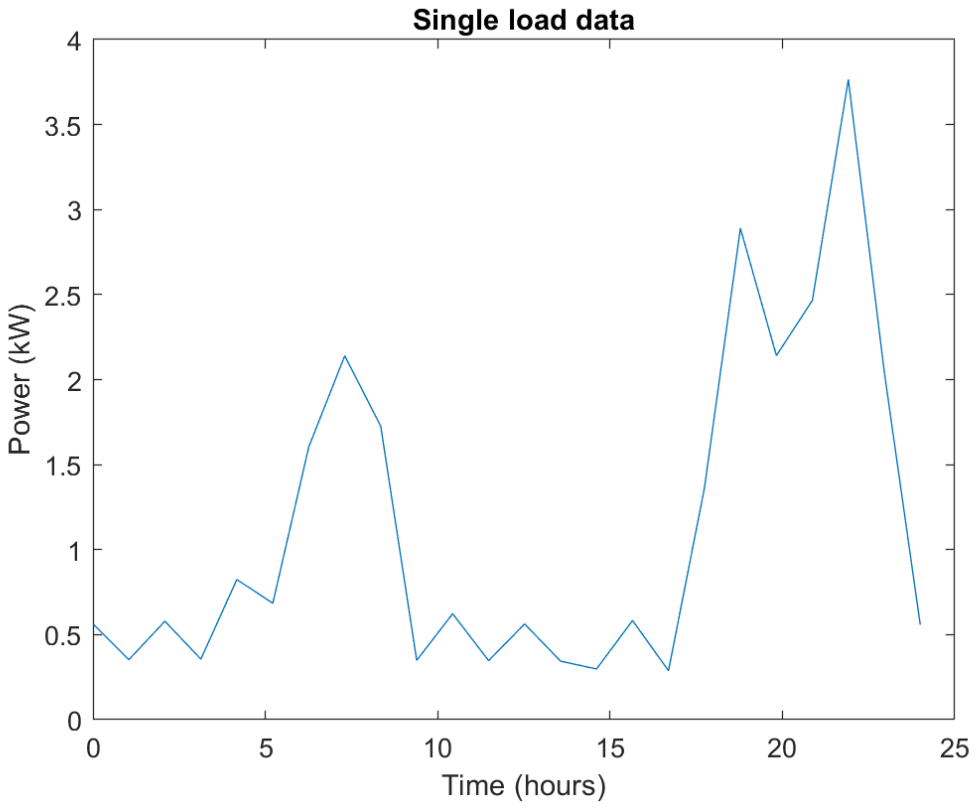

Figure 6 Household electricity consumption of a single household in Norway. Data taken from [66].

When multiple EVs are added, an equal number of different households are added as well from the same data source. This correlates to each household having their own EV that can be used for V2G. The single household load does not necessarily represent how every household uses their electricity. By adding multiple household loads, the result is a more realistic representation since it considers different user behaviors.

In Figure 7 the total consumption of 10 different households in Norway is presented which are used in the model. In the figure, the main consumption is during the evening, with smaller peaks in the morning and at noon. The consumption during the night and during the middle of the day is lower.

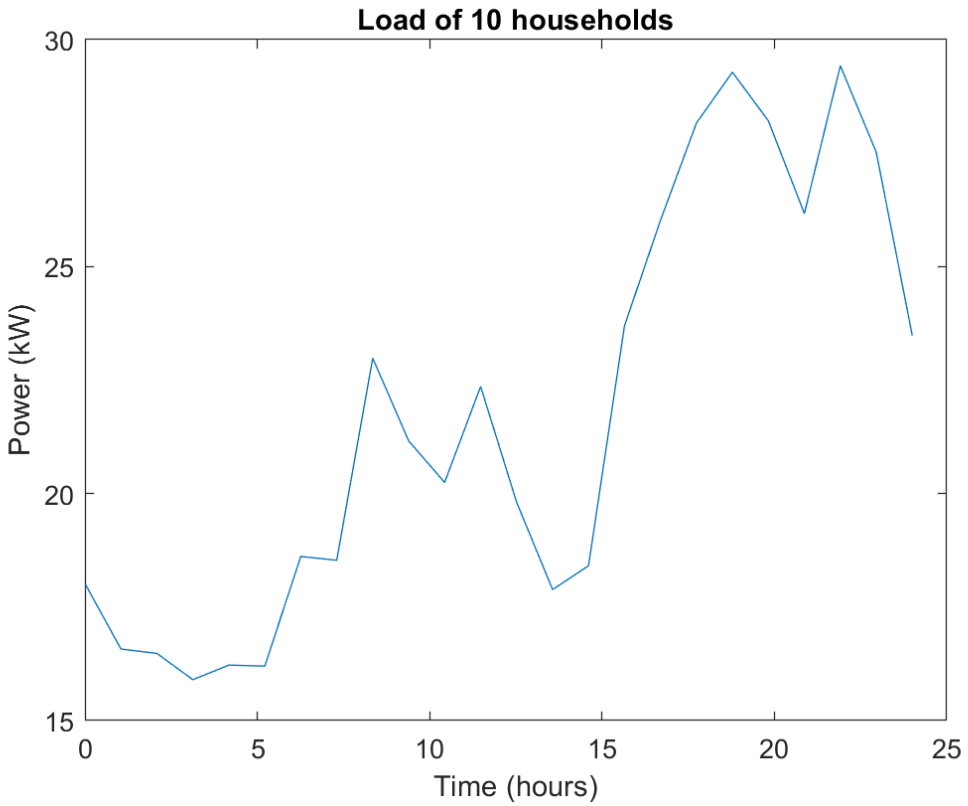

Figure 7 Household electricity consumption of 10 households in Norway. Data taken from [66].

4.4.2 Battery

The size and specifications of the EV battery have an important role in V2G since it decides how much power can be delivered, and for how long the battery can sustain that amount of power. The chosen battery is from a Renault 5 E-Tech. One reason for using this Renault is because 500 of them, all equipped with V2G technology, are currently used in an ongoing V2G project in Utrecht, Netherlands [20].

The EV can be used for bidirectional charging, and has an outgoing power capacity of 3.6 kW [67]. Therefore, the battery in the model, and thus the peak shaving, is limited

to the specified power of 3.6 kW. Additionally, the EV battery voltage is 400 V and its nominal capacity is 55 kWh. The charging power at home is 11 kW AC, and using a fast charging station the maximum power is 100 kW DC. Using a combination of city and highway driving, the range estimation of the EV in cold weather is 270 km [68].

Using a power of 11 kW, it would take approximately 2.5 hours to charge the EV from 25 % to 75 %. But since the model is simplified to a resolution of hours, the charging is modeled to take 3 hours. The range estimation is higher in warmer weather, but since the load data is from the first of February the weather is assumed to be cold.

The Ah rating of the battery can be calculated using Equation 1

$$Q_{Ah} = \frac{E_{Wh}}{V_{battery}} \tag{1}$$

where E_{Wh} is the nominal capacity of the battery, and $V_{battery}$ is the battery voltage.

Based on that $\frac{Driven\,distance}{Total\,range} = \frac{30.7}{270} \approx 0.11 = 11\%$, a 5.5 % SOC drop happens each time the EV is used with the chosen driving distance. Additionally, the SOC drop of 5.5 % equals 3.025 kWh of energy used during one hour. The corresponding current drawn from the battery is calculated using Equation 2

$$I = \frac{P}{V} \tag{2}$$

where P is the active power and V the voltage of the battery.

There are multiple ways of estimating the SOC. The chosen method is called Coulomb counting. It is chosen because of its simplicity and ease of implementation in the model. The downside of the method is the fact that the battery capacity, and efficiency are affected by operating temperature and current direction, which are not included in the method [69].

The Coulomb counting method is presented in Equation 3

$$\text{SOC}(t) = \text{SOC}(t_0) - \int_{t_0}^{t} \frac{\eta(\tau) I(\tau)}{Q_{Ah}} \, \mathrm{d}\tau \tag{3}$$

where t and t_0 is the time period, η is the efficiency for discharging and charging, I the current drawn from the battery, and Q_{Ah} is the rated capacity of the battery [69], [70].

4.4.3 Electricity prices

The first chosen electricity price is from Norway's bidding zone NO2. It is one of their more expensive zones, which makes it a good fit to evaluate the economic potential of

V2G. Additionally, using Norway's electricity prices is relevant since the load data is from Norway.

The electricity price data are presented in Figure 8, where the prices are in an hourly resolution for a day in February. The reasons for choosing a day in February are first because the load data is from February. Secondly, since electricity prices are generally higher during the winter.

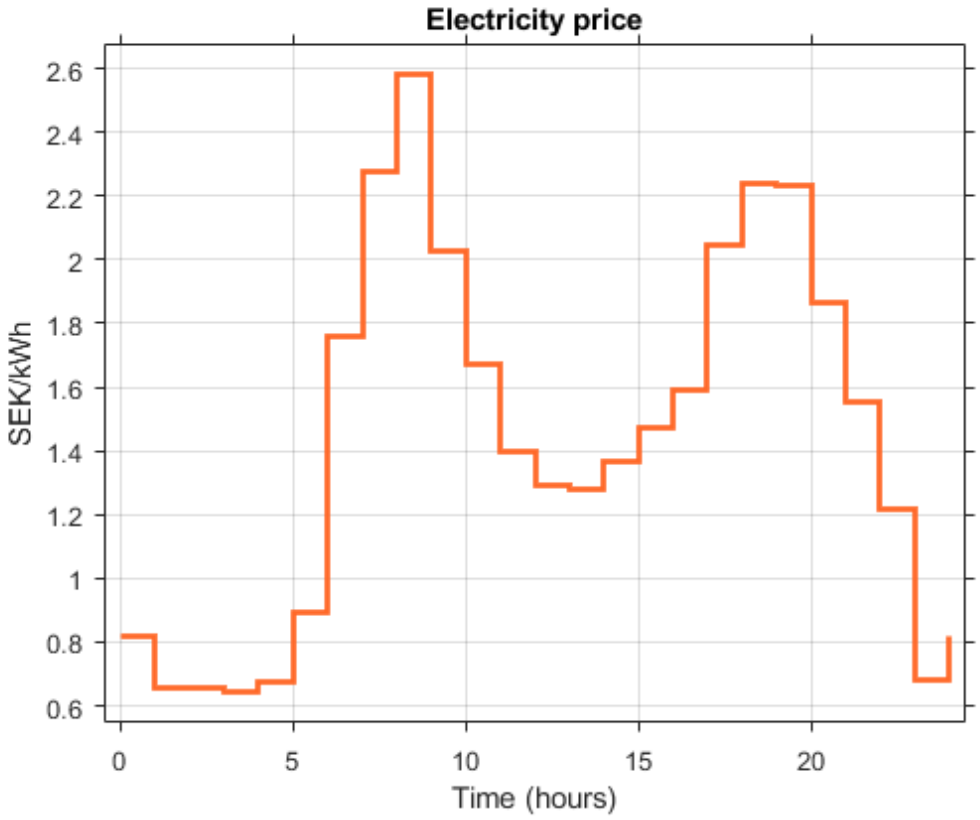

Figure 8 Hourly electricity prices in Norway, Monday 2025-02-03. Data taken from [71].

The second chosen electricity price is, instead of a variable value over 24 hours, a constant value. Recently, Norway had its highest electricity price in 15 years at 1.18 USD/kWh [72], which is equal to 11.4 SEK/kWh using an exchange rate of 9.66 SEK/USD. This value was used as a constant electricity price in the model. The main reason for doing so is to evaluate the potential of V2G in a worst-case scenario where the electricity price is abnormally high.

The electricity prices are needed to calculate the revenue by V2G. By multiplying the

power and electricity price the instantaneous revenue is calculated. In order to calculate the total revenue, for the whole simulation, integration is needed. This is seen in Equation 4

$$Total\ revenue = \int_0^T P_{battery}(t) * price(t)\, dt \tag{4}$$

where $P_{battery}$ is in [W], and $price$ is in [SEK/W].

4.5 Model setup

The simulation runs for 86400 seconds, which equals 24 hours. It is run offline, as running it in real-time would give no benefit for the results. Also, if run in real-time each simulation run would take 24 hours, which would not be optimal for testing and tweaking the model. The chosen solver is ode23t, and with a variable step the maximum step size is 5 seconds and the minimum step size is set to auto. A Matlab script is used in combination with the Simulink model. In the script, the load data for all households, peak shaving limits, user profiles, and when a SOC drop happens are defined. The constant values such as the peak shaving limits are used in the Simulink environment as constants that are connected to the corresponding Matlab workspace variable. The other two main Simulink blocks used to make use of the Matlab variables are firstly the ”From Workspace” block, which is used for the load data as it is a series of values. Secondly, the ”Repeating Sequence Stair” block is used for the user profiles and when a SOC drop happens, and it has a sample time of 3600 seconds which is the time between every data point, i.e. one hour.

The model can be divided into 3 main physical parts: Grid, load, and battery. These parts have different inputs and outputs, and some outputs for a specific part can be an input to another. An overview of the model can be seen in Figure 9. The green blocks represent input data, which are imported to the Simulink environment from the Matlab workspace. The yellow blocks represent the output of the model. Lastly, the blue blocks, they are used as the physical components or as calculations. Three parts and their algorithms will be described more in detail later in this section, as they are more advanced and are the basis for how the model behaves. These three parts are: battery, SOC estimation, and economic revenue.

In Figure 9, the battery and the grid are represented by blocks with their own names. The load is represented by a dynamic load block, which is a block in Simulink used to externally control the power consumed and requires an input. In the model, the inputs (green blocks) are imported from the Matlab workspace to the Simulink environment.

In this way, if other data should be used, the components in the Simulink environment can stay the same while changing the parameters in Matlab. The main principle of the model is that the power supplied by the battery is subtracted from the power consumed by the load, thereby lowering the power consumed from the grid.

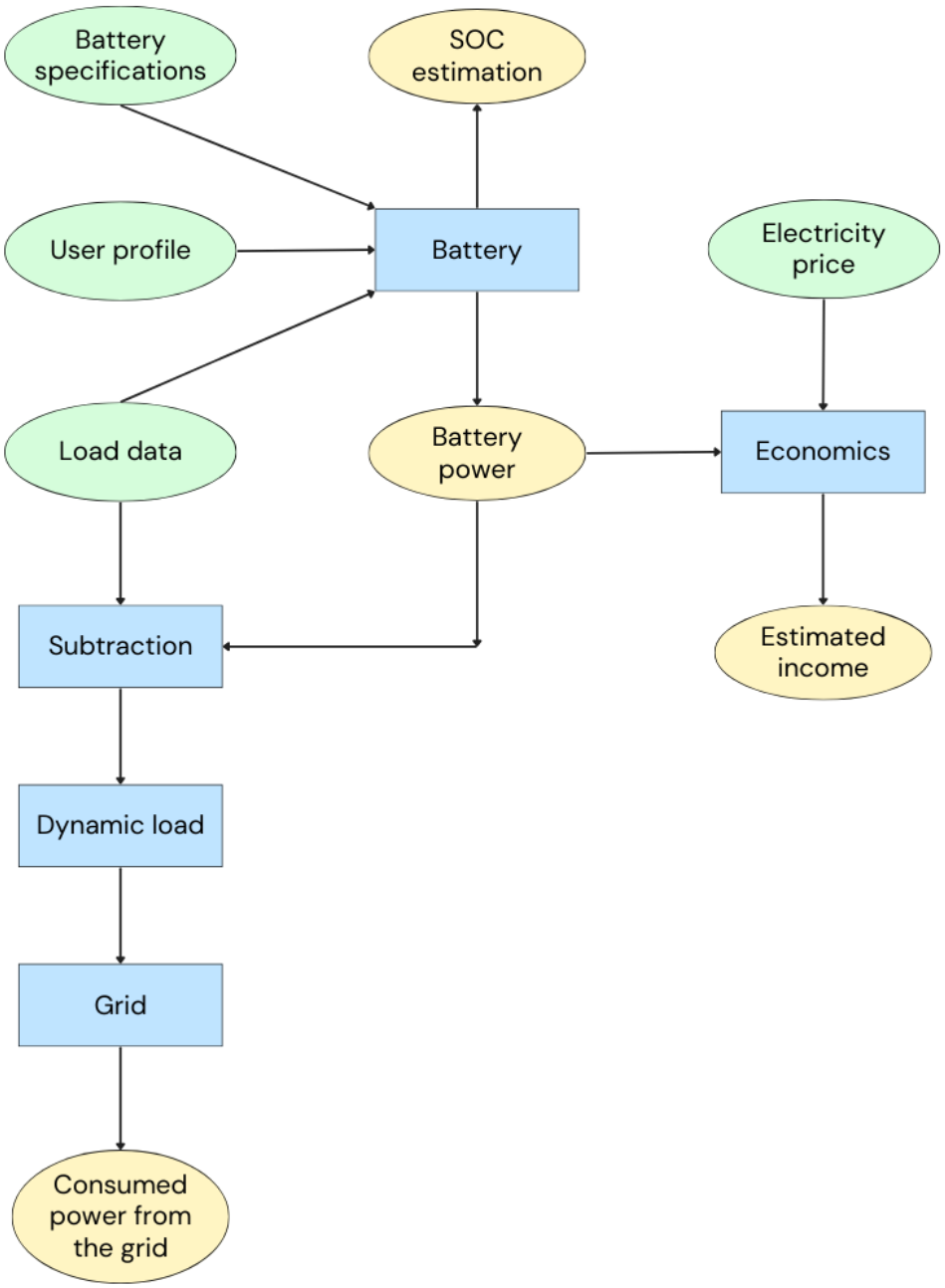

Figure 9 Illustration of the model set-up and the flow of information between components.

In the following two figures, the block representations are similar to the previous figure. Green blocks are input, yellow the output, and the blue blocks in these cases are the next ”step” in the algorithm.

In order for V2G to work properly, an algorithm is required. The algorithm in this model, for the battery, can be seen in Figure 10. By taking the power consumed by the load and subtracting the peak shaving limit, the amount of power required from the battery is calculated. If the sum is negative, it means that no peak shaving is needed since the power consumed is less than the peak shaving limit. If the sum is positive, it means that the power consumed is greater than the limit and that it needs to be shaved.

The next step is to check whether the power needed from the battery is within the specified limit of 3.6 kW. If not, the power from the battery is set to 3.6 kW. With the known power and voltage of the battery, the current drawn is calculated. In order to draw the current, the EV has to be available, which is checked is the following step.

Using the user profile as an input, if the EV is not available, the drawn current is 0. If the EV is available, the next step is to check if the SOC is sufficient, that is, greater than 25 %. If the SOC is sufficient, it is sent as a reference and as one of two inputs to a PI controller. The other input to the controller is the current, current drawn from the battery. The PI controller is used because real-world systems use feedback control. The result of this is that the current from the battery is not hard-coded, and mimics the behavior of a real controller, which is slightly delayed. The output of the PI controller is then used in a controlled current source which controls the battery discharge.

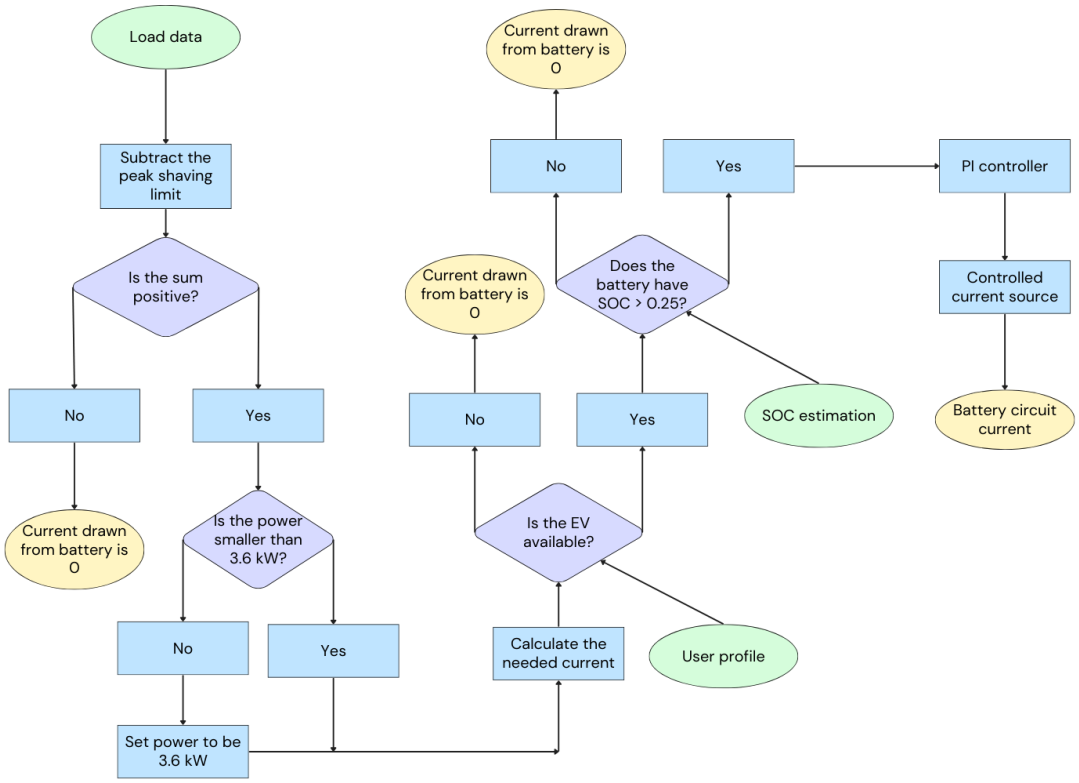

Figure 10 Algorithm which decides if and when the battery produces power for V2G.

To estimate how much money can be made by using V2G, there are mainly two things needed as inputs. The first input is the electricity price, which is important because V2G is used at times with high demand when the prices are usually higher. The electricity prices used are seen, as previously, in Figure 8 and the electricity price constant of 11.4 SEK/kWh. Secondly, the amount of power provided by the battery is needed. The amount of power from the battery can be calculated by multiplying the drawn current, from the battery algorithm in Figure 10, by the battery voltage, which is 400 V.

With the two inputs known, they both are converted from kW and SEK/kWh to W and SEK/Ws respectively. They are then multiplied, however, this gives an instantaneous rate of revenue which in this case is SEK/s. Integration is used in order to get the total value for the whole simulation time which is seen in Equation 4.

The battery is a key component in V2G. How and when the battery operates was previously explained, but since the charge of the battery is not unlimited, it needs to be controlled and measured. In Figure 11, the algorithm for estimating the SOC is pre-

sented. The first input is the user profile, which is created so that during the first and last hours when the EV is not available, a SOC drop occurs. The SOC drop occurs because the EV is in use for exactly one hour at a time. In the model, a constant current is added which is the current drawn from the battery. In the figure, the battery circuit current is also added. However, when the EV is in use, it is not available for V2G, and thus the battery circuit current is zero. So, it is always one or the other that is active, i.e. it is in use resulting in a SOC drop, or it is used for V2G. Both result in a decrease in SOC.

The next step is to integrate the drawn current, using the capacity of the battery and efficiency. Knowing that the initial SOC is equal to one, the Coulomb counting method in Equation 3 is used. The output is the estimated SOC and how it changes during the day.

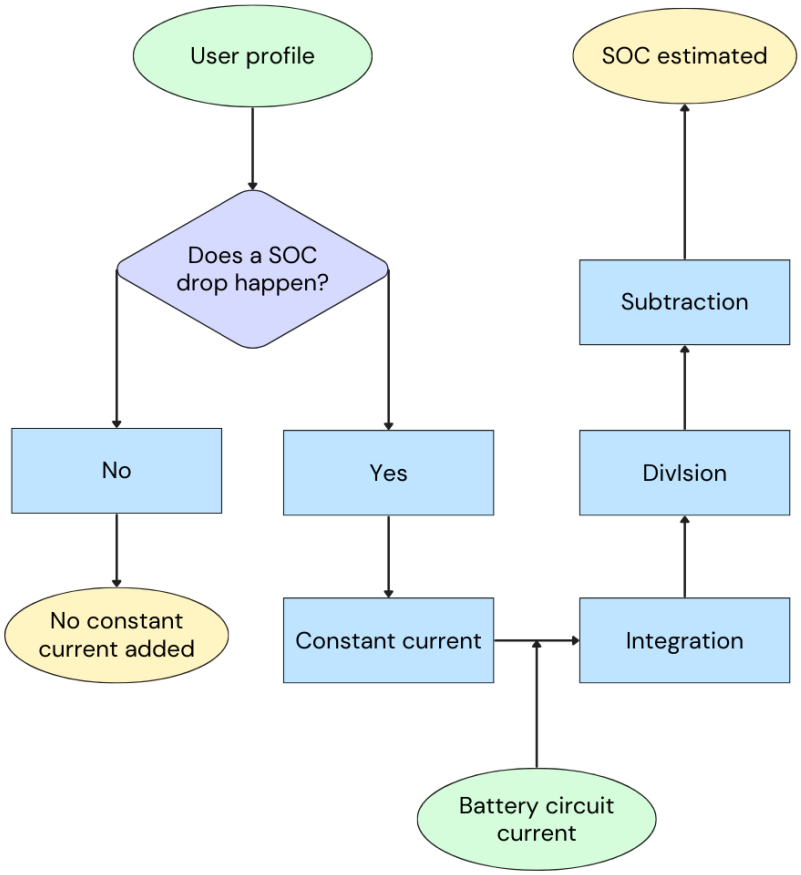

Figure 11 Algorithm for SOC estimation.

5 Results

In this section mainly three results are presented. The first two sections show the power from the battery, the consumed power from the grid, the SOC of the battery, and lastly the economic aspect. This is done for both single and multiple households. In the last section the results from charging multiple EVs at the same time, during a peak, is presented.

5.1 A single household with 1 EV

In this section the results from using a single EV with a single household is presented. It is done for both user profiles, which are presented in the same figures to easily compare them.

Figure 12 shows the amount of power produced and delivered to the grid during a 24-hour period by the batteries. The power is within the limit and peaks at around 1.9 kW for user 1 and at 1 kW for user 2. The batteries are primarily in use during the evening peak hours, which is expected as the EV is available at the same time as the demand from the single load is high. The power produced by user 1 just before 7 am is limited and abruptly stops at 7 am when the EV leaves for work and is therefore not available. However, the user 2 EV is available and can peak shave during the morning hour. At 6 pm both users utilize V2G, but at 8 pm user 2 leaves for work while user 1 is still able to use V2G.

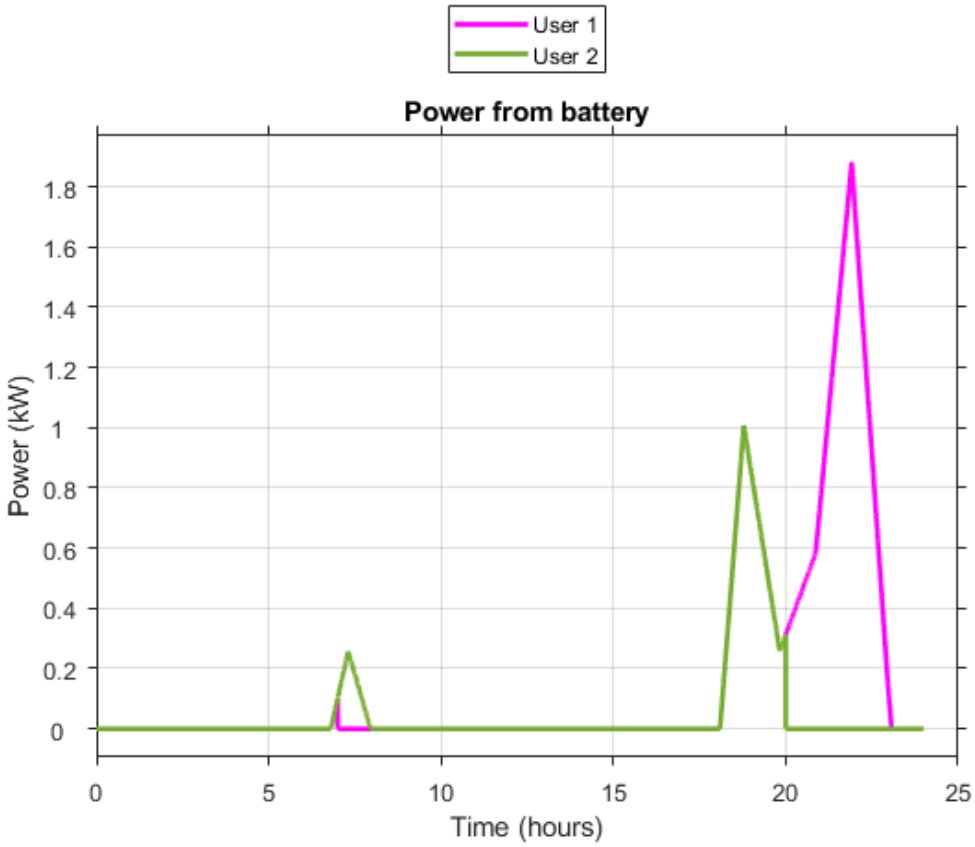

Figure 12 The power supplied to the load from the battery.

By subtracting the battery power from the consumed power, the amount of produced or needed power from the grid is calculated. The result of doing so is presented in Figure 13. In this figure, the peak shaving potential is clearly distinguished when compared to the original and actual consumed power in the previous Figure 6. In this case, the peak between about 6 pm and 11 pm is shaved by 50 % by user 1 while user 2 can peak shave until 8 pm. The peak shaving done right before 7 am is noticeable but minimal compared to the peak shaving in the evening, by both user 1 and user 2. During the day, there are no peaks above 50 % of the peak power, resulting in no peak shaving.

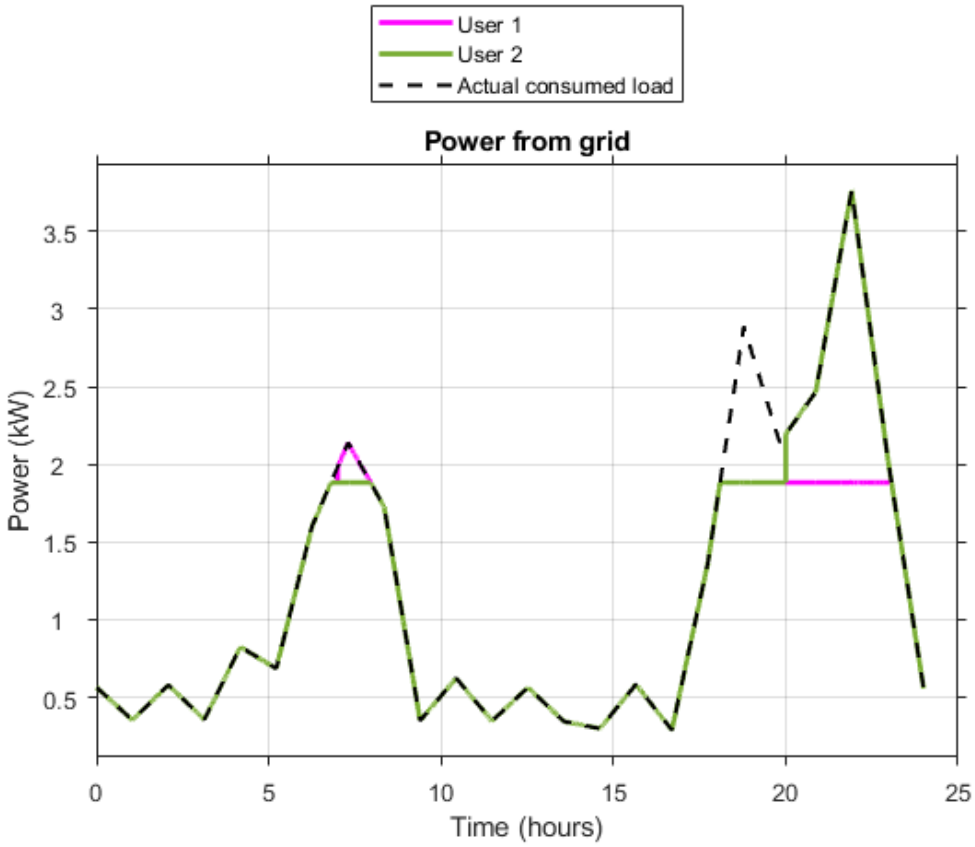

Figure 13 The consumed power as seen from the grid.

The SOC's of the EVs for both users are presented in Figure 14. For user 1, the drop before 7 am is negligible, and at 7 am and 4 pm the SOC drops linearly as expected when the EV is in use. At 6 pm the SOC drops successively during the rest of the evening while the peak shaving is active. At the end of the day, the SOC for user 1 is at 81 % after driving and peak shaving. User 2 leaves work at 5 am and is at 6 am able to do a noticeable amount of peak shaving. During the day, when the EV is available, the power consumption is still low and V2G can not be utilized. It is able to peak shave a smaller amount before leaving for work. At the end of the day, the SOC for user 2 is around 87 %. Both users are not near the SOC limit of 25 %.

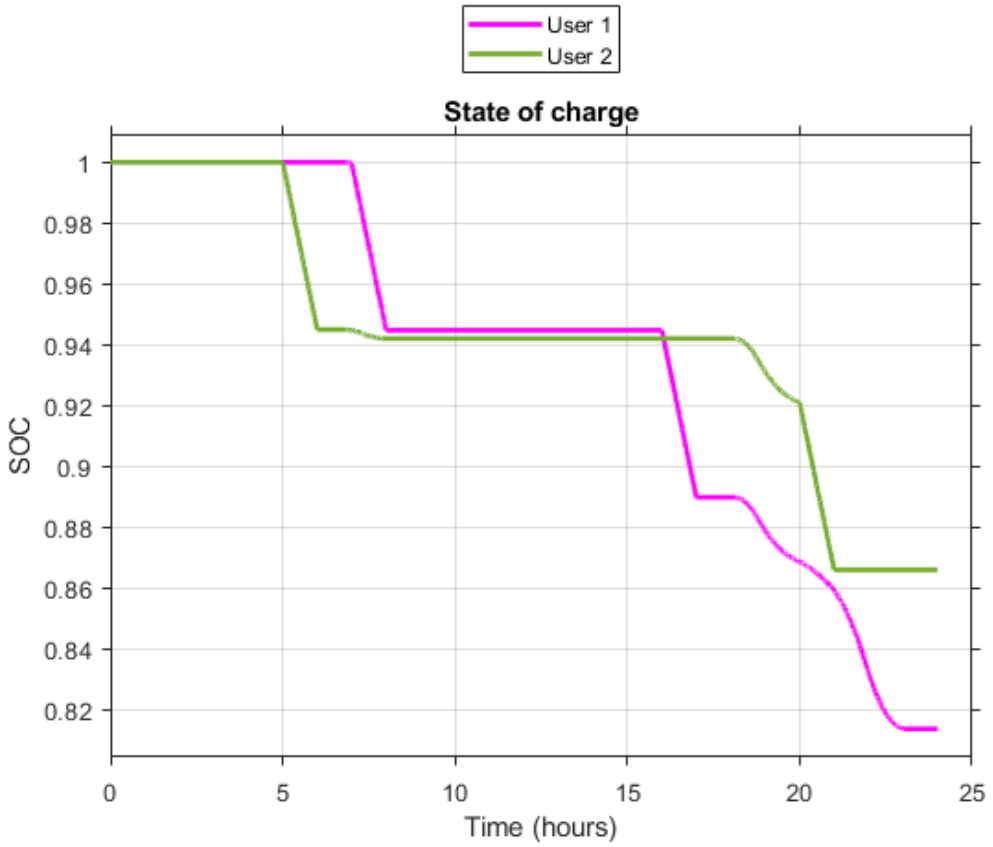

Figure 14 The SOC of the battery.

The resulting economic benefit for the EV owner in this specific household for the two users is seen in Figure 15. When using a real electricity price that varies during 24 hours, the revenue is low at around 7 and 3 SEK for user 1 and user 2 respectively. However, when using the higher, constant value, it is a clear increase and amounts to 45 SEK for user 1 and 14 for user 2. Overall, the money made from user 1 is greater than that of user 2, which is related to how much power was provided, since user 1 was able to peak shave the entire evening while user 2 was not.

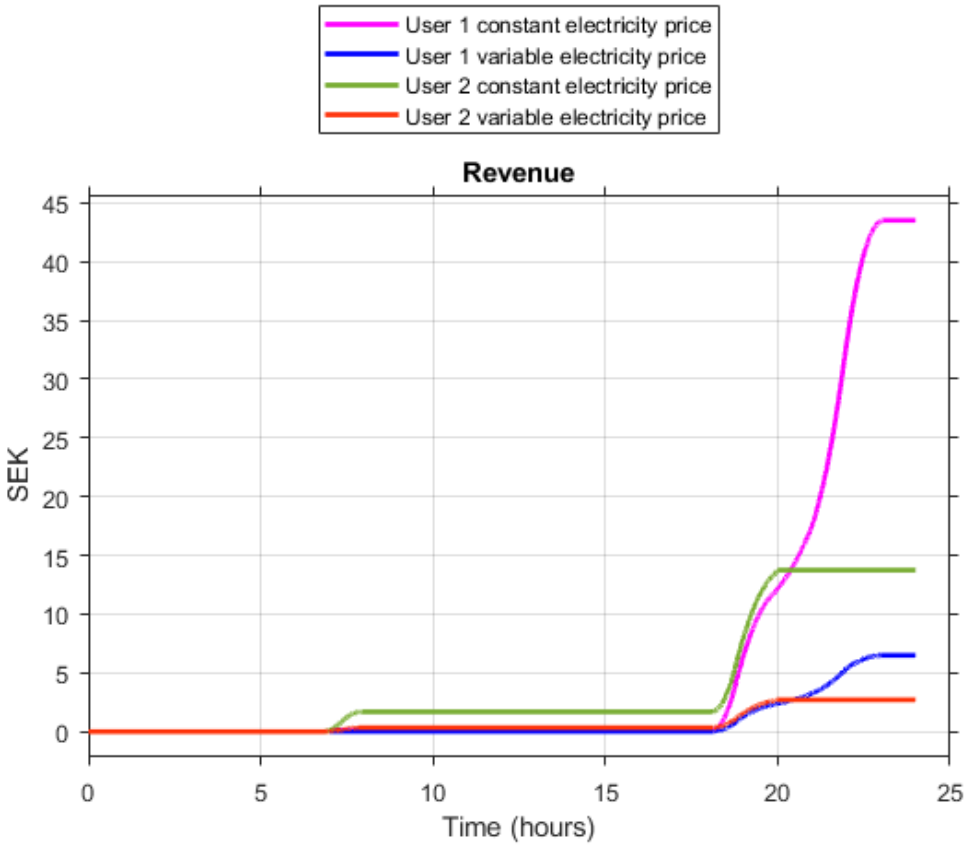

Figure 15 The calculated revenue from V2G using different prices.

5.2 Multiple households with 10 EVs

This section is similar to the previous one, with one main difference: in the results presented, there are 10 households and 10 EVs instead of 1. The type of results presented are the same, and it is the power from the batteries, the power from the grid, the SOC, and the economic benefits. It is also done for the 2 different user profiles, so there are 10 user 1's and 10 user 2's.

The power drawn from the 10 EVs is presented in Figure 16. Similarly to the single-load case, both users are able to peak shave mainly during the evening. However, the consumption during the day is larger, which makes it possible for user 2 to utilize V2G more than for the single-load case. Both user

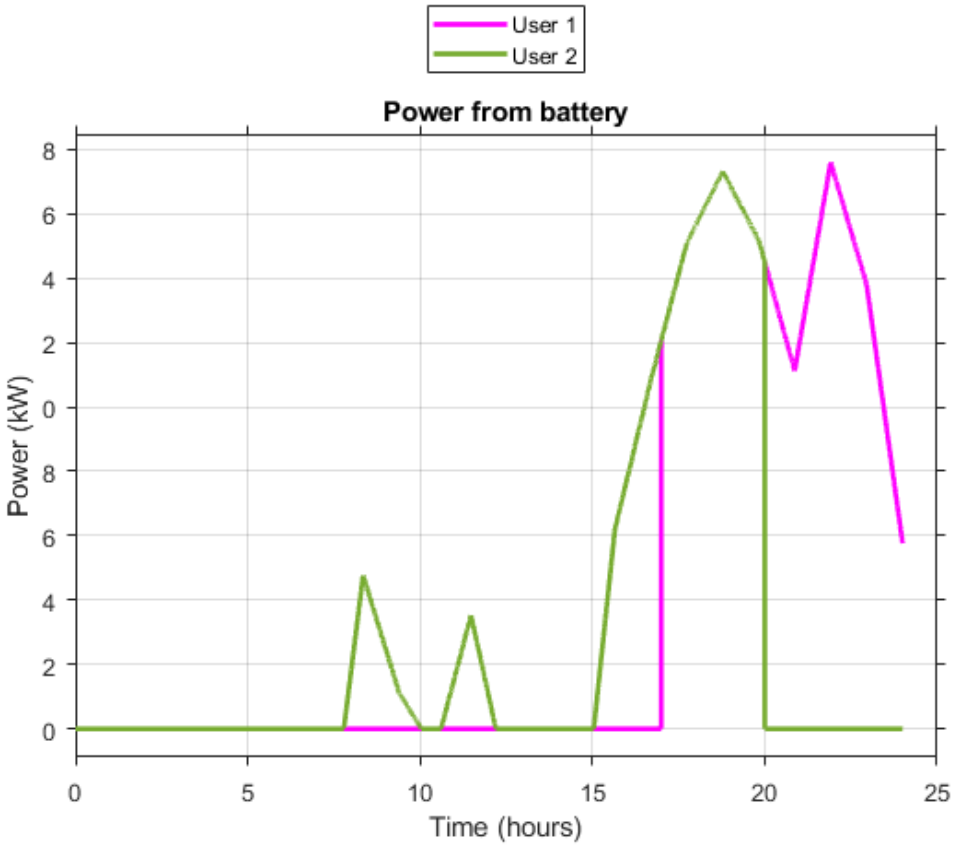

Figure 16 The power supplied to the loads from the batteries.

In Figure 17, the peak shaving potential for the different users are more obvious than for the single-load case. From around 7 am to 8 pm user 2 can provide a flattened power consumption, where user 1 still has clear peaks that are above the wanted limit. However, user 1 has the advantage after 8 pm, where a large peak occurs for user 2.

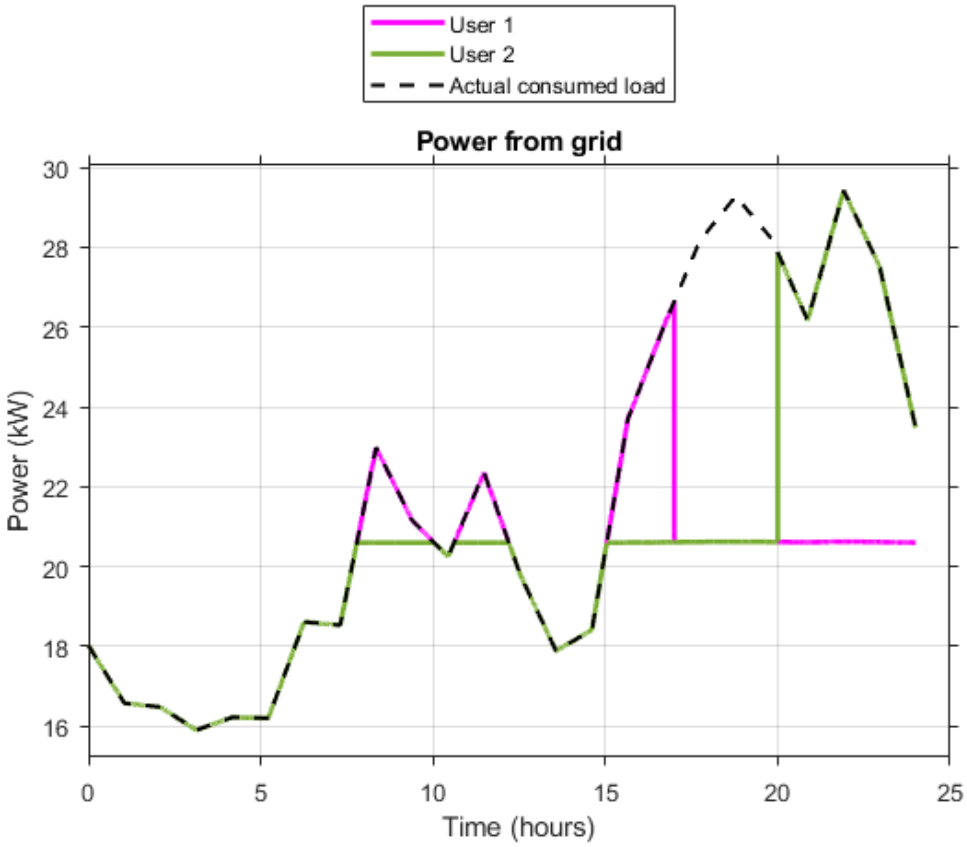

Figure 17 The consumed power as seen from the grid.

The resulting SOC for both users is presented in Figure 18. The SOC's are generally still high, at around 79 % and 82 % for user 1 and user 2 respectively, and do not differ from the SOC's in the single-load case in any major way.

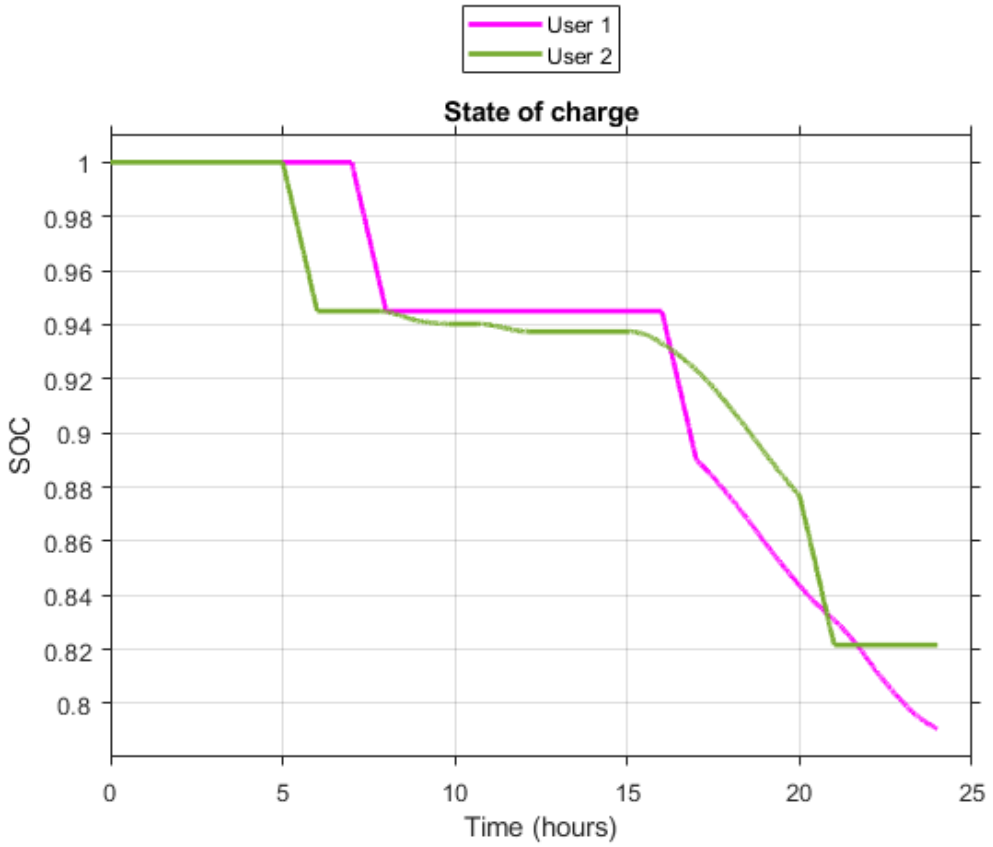

Figure 18 The SOC of the batteries.

The resulting economic revenue is presented in Figure 19. It has a similar shape as for the single-load case, with the constant electricity price resulting in a larger revenue for both users. The noticeable difference is that user 2 with a constant electricity price, in this case, earns money during the day and not only during the evening.

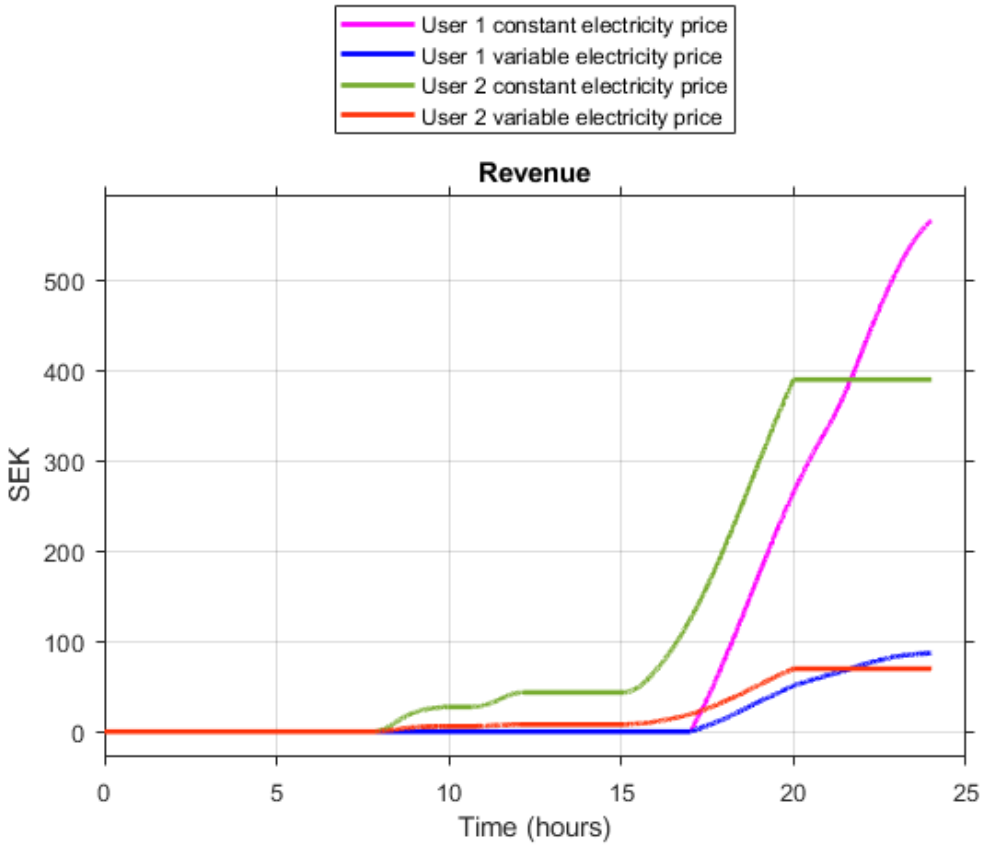

Figure 19 The calculated revenues from V2G using different prices.

5.3 Charging of the EV

The impact of charging one and two EVs is presented in Figure 20. The base load using the 10 households as previously peaks at around 29 kW. When adding so that one EV starts charging at full power of 11 kW at 5 pm the peak is clearly amplified by around 38 %. When an additional EV is added to the already existing one with the same charging power and duration, the base peak is amplified by almost 75 %. To put the impact into reference, in the single-load case the peak between 5 pm and 8 pm, which is when the EV is charging, is 2.8 kW. If the single household charges the EV with 11 kW, the new peak would be 13.8 kW which is an increase of 493 %.

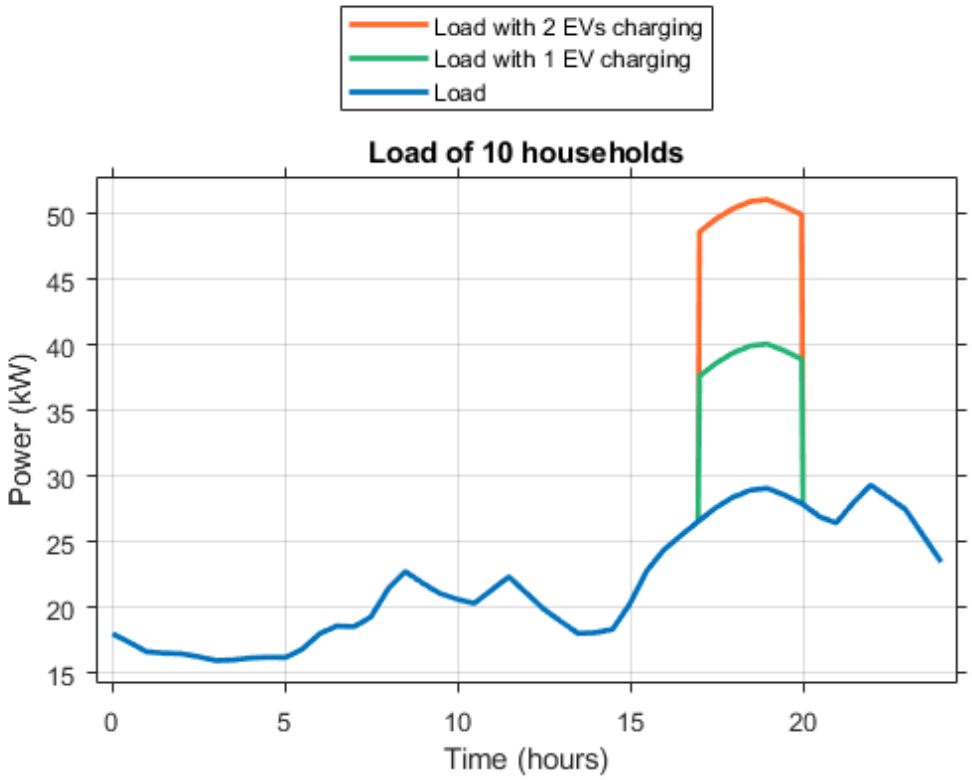

Figure 20 The consumed power while charging EVs.

6 Discussion

According to the results, V2G has great potential to be used for single and multiple households in Norway. The availability of the EV was a key factor in how much peak shaving could be done. The chosen load, for both single and multiple households, had most of their consumption in the evening. During most of the evening, user 1 was able to utilize V2G, which resulted in greater economic benefits compared to user 2, especially with a higher electricity price. User 2 had the benefit of being able to peak shave before 5 pm, when user 1 arrived. This was an advantage especially in the case of 10 households where during the day, the power consumption was higher than for the single-load case. The resulting SOC for both users, in both cases, was still sufficient and above 70 %. This result means that V2G can be used for further peak shaving by changing the previously set peak shaving limits of 50 % and 70 % of the peak power. It could also mean that the EV can be used further by the EV owner, for example even longer distances than the set distance to and from work. The fact that the 2 users have their EV available at opposite times, and were able to peak shave at different times, the most optimal would be to have a mix of both users so that they can complement each other. This was not done in the model, which only used 1 or 10 households with the same user profile. Charging the EV requires a large amount of power if charged at full speed. This was clearly visualized when one EV started to charge in the case of 10 households. The peak was amplified by 38 %, and by 75 % when charging 2 EVs. If all 10 EVs started to charge at the same time, the peak would thereby be amplified by 380 % which would be unwanted. Similarly, in the case of 1 household the peak was amplified by 493 % when a single EV was charged during the evening. In reality, everyone does not have the same usage patterns, so the chance of it happening would be low. However, it does demonstrate a point that smart charging is necessary in order to keep the grid stable by not allowing all EVs to charge with full power at the same time.

Norway was partly chosen because they have the largest share of EVs of all Nordic countries. However, not every vehicle in a neighborhood has to be an EV for V2G to work, as the results show that it can make a difference for a single household, and every decrease in peak demand could make a difference. Electrification of the transport sector is something all Nordic countries have in common, so even if Norway has a largest share of EVs right now it is difficult to say how it will be in, for example, 2050. The other Nordic countries have other similarities to Norway, one of which is that they all have a large share of RES. In addition, not only do they share and have similar climate goals, they also have a similar climate and culture, which means that electricity demand for heating and everyday chores should be similar as well. Therefore, the result of the study and how V2G can be used should not be limited to a specific area, or Norway, as similar countries have equivalent potential. If V2G was used on a larger scale, such as

cities, regions, or even countries, it would require a smart grid that in real time knows when, where, what, and for how long, EVs are available to know how much power it can provide. In the model the peak power consumption based on historic data and used to set a limit. It can be difficult to determine in the real world, but the system needs to know when it should start to peak shave. This would require a lot of data, not only from the continuous measurements but also from the users and their behavior in order to predict the potential peaks.

A downside of V2G is the battery degradation that occurs. Batteries have a limited number of charge and discharge cycles, and by utilizing V2G the battery will need to be changed earlier than it would have been necessary. EV batteries are expensive, and if the revenue from using a battery until it needs to be changed is less than the cost of a new battery, no EV owner would want to participate in V2G. The results show that there is an economic benefit, but would need to be compared with the loss that occurs when using the battery and at what price the electricity was bough in the first place when charging the EV. In that way, it could be determined whether any incentives are needed to increase the willingness of EV owners to participate in V2G. An additional downside related to increased battery degradation, is the fact that the production of batteries increases, which can lead to greater GHG emissions as it is an energy-heavy process. Furthermore, the GHG emissions are amplified by the large increase in EVs which also requires more batteries. A higher consumption of batteries also increases the number of batteries that are not properly recycled, which can lead to toxins in the soil and groundwater. Climate change can alter the availability of fresh water, which is used for agriculture and drinking, to name a few. By contaminating the groundwater with toxins from batteries the problem gets worse. This underlines the importance of properly recycling EV batteries as the number of EVs increases further.

The problem of GHG emissions from the energy-heavy battery production can be mitigated by using RES instead of fossil-fueled power. The Nordic countries have high RES, but are not the main producers of EV batteries. Instead, China, which has 60 % of its electricity from coal power, dominates the production of EV batteries [12]. An ethical aspect to consider is the fact that Cobalt is required in Li-Ion batteries. Cobalt is mainly mined in the Democratic Republic of Congo, where child labor is common. The mining conditions are toxic, and has a negative impact on the surrounding ecosystem and human health [12]. A solution would be that EV manufacturers have higher demands on the produced batteries, and avoid batteries that are produced with the use of fossil fuel, or for example, child labor. However, nearly all companies are driven by profit, and will most likely choose the cheapest option possible. And as a consumer, most EV are expensive as is, and further price increases could hinder the increase in EVs.

Another important consideration is the method of choice. First of all, the delimitations

and assumptions made. It was assumed that each household had an EV, and in reality the share of EVs is not 100 % in a neighborhood. The peak shaving effect for the case of 10 households is thereby not applicable in a real system unless the share of EVs is the same. The study focused on a day, 24 hours, but it could have been interesting to see the results for a full year with varying weather, load, and electricity prices in order to achieve a more detailed and realistic result. Power electronics is the basis for the bi-directional converters to work, but they were not modeled in this study. However, their efficiency was considered and implemented. The efficiency was high at 91 % for a single charge or discharge cycle. The effect of V2G would be decreased with a lower efficiency, as the power from the battery to the grid is directly dependent on the efficiency. Lower efficiency does not directly imply that the peak shaving potential would be lower, but it would drain the battery SOC faster, and the power from the battery could reach its limit. The power consumption limit were assumed based on the data for that specific day. In reality, the power consumption can be estimated instead to achieve a similar effect. When the EVs were driven they were assumed to do so for 1 hour, even though it was a 15.35 km trip. The time driving would likely be less than 1 hour, which would make the EV available for peak shaving for a longer duration resulting in a larger economic benefit.

The data that was used for the EV battery and household load are two of the things that determine the potential of V2G. There are larger batteries than the chosen one in other types of EVs, which would increase the potential. If a chosen load has smaller peaks, V2G might not be suitable. This could be, for example, an industrial building that might have a constant power consumption. A mix of different loads is preferable, as this would increase the potential of V2G for all hours of the day and be more realistic since all loads are not households. The results favored user 1, which was deemed to have a larger impact. However, one explanation could be that the chosen households data consisted of people with the same daily patterns as user 1. This implies that people might have gone to school/work between 8 am and 5 pm, and thus the consumption is lower during the day, as Figure 7 shows. If people worked between 9 pm and 6 am instead, the consumption during the day would probably have been higher, and the V2G potential for user 2 would be larger. To achieve a fair evaluation of the two users, the household data must match the user profile, which might not be the case in the model. It was assumed that when the user went to work, the EV was unavailable until it returned. If the user was able to utilize V2G while at work, the potential would be larger, as the EV would be available for 22 out of 24 hours instead of 14 hours. Lastly, the chosen loads were households. The potential of user 2 would be larger in another type of load where the main power consumption is during the day, like a school, an office or similar.

7 Conclusions

In this project, the potential of V2G and its negatives was studied by creating a model in Matlab/Simulink, consisting of 2 cases using 2 different user profiles. It follows the electrification of the transport sector, which will increase the number of EVs. The first case of the project was a single household load, and the second case consisted of 10 household loads. The household power consumption data is from Norway. The first user profile had its EV unavailable from 7 am to 5 pm, and the second from 8 pm to 6 am. When the EV was available, and the power consumption was high enough, peak shaving could begin according to an algorithm implemented in the model. With the increasing number of EVs, the importance of proper disposal of EV batteries becomes greater in order to not harm the environment. It is also necessary for EV producers and owners to take into consideration the ethical aspect, and under what circumstances the batteries are being produced.

The results show that using the EV batteries, power can be discharged to the grid and used to decrease peaks by up to 50 % in the power grid during periods of high demand. There was potential for additional peak shaving, but it was heavily dependent on the availability of the EV and usage patterns. What user is the most beneficial depends on the load, but a mix of both user profiles is preferable as they can utilize V2G at opposite times.

The results show that there are economic benefits for the EV owners that utilize V2G, but as the battery degradation is not considered in the model, the exact profitability cannot be calculated. Using a constant, and unusually high electricity price, the revenue from user 1 utilizing V2G can be up to 43 SEK per person and day. User 2 generally had lower revenue, but it can be because of how the load is chosen.

Charging an EV at full power can cause problems for the stabilitiy of the electric grid. In the case of 10 households, when charging a single EV during the evening when the demand is high, the base power consumption peak was amplified by 38 %. If all 10 households were to charge 10 EVs at the same time the peak would be amplified by 380 % which could cause problems for the stability of the grid. Similarly, in the case of 1 household the peak is amplified by 493 %. It underlines why smart charging is needed, to distribute the EV charging at periods of low demand and not amplify already existing peaks.

7.1 Future Work

There are several improvements in future work that can be made to improve the results. The model can be developed further to use power electronics, as this would be necessary in order to implement it in the real world. It can be achieved by, for example, using already existing converters to see if it is possible, and if not, what improvements to power electronics are needed. It is also necessary to investigate what technical limitations that the grid has, as it is necessary to be a smart grid to use V2G.

To see the potential of the 2 user profiles, more detailed data would be needed. The data would need to describe the user behavior and adapt the user profile thereafter. It could be the driving patterns, the working hours, the difference in power consumption during different seasons etc. It would also be an improvement to use data with a smaller time resolution, since when using hours the intra-hour behavior is not considered. To get a more realistic result, the simulation time should not be limited to 24 hours or a single type of load. By looking at 1 or more years, different kinds of loads, and varying electricity prices, the real-world potential becomes more realistic. Lastly, a method is needed to estimate when V2G peak shaving should start, as the current model uses static limits depending on the already known power consumption.

An important aspect that was not considered is the battery degradation. This would need to be included in any further work as the economical benefit is dependent on the battery degradation cost. Additionally, a more realistic model of the battery would be needed, as in the current model the battery performance is constant. This is especially important when utilizing the battery for V2G for a longer period of time.

As this report focuses mainly on power peaks in the electric grid, further work should also investigate how V2G can be used to mitigate the intermittency caused by some RES. The potential exists because of the combined amount of energy stored in EV batteries, and as the results showed large amounts of power can be supplied to the grid. However, the problem lies in that the weather is to some degree unpredictable and how can it be guaranteed that EVs are available for V2G at those times when needed.

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