Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

Balder Bryn Morsund

Analyzing the impact of increased electric vehicle penetration on cost and grid burden with bidirectional charging and solar energy production

Master's thesis in Energy and Environmental Engineering
Supervisor: Karen Byskov Lindberg
Co-supervisor: Åse Lekang Sørensen
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Abstract

The Norwegian government has set a target for all new personal vehicles sold in Norway to be zero-emission from 2025. This will lead to a significant increase in the number of electric vehicles. When the electrical car fleet expands, the energy demand of the transport sector and energy demand overall increases. This thesis answers how different grid tariff models, bidirectional charging with V2G, solar energy production, and energy meter locations impact the total cost and grid burden for an apartment block in Risvollan with 117 apartments and 70% EV penetration. The increase in EVs leads to smart and controlled charging rapidly emerging as a relevant topic. The question then arises about incentivizing controlled charging to avoid costly grid reinforcements. In the thesis, the Pyomo-based modeling tool BUTLER is adjusted to optimize the operational stage of the apartment block with bidirectional charging. The model has complete information on the future, optimizing for 2018, with measurement data for the apartment electricity load from Risvollan and EV charging session information for 82 EVs across Norway. A peak per monthly penalty tariff model leads to a decrease in maximum peak load 39% lower than uncontrolled charging. The peak load burden is negligible compared to having no EVs, thereby removing the need for grid capacity reinforcements due to higher EV penetration. On the other hand, solely having energy pricing tariffs leads to an increase in the maximum peak of up to 44% compared to uncontrolled charging. The amount of energy discharged by the EVs was generally low, but it occurred at the morning and afternoon peaks, thereby cutting costs and grid burden. The maximum income per kWh discharged from the EV achieved in a case is 0.69 NOK, reducing the total costs by 0.45%. The amount discharged on average per EV was far below what is considered to cause more than negligible capacity reduction on the EV batteries. Using the EVs as energy storage with bidirectional charging further increases the effectiveness of the solar panels, increasing the yearly self-consumption to 82%, from 72% without bidirectional charging. Having a separated energy meter for the apartments and the garage with peak per month tariffs leads to a flat charging profile over the day due to the flexibility of the EV charging, but when aggregated with the apartment electricity load, it leads to an overall increase in grid burden. This suggests that looking at EV charging load and apartment electricity load together can decrease the grid burden.

Sammendrag

Den norske regjering har satt et mål om at alle nye privatbiler solgt etter 2025 skal være nullutslipp. Dette vil føre til en stor økning i antallet elbiler og med det en økning i energibehovet til transportsektoren. Denne oppgaven undersøker hvordan forskjellige nettmodeller, toveislading med V2G, solenergiproduksjon, og plassering av strømmåler påvirker totale kostnader og nettbelastning for en boligblokk med 117 leiligheter og en elbilandel på 70%. Økningen i andelen elbiler gjør at smart og kontrollert lading får økende relevans. Det blir da viktig å besvare hvordan incentivere kontrollert lading for å unngå dyre oppgraderinger av nettet. Det Pyomo-baserte modelleringsverktøyet BUTLER er tilpasset for å optimalisere den operasjonelle fasen av en boligblokk med toveis elbillading. Modellen har komplett informasjon om fremtiden og optimerer for 2018, med måledata fra leiligheter på Risvollan og elbilladesesjoner fra 82 elbiler. En månedlig effekttariff fører til en nedgang i lasttopp 39% lavere enn med ukontrollert lading. Lasttoppøkningen blir neglisjerbar sammenlignet med lasttoppen uten elbiler, og fjerner dermed behovet for nettoppgraderinger. På den andre siden, med kun prisstyrt kontrollert elbillading fører til en økning i lasttoppen med opp til 44% sammenlignet med ukontrollert lading. Mengden med energi utladet fra elbilene var generelt lav, men skjedde samtidig med morgen- og ettermiddags-lasttoppen. Den høyeste inntjeningen oppnådd per kWt utladet for elbilene er 0.69 NOK, som reduserer de totale kostnadene med 0.45%. Mengden energi utladet per elbil var under hva som er antatt å forårsake mer enn neglisjerbar kapasitetsreduksjon for elbilbatteriene. Å benytte elbilens toveislading økte effektiviteten av solenergiproduksjonen og økte eget forbruk fra 72% til 82% årlig. Å ha en separat energimåler for leilighetene og garasjen med effekttariff førte til en flat elbilladeprofil, men førte til en økning i lasttoppene. Elbillading og leilighetsforbruk bør sees på i sammenheng for å begrense nettbelastningen.

Acknowledgements

I would like to thank my supervisor, Karen, and Co-supervisor, Åse, for continual support and guidance throughout this journey. I would also like to thank Marius Bagle and Kasper Thorvaldsen for providing help when stuck in some technicality. Lastly, I would like to thank Emma for cheering me on the whole way.

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Motivation

The Norwegian transport sector accounts for almost one-third of total mainland greenhouse gas emissions [8]. Electric vehicles(EVs) will be essential to offset these emissions in the future [13]. The Norwegian government has set a target for all new personal vehicles sold in Norway to be zero-emission from 2025 [14]. This will lead to a significant increase in the number of electric vehicles. When the electrical car fleet expands, the transport sector's energy demand and energy demand overall increase. This leads to potential increases in the grid burden. The current peak load hours of the grid occur in the afternoon. Today, most EV charging coincides with this peak. If current EV charging trends of charging in the afternoon continues, this could cost over 10 billion NOK in grid reinforcement investments by 2040 [12]. In contrast, if the charging is shifted out of peak load hours, the grid reinforcement costs due to increased EV demands could be negligible. EV loads become a valuable source of flexibility in the grid [20] since the vehicles are parked 80-90% of the time [25] [28],

16% of the Norwegian personal vehicle fleet consists of EVs. The number of EVs is rapidly rising, with two-thirds of all new vehicles bought being electric [4]. Outside Norway, trends are in the same direction, with The International Energy Agency(IEA) expecting 200 million EVs in the streets by 2030 [1].

The increase in EVs leads to smart and controlled charging rapidly emerging as a relevant topic [35]. The question then arises about incentivizing controlled charging to avoid costly grid reinforcements. Norway is discussing new grid tariffs to incentivize load shifting, moving towards paying for max energy capacity used in addition to the total amount of energy used [24]. As electricity prices increase, customers in Norway are becoming more price aware and want to control their electricity consumption. This has led to more loads becoming controlled by price signals. Blindly moving charging to the cheapest night hours could lead to new load peaks instead of peak shaving [10]. This stresses the importance of the peak load tariff design.

With the emergence of bidirectional EV chargers, EVs can also contribute to reducing the grid burden by feeding back electricity during peak hours, through vehicle-to-grid(V2G) or vehicle-to-home (V2H) [37]. The viability of this mode of operation depends mainly on battery degradation due to the increased number of charging cycles[18], but it is becoming more viable with increasing electricity prices.

1.2 Scope

The scope of the thesis is to analyze the effect of different charging strategies for a 70% electric vehicle penetration on an apartment block with electricity measurement data from 117 apartments in Risvollan, Norway. The research question to be answered through this analysis is how different grid tariff models, bidirectional EV charging, solar energy production, and energy meter locations impact total cost and grid burden.

The Pyomo-based modeling tool, BUTLER, as described in the master thesis [2], is adjusted to accommodate V2G, the EV input data, price inputs, and create an analysis framework.

This thesis uses real input data, but is simulated with full information for prices, EV connection times, and energy usage of the apartments. Hence the study will show the maximum potential for controlled charging for different strategies under different price regimes and vehicle-to-grid. Therefore achieving these results in real life is unattainable, but can give an idea of the effectiveness of the control strategies. Hence if the stategies are shown efficient at cutting costs or grid burden in these scenarios, the effect might not be as significant in real life, but if the effect is minuscule, it is more or less guaranteed to be negligible in practice.

1.3 Limitations

Several limitations and assumptions were made in this study, aiming to simplify without losing significance in the results. The optimization is limited to the operational phase. The investment cost of the technologies needed for the different solutions is ignored. Installation of PV panels will be highly beneficial, as costs are ignored, but the scope is to see how PV panels impact the different charging strategies and not if PV panels are a good investment.

The only optimization variables in this study are those connected to the charging and discharging of the EVs when connected. The connection time and charging demand of each charging event are given. Hence car owner decisions are not considered and can not be influenced in this study. Battery degradation of the EV batteries is ignored for the optimization, which is quite impacting as this constitutes a significant part of the cost of vehicle-to-grid operation. However, this will be discussed based on other studies of battery degradation. EV charging efficiency, charging power, and battery life cycle are likely to increase in the future, but the study ignores this.

The EV measurement data originate from 12 different places in Norway over three years, but are all assumed to happen in Trondheim in 2018. The study ignored weather and temperature changes, which would have affected the EV charging demand and the efficiency of charging and discharging. Cold temperatures increase the electricity demand of the apartments and the EVs, so some demand spikes might be flattened in this discrepancy between the temperature at the location of the study and the local temperature of the EV measurement. The study will also be limited to looking at the grid price model of one DSO, the regional DSO of Trøndelag, Tensio. This is to limit the number of cases.

2 Theory

2.1 Plug-in electric vehicles

Plug-in electric vehicles are fully or partly powered by electric energy from a battery. Typical battery sizes for Plug-in hybrid electric vehicles (PHEVs) are 5-15 kWh and 25-40 kWh for Battery electric vehicles (BEVs) [5]. The charging of PEVs can be categorized into three groups [10]:

- Slow charging, 1-phase AC, charging from standard electric plugs. At 230v and 16A, standard in many European countries, charging at 3.7 kW.
- Fast charging, 3-phase AC, surpassing the power of standard electric plugs, potentially available in residential or commercial areas. The charging power is normally between 10 and 20kW
- Ultra-fast charging, 3-phase AC or DC, requiring external chargers, reaching 50 kW or more.

Given the loads' size and increasing EV penetration, it could lead to problems for the electrical grid such as voltage deviations, power loss increase, transformer, and line overloads and harmonics [9].

2.2 Charging strategies for PEVs

In this thesis, controlled or smart charging is a reference to charging based on an optimization algorithm. The optimization algorithm is only based on price signals, reducing costs.

Therefore reducing the grid burden will come indirectly from price signals, such as peak tariffs, and not built into the optimization. Controlled charging is opposed to dumb charging, or static charging, where the EV starts charging at plug-in and charges until fully charged.

With low EV penetration, no specific EV integration is needed, and EVs can charge uncontrolled without excessive impact on the grid. To delay or prevent costly grid reinforcements, controlled or smart charging integration must be considered when the penetration increases. The most common strategy today is economically incentivizing night charging. However, this method can cause further power demand problems, with all PEVs starting charging simultaneously [27].

From the view of the DSOs, the PEVs could be categorized as a simple load with uncontrolled charging or off-peak charging, a flexible load with smart charging and valley filling, or a mobile battery unit with smart charging and peak shaving. These cases are illustrated in figure 1.

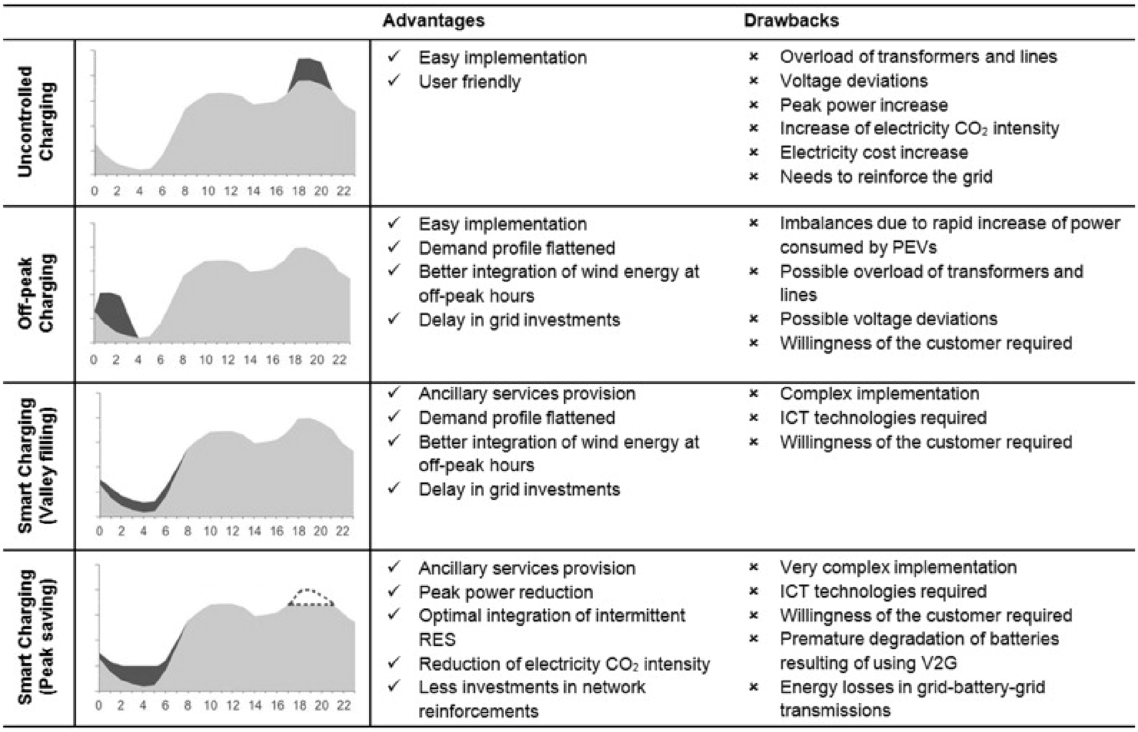


Figure 1: Advantages and drawbacks of the different PEV integration approaches. From [10]

The following paragraph is adapted from the project thesis [22]. The study [11] analyzed charging station data from a dutch case to simulate and analyze the flexibility of EV charging demand. They received data on plug-in time, connection time, and required energy. Charging sessions were defined as transactions with a charging duration and a connection duration. The flexibility potential was defined as the difference between the two. This differed from earlier studies which, for the most part, assumed a specific plug-in time and an average charging duration instead of basing it on real-world data. It was found that 59% of the total EV demand could be shifted for more than 8 hours and 16% for more than 24 hours. This pattern enabled a high degree of evening peak congestion management, contrary to dumb charging, further aggravating existing household peaks. In addition, they found smart charging to reduce congestion, minimize charging costs and increase the utilization of renewable resources. Similarly, it was found in another study [19] that most EV charging takes place during peak hours, between 16:00 and 21:00. This study was based on real-world data from San Francisco Bay Area, California, US, for approximately 400 households. In addition, it was found that with the introduction of distributed energy resources, EVs can either pose a problem, further increasing the disparity between peak load hours and peak generation hours, or be a solution, if incentivizing increasing of coincidence, charging at the same time as there is distributed energy source production. It was also found that incentivizing frequent plug-ins yielded the highest number of optimized charging events, resulting in 70% of charging being optimized at home. When disincentivizing over-generation, 63% of charging was shifted out of peak hours. When incentivizing plug-in during the hours with the highest solar production, they saw an increase in 6% of charging between 10:00 and 14:00 and found that it should be paired with peak hour shifting to utilize the full charging schedule. On average, the cost saved was between $0.20 and $0.77 per kWh charged.

2.2.1 Charging event characteristics

The energy demand of a charging session is dependent on the state of charge of the battery at the plug-in time, the end state of charge, the battery capacity, and charging efficiency. The time needed to recharge is dependent on the charging capacity, which is limited by the charging point, or characteristics of the EV as illustrated in figure 2 [29]. When the time needed to recharge is shorter than the time connected to the charging point, there are periods of non-charging idle time [29]. The EV could charge during this idle time, which constitutes the idle energy capacity. The idle energy capacity depends on the charging power, the battery capacity, and connection time of the EV [36].

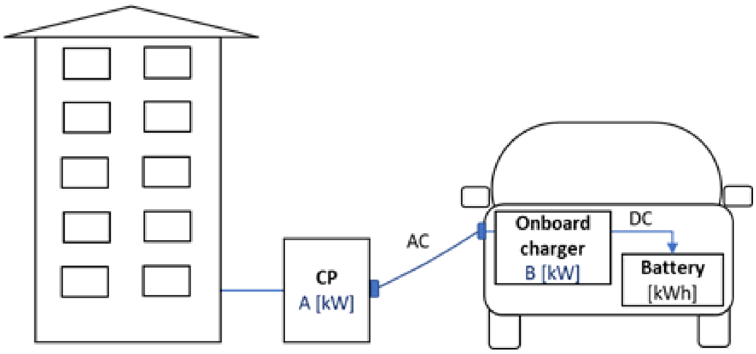


Figure 2: Charging power is limited by available AC power (A) and EV onboard charger capacity (B). From [29]

2.3 Vehicle-to-grid (V2G)

The batteries and power electronics of PEVs enable them to be an energy resource and feed electricity to the grid. When stationary, the PEV can feed either back to the grid or serve residential power demand, vehicle-to-home (V2H) [37]. This mode of operation is called vehicle-to-grid (V2G). The ancillary services provided include energy trading, earning the PEV owner money by spot price arbitrage, or providing grid services such as voltage, frequency, and load control [17].

2.3.1 Cost of V2G and battery degradation

The batteries of PEVs degrade with each charging cycle. The degradation rate depends on how much the battery capacity is discharged, referred to as the depth of discharge. V2G services increase both the amount of charging cycles and depth of discharge, increasing the rate of battery degradation [3].

There is still uncertainty regarding the effect of V2G on battery degradation. [6] found that the lifespan might be reduced by up to 50%. The Norwegian Water Resources and Energy Directorate (NVE) analyzed the cost of V2G in a Norwegian context [18]. A car in Norway drives around 12 000 km/year [23]. 6.8 km/kWh was assumed for a Nissan leaf, leading to an annual consumption of around 1800 kWh. Assuming 1 hour of discharge daily of 5 kWh, the annual consumption would almost double, halving the battery lifetime. Assuming battery degradation to be the only major cost component of V2G, with annuity factors of 0% and 15%, with the assumptions made by [18], the cost would be between 0.82 NOK and 0.41 NOK per kWh discharged. The annuity factor represents the car owner's valuation of future costs. As battery costs decrease and spot prices are likely to become more volatile, it was concluded that V2G is likely to be profitable in the future.

In [16] battery degradation due to V2G was found to be potentially less severe and affected by battery size. For a Nissan Leaf with a battery capacity of 30 kWh and a Tesla S with 100 kWh battery capacity for regular operation for 20 years, the battery health was found to be 83% and 97%. Delivering V2G services once a week had a marginal effect on battery health. Delivering V2G services seven times a week decreased battery health to 77% and 93%. The model did not include degradation due to aging, which could put the Nissan leaf under 70% battery health level, which usually is acceptable for mobility purposes over a 20-year lifetime. On the other hand, the Tesla S seemed to be a robust case, showing that with greater battery capacities, degradation becomes a less important factor, which is the trend for PEVs. The temperature was also shown to have the most significant impact on battery degradation, with the cold Norwegian climate being an advantage, slowing down the battery degradation.

2.4 Theoretical minimum viability of V2G

This section analyzes the minimum theoretical viability of a V2G charge and discharge cycle. It is looked at which factors influence the profitability of V2G and what circumstances are required.

Battery degradation is ignored but could be included in the cost of charging. It is assumed there is an available hour for charge and discharge while still covering the demand of the charging session. For simplicity, it will be looked at hourly, but it could be extended or shortened to any time.

The bottom line is that for V2G or V2H to be viable, due to the round trip efficiency losses, the difference between the cost of charging that hour and the income, or cost reduction, from discharge must satisfy

$$\pi > \frac{I^{dch} - C^{ch}}{\eta_{roundtrip}} \tag{1}$$

,where π is the profit from the charge and discharge cycle.

The costs are dependent on the spot price of the hour discharged, taxes and max import penalty costs, and the availability of local energy production, for example, from PV panels.

The income is dependent on the spot price of the hour discharged, prosumer compensation, if discharging to the grid, and whether or not there is available local electricity demand to be covered.

Local energy production has alternative uses, either exporting to the grid or covering local electricity demand, so there is an alternative cost to using local energy production.

2.5 Commercially available smart charging

This section is adapted from the project thesis [22].

The Norwegian electricity retailer, Tibber, provides a smart charging service for households. In this charging service, the customer inputs the time of departure, and the charging is then shifted to the hours of the lowest cost, prioritizing finishing charging the car battery. The service is provided for EVs from Audi, BMW, Jaguar, Mini, Tesla, Volkswagen, and Volvo, and all charging with the Easee charging point [34].

The Belgian company EnergyVille offers a more comprehensive smart charging system for households and shared parking spaces. Based on input on connection length and desired charge level, the charging can be optimized by user preference based on peak shaving, increasing renewable usage, or balancing demand and supply [7].

2.6 Mixed-Integer Linear Programming

The optimization problem is solved using Mixed Integer Linear Programming (MILP). It is commonly used for problems in the form of

$$\min c^T x \tag{2}$$

$$Ax = b \tag{3}$$

$$i \leq x \leq u \tag{4}$$

where equation 2 defines the objective, equation 3 the linear constraints and equation 2 the bound constraints. In addition, integrality constraints define that some or all x_j must take integer values. The integrality constraints enable discrete variable decisions, for example, whether or not a technology is used at a given hour.

2.6.1 Branch-and-Bound

The MILP is solved using the linear-programming-based branch-and-bound algorithm. Starting with the mixed-integer problem, P_0, all the integrality restrictions are removed. This results in a linear programming relaxation of the mixed-integer problem. The optimal solution is found if all integrality constraints are satisfied with this solution. This is seldom the case, and the procedure forward is to choose a restricted integer variable whose value in the relaxation is fractional and restrict it between integers. For example if the value in the relaxation for x is 3.4, the x is then restricted by $x \leq 3.0$ and $x \geq 4.0$, effectively excluding the value 3.4 for this variable.

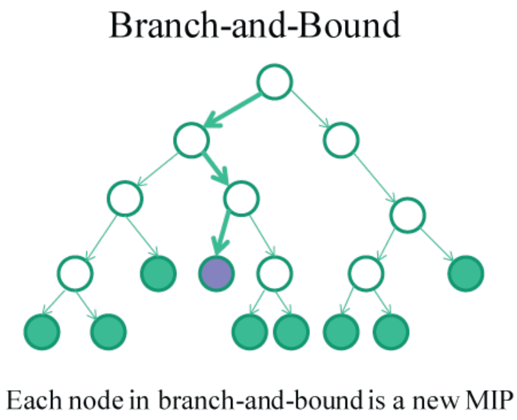


Figure 3: Illustration of Branch-and-Bound. From [15]

These two imposed restrictions form two new mixed-integer problems P_1 and P_2, where x is the branching variable. If both MIPs have feasible solutions, the optimal can be chosen. Otherwise, the procedure is repeated, generating a search three, with P_0 as the root node. If reaching a solvable node, this MIP is the solution to the original MIP. [15]

3 Data overview

3.1 Building electricity data

The building electricity data is a representative selection of 117 apartments from the housing cooperative Risvollan described by [30]. the data was gathered in 2018. Risvollan comprises 1058 apartments with an average annual electricity use of 4 362 kWh. Heating is supplied through district heating. The average maximum hourly load is 3.2 kWh/h and a coincidence factor of 0.323. Risvollan was constructed in the 1970s. There are one to four-bed room apartments, of sizes 52.9m^2, 83.5m^2, 104.8m^2 and 107.2m^2 respectively. 78% of the apartments are either two or three-bedroom apartments. The age demographic is 24% under the age of 20, 40% between 20 and 50, and 33% over the age of 50.

The peak load for the 117 apartments in the selection is 132.14 kWh/h 2018-12-31 16:00. The average load is 65.79 kWh/h for the whole year, 55 kWh/h for April to September, and 71.2 kWh/h for October to March. The load profile and duration curve can be seen in figure 4

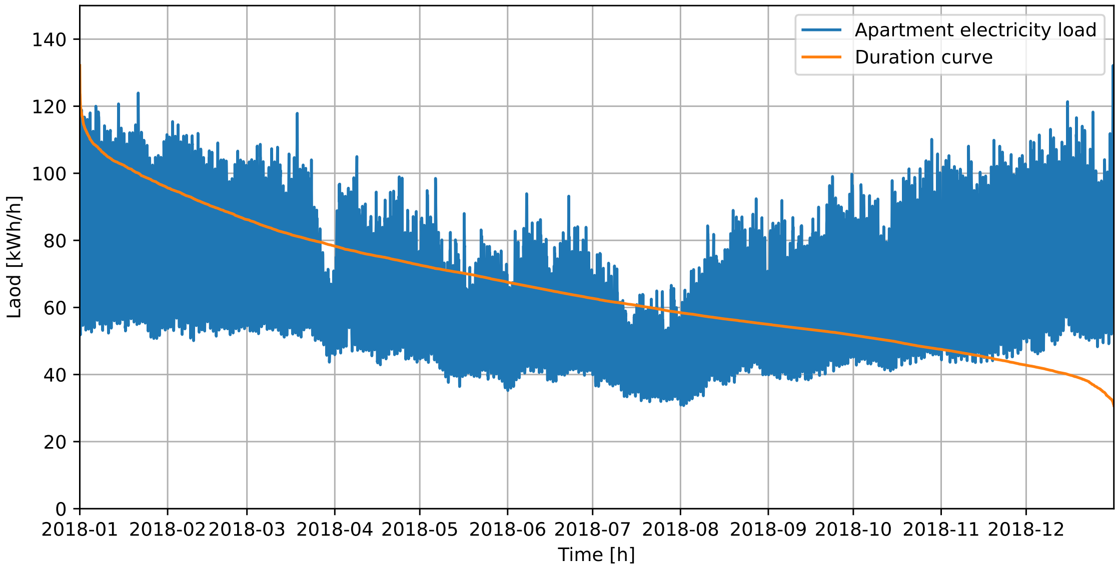


Figure 4: Apartment electricity load and duration curve

The average electricity use profiles for Risvollan can be seen in figure 5 for winter and summer. As heating is not served by electricity, the summer and winter profiles are of similar magnitude. There is an evening peak every day between 15:00 and 20:00. However slightly more spread out during the weekends.

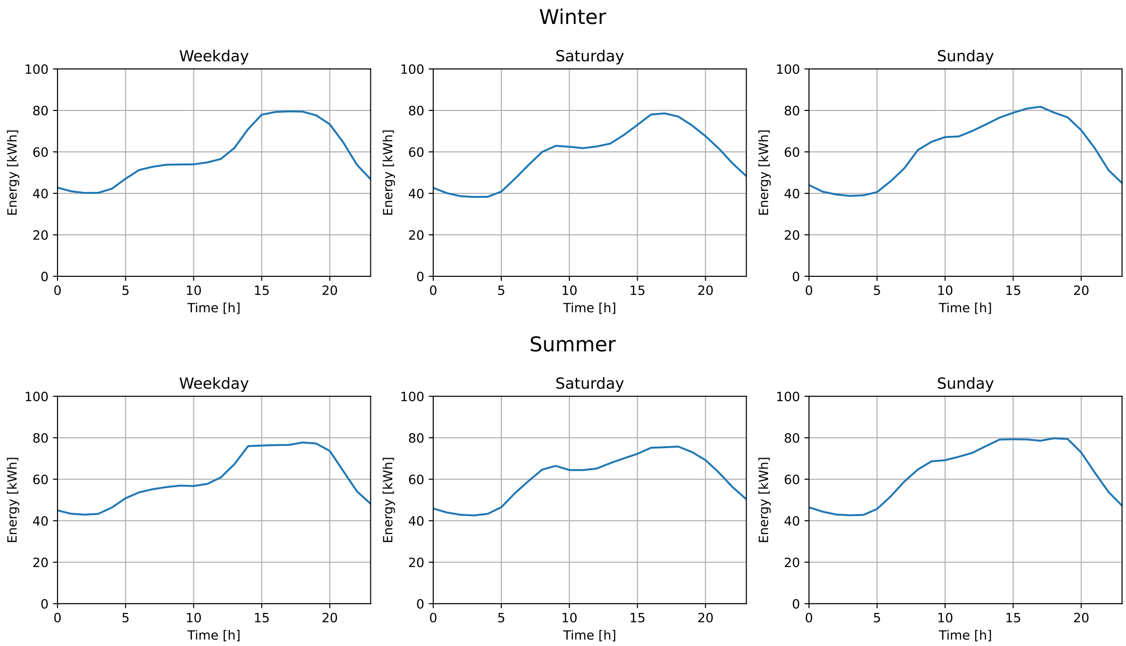


Figure 5: Average day profiles for the building electricity use

3.2 EV data

The EV charging session data used in this study is based on data from [29]. The data is based on 35 000 charging sessions for 267 users and 12 residential locations in Norway.

Table 1 shows the input data available per session.

Table 1: Input data divided into charging report data and estimated data per charging session. Adapted from [29]

Input data from EV charging reports	Estimated output data
User ID	Charging power [kW]
Session ID	Battery capacity [kWh]
Plug-in time	SoC at plugin [%]
Plug-out time	
Connection time [h]	
Energy charged [kWh]	

The data was collected between February 2018 and August 2021. This study only includes data collected pre-COVID-19. The data was also transformed to fit 2018. The complete data sets consist of 82 EVs over 15092 charging sessions.

Table 2: EV charger limit and battery size for the EVs in the selection

EV lim	Number of Evs	Battery size	Number of Evs
Less than 4 kW	51	Less than 20 kWh	22
Between 4 and 8 kW	21	Between 20 and 50 kW	41
Above 8 kW	10	Above 50 kW	19

Figure 6 describes the session input data to the model, divided over the 12 locations. All locations have an afternoon peak around 16:00-17:00, coinciding with the end of a typical workday in Norway, and a corresponding morning peak at around 7:00-8:00. The overall average connection time is 12.7 hours, and the 90 percentile of the sessions last less than 22.1 hours. The average energy charged per session is 12.7 kWh, with an average of 3.9 charging sessions per week.

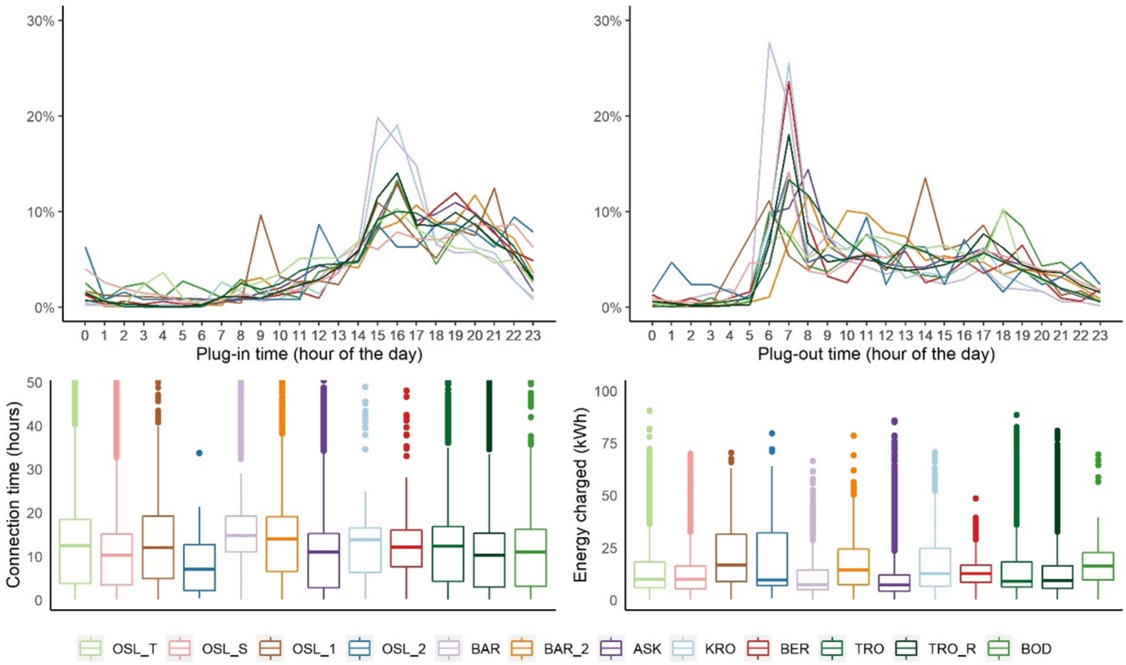


Figure 6: Plug-in times, plug-out times, connection times, and energy charged in the EV data locations. From [29]

The daily load profiles are shown in figure 7

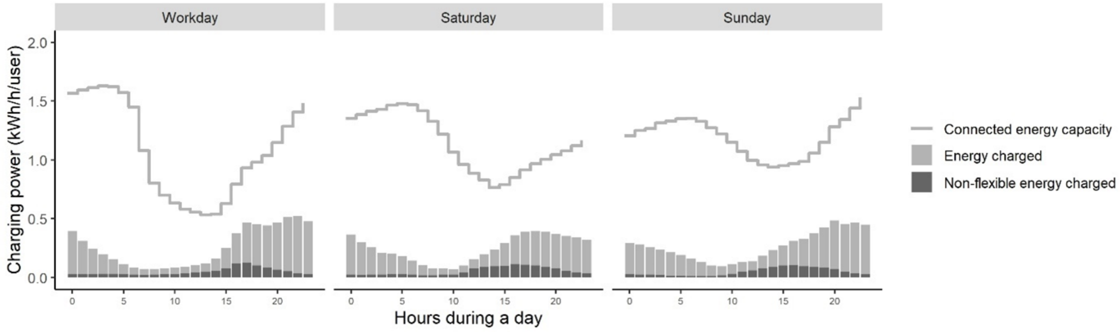


Figure 7: Fig. 10. Daily load profiles per user: Energy charged, non-flexible energy charged (idle time < 1h). From [29]

3.3 PV data

The PV production data is simulated for Risvollan with the software PVsyst with climate data from 2018 and is described in [31]. The installed PV capacity is 117 kWp, with input data to PVsyst described in table 3.

Table 3: Input data and system information for the simulated PV systems, with climate data for 2018 from [30]

Location	Latitude 63.39° N, Longitude 10.44° E, Altitude 116 m
Horizon	From GVGIS website API
PV module	Si-poly, 285 Wp, 72 cells (generic), 14.78% efficiency at STC
Inverter	12 kWac inverter (generic)
PV capacity [kW_p]	1
Module area [m^2]	6.8
Produced electricity [MWh/year]	0.75
Spesific prod [kWh/kWp/year]	754

3.4 Spot Prices

An essential part of the grid costs is the spot price cost, which varies based on demand and supply on the Nord Pool spot market. The spot prices are gathered from Nordpool [26], with prices from N03, Trondheim 2018 and NO1, Oslo 2021, as seen in figure 8.

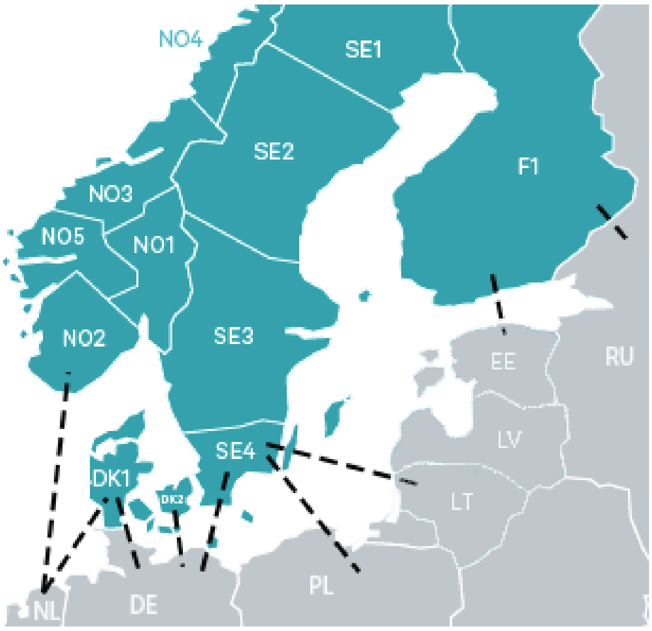


Figure 8: A map overview of the Nord Pool market coupling from [21]

The baseline is the prices for Trondheim in 2018, with the prices from Oslo 2021 as a sensitivity analysis, as this year had more volatile prices, with more significant price differences. The hourly spot price curves can be seen in figure 9.

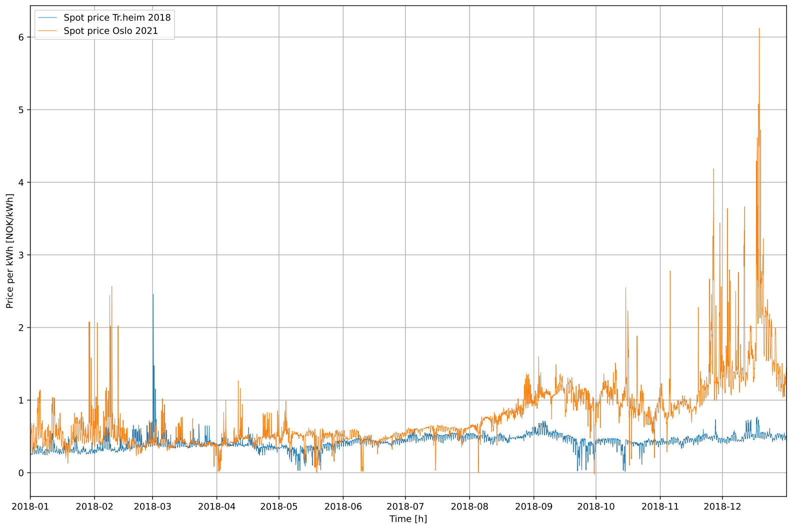


Figure 9: Spot prices for Trondheim 2018 and Oslo 2021

4 Model description

In this section, firstly, the set, variables, and parameters are presented, followed by the equations used for the optimization, the objective function, energy balance constraints, and EV constraints.

4.1 Sets, variables and parameters

Table 4: Nomenclature and description of model sets, variables and parameters

Symbol	Description	Unit
	Sets	
$\mathcal{V}$	Set of all electrical vehicles	-
$\mathcal{E}$	Set of all charging events	-
$\mathcal{T}$	Set of all time steps in the model	-
$\mathcal{T}_e$	Set of all time steps per event in E	-
$\mathcal{M}$	Set of all months in the model	-
$\mathcal{T}_m$	Set of all time steps per month in M	-
	Variables	
y_t^{imp}	Energy imported at time step t	h
y_t^{exp}	Energy exported at time step t	h
$y_m^{\text{max\_imp}}$	Max energy imported per month	kW/month
$y_t^{\text{imp,apt}}$	Energy imported for use in apartments at time step t	kWh/h
$y_t^{\text{imp,cmn}}$	Energy imported to charge the EVs at time step t	kWh/h
$y_{v,t}^{\text{ch}}$	Energy charged per EV at time step t	kWh/h
$y_{v,t}^{\text{dch}}$	Energy discharged per EV at time step t	kWh/h
δ_t^{ch}	=1 if battery is charging at time step t	Boolean
z^{SoC}	State of charge of the battery at time step t	%
	Parameters	
D_t^{EL}	Electricity demand of the apartments at time step t	kWh/h
Y_t^{PV}	Energy produced by PV panels at time step t	kWh/h
$D_{v,t}^{\text{EV}}$	Uncontrolled charging demands per EV per time step t	kWh/h
$\Lambda_{v,t}^{\text{EV}}$	Availability of the EV per EV at time step t	Boolean
$D_{v,e}^{\text{EV}}$	Energy demand per charging event e	kWh
EV_v^{lim}	Charger limit per EV	kW
EV_v^{bat}	Battery size per EV	kWh
η^{ch}	Battery charging efficiency	-
η^{dch}	Battery discharging efficiency	-
z_{init}^{SoC}	Initial state of charge of the battery at plug-in	%
δ^{V2G}	Activation of V2G operation mode	Boolean
δ^{PV}	Activation of PV	Boolean
δ^{UNC}	Activation of uncontrolled charging	Boolean
δ^{apt}	Activation of energy flow from garage to apartments	Boolean
C^{fxd}	Total fixed costs	NOK/year
P_t^{spot}	Spot price at time step t	NOK/kWh
C^{eno}	Enova fee	NOK/kWh
C^{cons}	Energy consumption fee	NOK/kWh
C^{trans}	Energy transport fee	NOK/kWh
C^{VAT}	25 % value added tax	Percentage
C^{comp}	Prosumer compensation	NOK
C_m^{pty}	Peak per month penalty cost	NOK/month/kW

4.2 Objective function

The main objective is to minimize the costs in the operational phase, given by the equation 5. It is dependent on the import and export costs defined in equation 6 and 7

$$C_{tot} = C^{fxd} + \min\left(c_{imp} - c_{exp}\right) \tag{5}$$

$$c_{imp} = \sum_{m \in \mathcal{M}} \sum_{t \in \mathcal{T}_m} \Big(C^{\text{eno}} + C^{cons} + C^{trans}) y_t^{\text{imp}} + \delta^{PPM} (C_m^{\text{pty}} y_m^{\text{max\_imp}}) + P_t^{\text{spot}} y_t^{\text{imp}} C^{VAT} \Big) \tag{6}$$

$$c_{exp} = P_t^{\text{spot}} y_t^{\text{exp}} (1 + C^{comp}) \tag{7}$$

4.3 Energy balance constraint

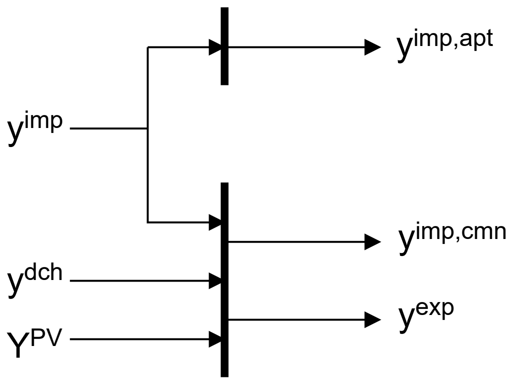
The energy balance for the system dictates the flow of energy. The energy imported by the system from the grid is the sum of the energy use of the apartments and the common electricity use, as shown in equation 8. The common electricity use is the sum of the energy charged and discharged for every EV, the PV produced and the energy exported to the grid as shown in equation 9. For this study, the apartment energy use is uncontrollable and equal to the electricity demand of the apartments, as shown in equation 10. For the *apt*-cases, energy from PV production and V2G discharge can be used by apartment electricity load when the boolean $\delta^{apt} = 1$.

$$y_t^{\text{imp}} = (1 - \delta^{apt}) y_t^{\text{imp,apt}} + y_t^{\text{imp,cmn}}, \quad \forall t \in \mathcal{T} \tag{8}$$

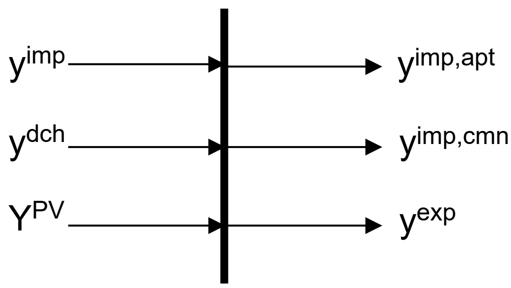
$$y_t^{\text{imp,cmn}} - y_t^{\text{exp}} = \sum_{v \in \nu} (y_{v,t}^{\text{ch}} - \delta^{V2G} y_{v,t}^{\text{dch}} \eta^{dch}) + \delta^{apt} y_t^{\text{imp,apt}} - \delta^{\delta^{PV}} Y_t^{\text{PV}}, \quad \forall t \in \mathcal{T} \tag{9}$$

$$y_t^{\text{imp,apt}} = D_t^{\text{EL}}, \quad \forall t \in \mathcal{T} \tag{10}$$

Figure 10 shows the energy balance schematically for $\delta^{apt} = 0$ and δ^{apt} = 1.



(a) δ^{apt} = 0



(b) δ^{apt} = 1

Figure 10: Energy balance load flow diagrams

4.4 EV constraints

The charging and discharging of each EV, v, limited by equation 11 and 12

$$y_{v,t}^{\text{ch}} \leq \Lambda_{v,t}^{\text{EV}} EV_v^{\text{lim}} \delta_t^{ch}, \quad \forall t \in \mathcal{T}_e \tag{11}$$

$$y_{v,t}^{\text{dch}} \leq \delta^{V2G} \Lambda_{v,t}^{\text{EV}} EV_v^{\text{lim}} (1 - \delta_t^{ch}), \quad \forall t \in \mathcal{T}_e \tag{12}$$

The charging for each hour is also limited by

$$y_{v,t}^{\text{ch}} \geq \delta^{UNC} D_{v,t}^{EV}, \quad \forall t \in \mathcal{T}_e \tag{13}$$

For each event, e, the charging and discharging must be greater or equal to the total demand of the event.

$$\sum_{t \in \mathcal{T}_e} (y_{v,t}^{\text{ch}} - y_{v,t}^{\text{dch}}) \geq D_{v,e}^{\text{EV}}+, \quad \forall e \in \mathcal{E}, \forall v \in \mathcal{V} \tag{14}$$

The state of charge is constrained by

$$z_t^{\text{SoC}} \leq 100 * \Lambda_{v,t}^{\text{EV}}, \quad \forall t \in \mathcal{T}_e \tag{15}$$

And further by

$$z_t^{\text{SoC}} = z_{t-1}^{\text{SoC}} + \frac{y_{v,t}^{\text{ch}}}{EV^{bat}}_v * 100\% * \eta^{ch} - \frac{y_{v,t}^{\text{dch}}}{EV^{bat}}_v * 100\% *, \quad \forall e \in \mathcal{E}, \forall v \in \mathcal{V} \tag{16}$$

For the first hour

$$z_t^{\text{SoC}} = Z_{init}^{\text{SoC}} + \frac{y_{v,t}^{\text{ch}}}{EV_v^{bat}} * 100\% * \eta^{ch} - \frac{y_{v,t}^{\text{dch}}}{EV_v^{bat}} * 100\% \tag{17}$$

5 Case study

In order to illuminate different aspects and effects of grid price models, charging strategies, DER production, and billing meter location, several different cases will be studied. Firstly the system components will be introduced, before the billing meter locations, then the grid price models and lastly an overview of all the case labels and cases.

5.1 System components

The main components of the case study are the apartment electricity load, the charging demand and battery discharge of the EVs, the PV production, and the power grid. These components constitute the system's energy flows, shown in figure 11. The arrows of the lines describe the direction of the energy flow and the color of the energy source. As seen from the figure, the base configuration is for the power grid to serve the apartment electricity demand and the charging station demand.

The label of the switches corresponds to case labels, δ^{PV} referring to the PV-cases with PV production, δ^{V2G} referring to the V2G-cases with battery discharge, and δ^{apt} referring to the apt-cases where local energy production from PEV discharge and PV production can serve apartment electricity demand.

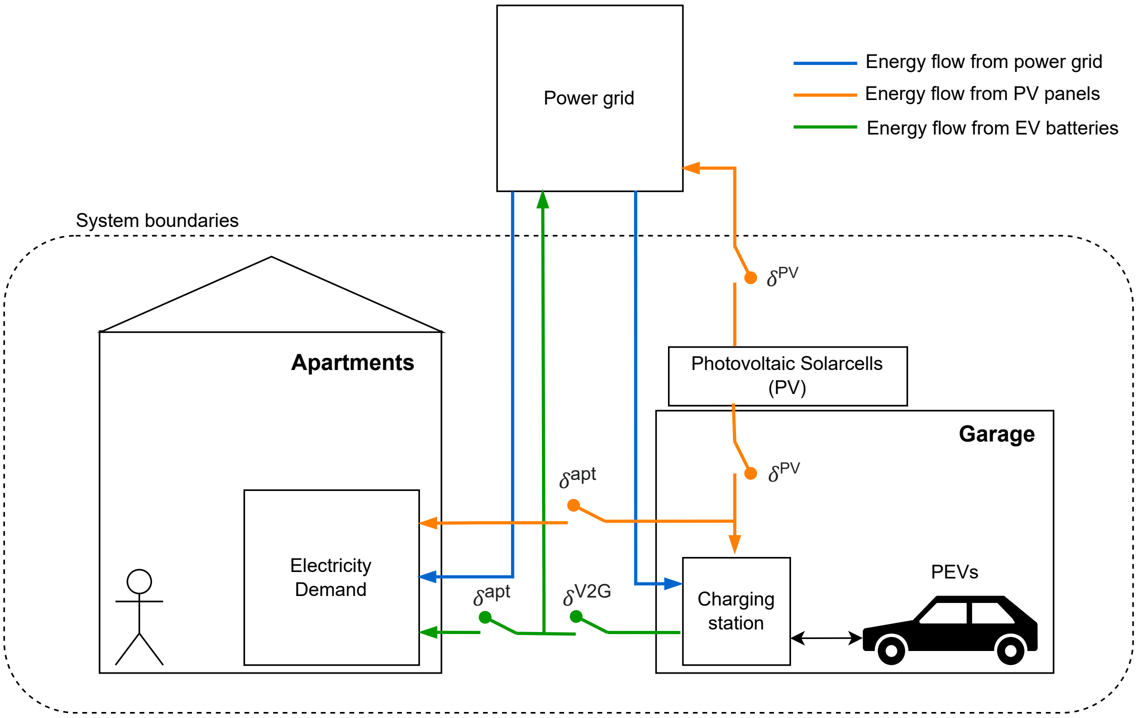


Figure 11: Energy flow in the different cases

The apartment electricity load is described in section 3.1, and the PEV charging demand is described in section 3.2.

5.2 Grid tariffs

As Risvollan is situated in the zone of the DSO, Tensio, their grid rental prices for 2018 are used as a reference [32].

Table 5: Grid rental prices 2018 from [32]. VAT is included in all prices

		EP	PPM
C^{fxd}	Fixed cost, apartments [NOK/year]	1875	1875
C^{fxd}	Fixed cost, garage [NOK/year]	10000	10000
C^{eno}	Enova tariff [Øre/kWh]	1.25	1.25
C^{cons}	Consumer tariff [Øre/kWh]	20.725	20.725
C^{trans}	Energy transport tariff [Øre/kWh]	20.625	6.25
C_m^{pty}	Peak load tariff(Jan,Feb,Nov,Des) [NOK/month/kW]	0	75
C_m^{pty}	Peak load tariff (Mar-Okt) [NOK/month/kW]	0	56.25

As described in section 5.4, the total cost is assumed to be one metering point, except for the sep-case where there are two separate cost calculations. To make the total cost more realistic, however, one fuse box/billing point is assumed per apartment. The fixed apartment cost, as seen in table 5, is for a fuse of 63A at 230V or less. The fixed cost for the garage is for a fuse of 125A at 230 or greater. The total fixed cost is assumed to be the same for both the energy pricing tariff(EP), and peak per month tariff(PPM).

5.2.1 Peak penalty cost

A peak penalty cost is a penalty cost aimed at reducing peak loads by penalizing the peak load, for example, within a month, per kW. This creates a clear incentive to flatten the load throughout the month.

5.3 Export to the grid

When exporting surplus energy to the grid, the consumer is paid the spot price at the hour of export. However, DSOs compensate for reduced grid losses due to the locally produced energy. Consumers that produce surplus energy can sign a plus customer agreement with Tensio, gaining a reduction in grid costs equal to

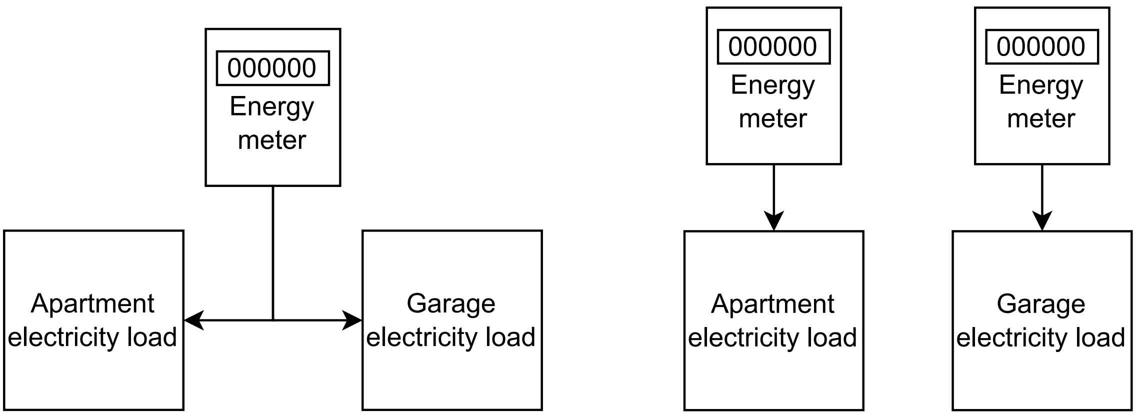
$$Reduction[NOK] = Export[kWh] * SpotPrice[NOK/kWh] * MarginalLossRate[\%] \quad (18)$$

There was no defined plus customer agreement for 2018, so the marginal loss rate is from the Tensio 2019 agreement [33]. The marginal loss rate is 6.5% for winter days, 6% for winter nights/weekends, and 5% for the rest of the year. Winter/summer is defined in the same way as table 5

These prices are also used for the sensitivity analysis of spot prices from Oslo 2021.

5.4 Billing meter location

The two billing meter locations are shown in figure 12. Most cases are described by figure 12a, where minimizing the costs according to the objective function 5, both done apartment demand and PEV demand are taken into consideration. This is crucial for the PPM-cases as a significant part of the peak penalty cost is related to the cost. For the sep-case, they are calculated separately with two meters as seen in 12b, however, the fixed cost is assumed to be the same.



(a) Billing meter location for the majority of cases

(b) Billing meter location for the sep-case

Figure 12: Billing meter locations for the different cases

5.5 Method

The first step of the optimization is data import. In this step, the apartment electricity demand, technology parameters, grid price parameters, spot price, solar irradiation, and EV data is loaded into the model. The EV charging session data are grouped into user ID, plug-in and plug-out time, charging demand, charging power, battery size, and the initial state of charge. This data is used to create a Boolean parameter with the hourly resolution of the car availability per EV, 1 if the car is connected and 0 if disconnected. This data is then sent to the optimization.

5.6 Case label description

The different case classes are EP, PPM, PV, V2G, STC, apt, and sep. They will be described in this section.

STC
Cases labeled STC have uncontrolled, dumb EV charging, meaning that they start charging when plugged in and until fully charged. All cases except STC include controlled charging, following the optimization explained in section 4.2.

EP
EP refers to energy pricing, with the grid cost only varying based on the spot price, as explained in section 5.2.

PPM
PPM refers to peak per month tariff pricing, with a lower energy transport tax but a peak tariff tax, based on the max energy import month. As explained in section 5.2

PV
Cases labeled PV include photovoltaic energy production, which can either be used for garage electricity use, in this thesis, charging the EVs or exported to the grid. The energy produced can also be used for the apartments in the apt-cases.

V2G
In the V2G-cases, energy can be discharged from the EV batteries for garage electricity use or exported to the grid. This is further explained in section 4.4 In the apt-cases, the energy produced can also be used for the apartments, meaning that for simplicity, V2G in this thesis signifies bidirectional charging.

OSL21
The OSL21 label signifies that the case uses the spot prices from the Nordpool region Oslo from 2021, and the other cases use spot prices from the Nordpool Trondheim region from 2018.

apt
Cases labeled with apt signify that the apartment electricity usage can also consume the local energy production from PV and V2G, putting the apartment electricity demand behind the same meter as the garage electricity usage.

sep
In cases labeled sep, there are two separate billing meters, where the garage electricity usage is billed according to a peak per month tariff model, while the apartment electricity use is billed according to an energy pricing model. The fixed cost is kept the same.

6 Results

In this section, the result of the case study is presented. First, the total costs are investigated and compared in section 6.1. Then the different case's impact on grid burden is explored in section 6.2 . This is followed by three sensitivity analyses, spot prices from Oslo 2021, separated metering points and EV charger capacity of 10kW in section 6.3, 6.4 and 6.5 respectively.

6.1 Cost reduction

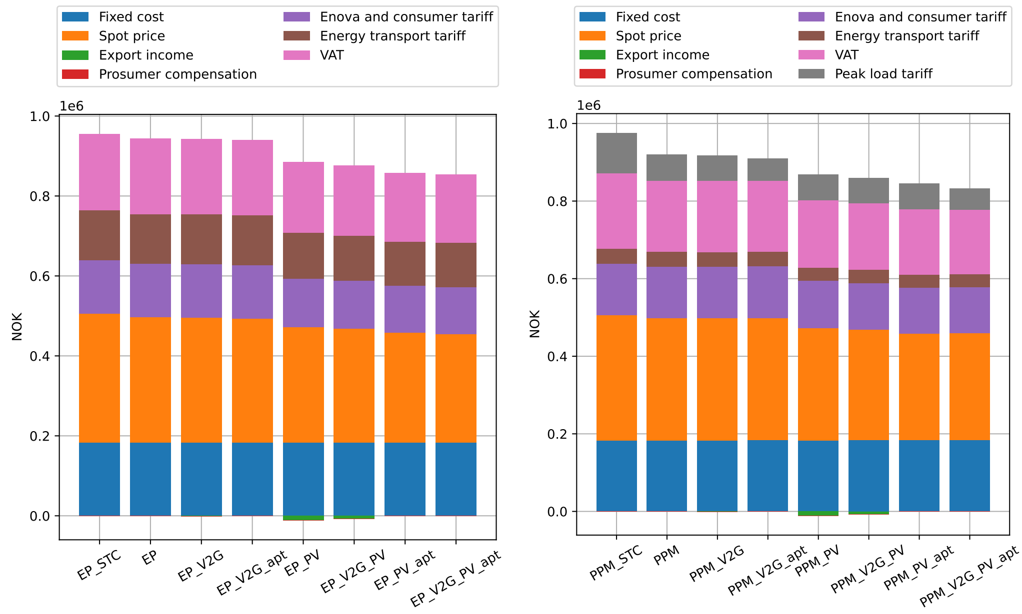
Firstly an overview of the cost of all the cases will be given before the classes of cases, and their impact on total cost will be explored individually, in the order of grid tariffs, PV production, V2G, and metering location.

Table 6 shows the KPIs of all the cases with the spot prices for Trondheim 2018. As shown in table 6, the most expensive case is the PPM_STC-case. This case has dumb, uncontrolled charging with a peak tariff price model. The objective function value is 976042 NOK, the peak load of 218 kW, and daily peak hour on average around 18:00. The second most expensive is the EP_STC, dumb charging with energy pricing, with the same peak load and average daily peak load. This is because these cases have the same load profiles, with only the price model varying. The case with the lowest total cost is PPM_V2G_PV_apt, with a total cost of 833 023 NOK. This is due to the case having the most opportunities to cut cost through V2G discharge, PV production, using local energy production for the apartment electricity load, and lastly, cutting cost through keeping the peak loads low, and not only through using electricity at the cheapest hour, as in the EP-cases.

Table 6: Key performance indicators for the main cases

Case	**Objective value [NOK]**	**Sum imported [kWh]**	**Sum exported [kWh]**	**Peak load [kW]**	**Daily peak hour [h]**
PPM_STC	976 042	759 983	0.00	218.93	17:54
EP_STC	955 744	759 983	0.00	218.93	17:54
EP	943 822	756 445	0.00	289.18	04:54
EP_V2G	942 224	757 861	530.21	291.37	04:42
EP_V2G_apt	939 988	759 931	0.00	293.03	04:54
PPM	920 430	756 464	0.00	132.91	01:18
PPM_V2G	916 237	756 938	266.10	132.14	01:00
PPM_V2G_apt	909 971	758 209	0.00	120.63	00:18
EP_PV	873 039	692 702	24 433	289.18	07:00
EP_V2G_PV	868 559	684 936	15 050	289.99	07:42
EP_PV_apt	857 390	668 244	0.00	289.18	04:42
PPM_PV	856 923	692 815	24 558	132.91	04:54
EP_V2G_PV_apt	853 603	671 610	0.00	293.03	04:42
PPM_V2G_PV	851 959	684 681	15 114	132.9	05:36
PPM_PV_apt	844 832	668 254	0.00	132.91	01:30
PPM_V2G_PV_apt	833 023	670 086	0.00	120.6	00:18

Figure 13 shows the cost breakdown of the cases with prices from Trondheim 2018, divided into EP in sub-figure (a) and PPM in sub-figure (b) and sorted from highest to lowest total cost. For the EP-cases, all the costs are linked to the amount of energy imported, apart from the fixed cost and export income. This is because their relative sizes stay the same as the total costs vary. There is a clear objective value drop in both (a) and (b) with the introduction of PV. From (b) it is clear that the higher total cost in PPM_STC is due to the peak load tariff.



(a) EP (b) PPM

Figure 13: Breakdown for the value of the objective function of the cases

In table 7 the cost breakdown for all cases with Trondheim 2018 prices are presented in numbers.

Table 7: Cost breakdown

Case	**Fixed Cost [NOK]**	**Spot price cost [NOK]**	**Export income [NOK]**	**Prosumer compensation [NOK]**	**Grid Tax [NOK]**	**Energy transport tax [NOK]**	**Peak tariff tax [NOK]**	**VAT [NOK]**	**SUM [NOK]**
EP_STC	183 500	322 093	0.00	0.00	133 605	125 397	0.00	191 148	955 744
EP	183 500	313 761	0.00	0.00	132 983	124 813	0.00	188 764	943 822
EP_PV	183 500	288 194	-11 114	-555.70	121 777	114 295	0.00	176 941	873 039
EP_V2G	183 500	312 716	-852	-42.64	133 232	125 047	0.00	188 623	942 224
EP_V2G_apt	183 500	309 506	0.00	0.00	133 595	125 388	0.00	187 997	939 988
EP_V2G_PV	183 500	284 260	-7 546	-377.33	120 411	113 014	0.00	175 296	868 559
EP_V2G_PV_apt	183 500	270 498	0.00	0.00	118 069	110 815	0.00	170 720	853 603
PPM_STC	183 500	322 093	0.00	0.00	133 605	37 999	103 635	195 208	976 042
PPM	183 500	314 604	0.00	0.00	132 986	37 823	67 429	184 086	920 430
PPM_PV	183 500	288 681	-11 170	-558.54	121 797	34 640	66 303	173 730	856 923
PPM_V2G	183 500	314 412	-522.84	-26.14	133 069	37 846	64 600	183 357	916 237
PPM_V2G_apt	183 500	315 350	0.00	0.00	133 293	37 910	57 923	181 994	909 971
PPM_V2G_PV	183 500	285 077	-7 393	-369.68	120 366	34 234	64 600	171 944	851 959
PPM_V2G_PV_apt	183 500	276 594	0.00	0.00	117 801	33 504	55 018	166 604	833 023

6.1.1 Effect of grid tariff models on total costs

This section will present the direct effect of the two different grid tariff models, energy pricing(EP) and peak per month (PPM), on the total cost. Table 8 and 9 shows the difference in objective function value, for the EP and PPM cases respectively, compared to the corresponding STC-case.

As seen from figure 13, for both EP and PPM, the sequence of cases based on objective function value is the same. Hence, the price regime does not alter the priority of the different technological implementations and metering points. What is most noticeable is the steep cost decrease from uncontrolled to controlled charging from the case PPM_STC to PPM, where the objective value goes down 5.7% from 976042 NOK to 920430 NOK, as seen in table 9. The corresponding price drop for energy pricing is 1.2%. This is because of the reduction in peak power tariff costs for the PPM case, which is not there for the EP-case. It shows that, at least for that year's prices, solely optimizing based on spot price does not cut costs significantly.

The other significant price drop occurs for both EP_PV and PPM_PV. Introducing PV panels is a significant price drop for both price models, more for the EP cases, as PV panels contribute little towards reducing peaks, and therefore the reduction in energy cost is the driving factor, as can be seen from table 6, where peak load is not reduced in any of the PV cases, compared to the non-PV-cases.

Table 8: Impact of optimal charging on the value of the objective function of the EP-cases

Case	**Objective function value [NOK]**	**Diff(EP_STC) [NOK]**	**Percentage dif [%]**
EP_STC	955 745	0	0.0
EP	943 822	11 922	1.2
EP_V2G	942 224	13 521	1.4
EP_V2G_apt	939 989	15 756	1.6
EP_PV	873 040	82 705	8.7
EP_V2G_PV	868 559	87 185	9.1
EP_PV_apt	857 391	98 354	10.3
EP_V2G_PV_apt	853 604	102 141	10.7

Table 9: Impact of optimal charging on the value of the objective function of the PPM-cases

Case	**Objective function value [NOK]**	**Diff(PPM_STC) [NOK]**	**Percentage dif [%]**
PPM_STC	976 042	0	0.0
PPM	920 430	55 612	5.7
PPM_V2G	916 238	59 804	6.1
PPM_V2G_apt	909 972	66 070	6.8
PPM_PV	856 924	119 118	12.2
PPM_V2G_PV	851 960	124 082	12.7
PPM_PV_apt	844 832	131 210	13.4
PPM_V2G_PV_apt	833 023	143 019	14.7

6.1.2 Impact of PV panels on total cost

This section will present the effect of PV panels on total costs. As investment cost is ignored, the installation of PV panels is, in principle, free power, but as mentioned in the scope, the goal is to see how the charging strategies are affected by PV panels, which will be shown in this section. As seen from table 6, installing PV panels significantly affects the objective function value. Table 10 compares the cases with and without PV. From the EP case to the EP_PV case, there is a 70783 NOK reduction, or 7.49% in objective value, and 64507 NOK, or 6.89%.

Table 10: Case-wise cost reduction of implementing PV

Case	Objective value [NOK]	Difference [NOK]	Percentage [%]
EP	943 822		
EP_PV	873 039	70 782	7.49
EP_V2G	942 224		
EP_V2G_PV	868 559	73 664	7.81
EP_V2G_apt	939 988		
EP_V2G_PV_apt	853 603	86 385	9.19
PPM	920 430		
PPM_PV	856 923	63 506	6.89
PPM_V2G	916 237		
PPM_V2G_PV	851 959	64 277	7.01
PPM_V2G_apt	909 971		
PPM_V2G_PV_apt	833 023	76 948	8.45

Table 11 show the how much energy is exported, and the self consumption for all PV cases. As seen from table 10 and table 11, the objective value is reduced with increasing self consumption.

PV generally has a lesser effect on the PPM cases than on the EP cases. This is since a substantial portion of the PPM price is a peak power tariff. The PV production is next to zero during the winter and can not affect the peak power tariff during these months. The tariffs and taxes on energy usage are higher for EP because of the lack of effect tariff, leading to the PV used having more effect.

Table 11: Self consumption of the PV cases

Case	Sum exported [kWh]	Self Consumption [%]
PPM_PV	24 558	72.1
EP_PV	24 433	72.2
PPM_V2G_PV	15 114	82.8
EP_V2G_PV	15 050	82.9
PPM_V2G_PV_apt	0	100
PPM_PV_apt	0	100
EP_V2G_PV_apt	0	100
EP_PV_apt	0	100

The total amount of produced energy from the PV panels is 88 201 kW, so as seen by table 11, the self-consumption is relatively high for all PV cases. This holds even for the cases where the PV only shares a metering point with the garage and hence the EV charging demand. Figure 14 shows the average charging profiles for March-September for different cases. The red shaded area is the average PV production in the same period.

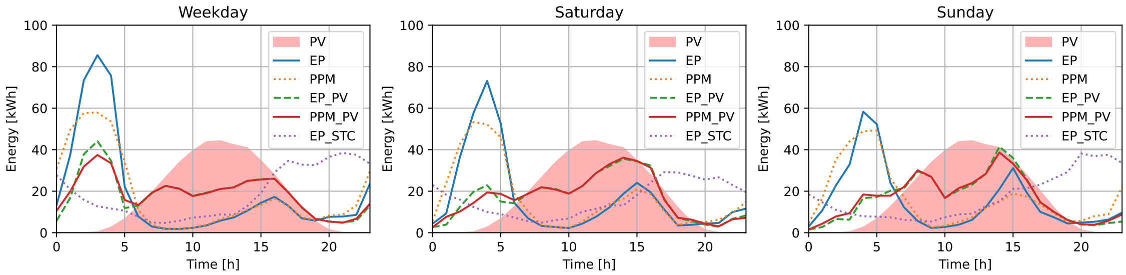


Figure 14: Average daily charging profiles March-September

As seen from figure 14, for the PV-cases, during summer, the night peaks are much lower, and the charging pattern is more even, as as much charging as possible is moved to hours with PV-production. This is linked to the price difference between energy imported and energy exported. Taxes and tariffs are paid on imported energy, which is much higher than consumer compensation.

For the EP cases, 67.6 [Øre] is paid per NOK imported in tariffs and taxes per kWh imported, while the sum is 53.6 [Øre] for PPM-cases. On the other hand, the compensation for export is related to the spot price, as described in equation 18, which on average for the summer half of the year is 2.1 [Øre] per kWh exported.

Even though the uncontrolled utilizes more of the PV production, EP, PPM nor EP_STC is close to the amount of PV used in EP_PV and PPM_PV which is at 72%. Hence, the most economical choice is to use as much self-produced energy as possible. This stresses the importance of two things, controlled charging and controlled charging, considering the self-production of energy.

6.1.3 Impact of enabling V2G on total costs

Vehicle-to-grid operation impact on objective function value is slight but not negligible. As shown in this section, the effectiveness of V2G can be interpreted differently when considering cost reduction or sum discharged.

Table 12 shows the key performance indicators for the V2G cases. The sum discharged is substantially lower for all cases than what is connected with an increased rate of battery degradation, as discussed in section 2.3.1. The NOK per kWh discharged is calculated as total cost reduction compared with the same case without V2G divided by the total sum discharged. The case PPM_V2G is notable with a low amount discharged and high NOK per kWh charged.

Table 12: Overview of V2G KPIs

Case	Total cost [NOK]	Sum imported [kWh]	Sum exported [kWh]	Sum discharged [kWh]	NOK per kWh discharged
EP_V2G	942 224	757 861	530	11 526	0.138
EP_V2G_PV	868 559	684 937	15 050	17 827	0.251
PPM_V2G	916 237	756 938	266	6 031	0.695
PPM_V2G_PV	851 959	684 681	15 114	15 166	0.327

Table 13 shows the total cost difference for the cases with and without V2G. As can be seen from table 13, the cost reductions from implementing V2G are minuscule. If comparing the objective value reduction from 13 and sum discharged from table 12, the price reduction per kWh discharged is 0.13 [NOK/kWh], 0.25 [NOK/kWh], 0.69 [NOK/kWh] and 0.33 [NOK/kWh] for EP_V2G, EP_V2G_PV, PPM_V2G and PPM_V2G_PV respectively.

Table 13: Case-wise cost reduction of implementing V2G

Case	Total cost [NOK]	Difference [NOK]	Percentage [%]
EP	943 822		
EP_V2G	942 224	1 598	0.16
EP_PV	873 039		
EP_V2G_PV	868 559	4 480	0.51
PPM	920 430		
PPM_V2G	916 237	4 192	0.45
PPM_PV	856 923		
PPM_V2G_PV	851 959	4 963	0.57

Figure 15 shows the average daily discharge profile with spot price on the right axis for Trondheim 2018 prices. The average discharge profile peaks at the evening price peak, where the spot price peaks and many vehicles are connected. Therefore there will also be a portion of non-flexible charging happening at this time, which can then be covered by other discharging vehicles. For the V2G-PV cases, there is also quite a bit of discharge during night hours. This is probably because the PV has enabled vehicles connected during the daytime to charge at the less expensive hours with PV production, to discharge the other EVs during nighttime later. The size of this transfer can be read from table 11, where the self-consumption increases by 10% points for both EP_V2G_PV and PPM_V2G_PV, compared to EP_PV and PPM_PV. In short, V2G enables the use of energy produced by PVs to charge EVs at night. The total export falls by around 6000 kWh when introduced for EP_V2G_PV and PPM_V2G_PV.

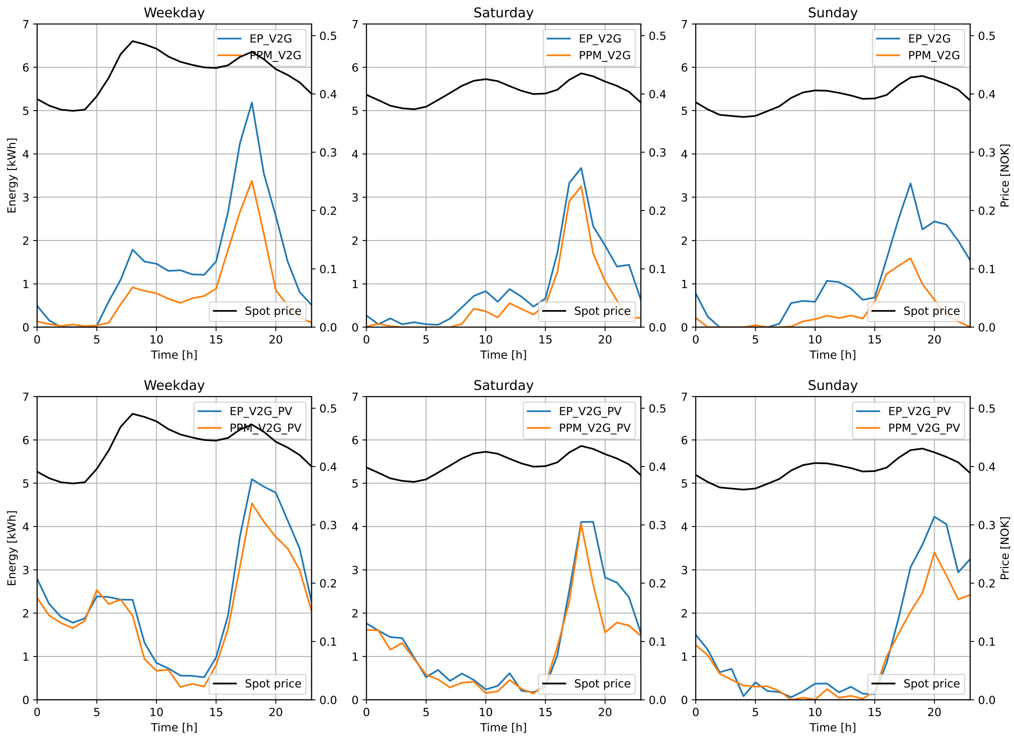


Figure 15: Average daily discharge profile, energy discharged on the left axis, and price on the right axis.

Figure 16 shows the daily average inflexible charging, which cannot be moved due to charging demand constraints. As seen from the figure, the weekday average discharge pattern follows the inflexible charging, charging that cannot be moved, especially for PPM without PV, both being around 3 kWh at 17:30. This is where the electricity use in the apartments peak;

therefore, it is essential to discharge to flatten the peak. The total inflexible charging is 8626.95 kWh, and the sum discharged for the PPM_V2G case is 6031.8 kWh, with only 266 kWh to the grid, so the discharge is going for load flattening. For the EP_V2G case, it is slightly higher, as there is more relative incentive to discharge at hours with higher cost.

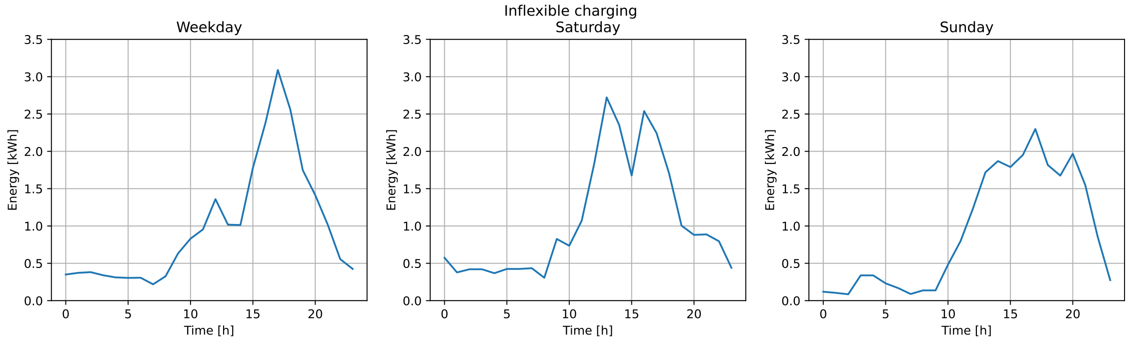


Figure 16: Average daily inflexible charging

Figure 17 shows the average daily charging profiles for the PV and V2G cases. As seen in table 11, when including V2G, the self-consumption increases as cars available during hours with PV production charge, to discharge to the other EVs. With V2G, more charging is happening at the daytime. The EVs are generally connected more at daytime during the weekends, and as a result, the difference between charging profiles for the cases with and without PV are more similar, in addition to prices being more even, meaning less incentive for V2G.

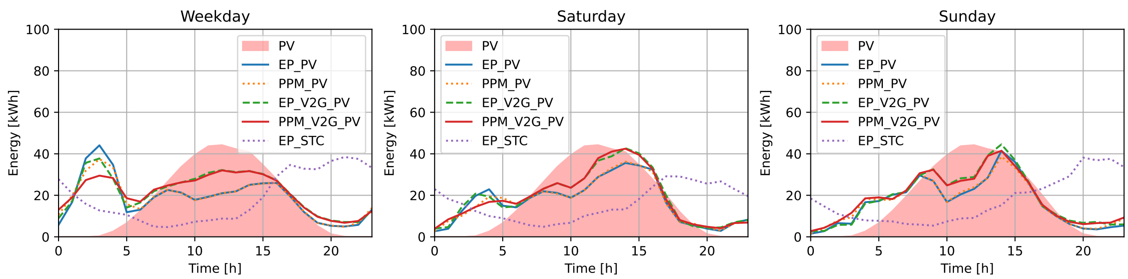


Figure 17: Average daily charging profiles March-September for V2G-cases

6.1.4 Impact of apartment demand supplied by energy flow from PV and V2G on total cost

The difference between the apt-cases compared to the other cases is the ability for PV to be used for apartment electricity and enabling vehicle-to-home (V2H). This increases the effectiveness of both, especially for PPM, where the apartment peaks can now also be flattened, reducing the max peaks and, therefore the penalty costs. In this section, the impact of apartment demand supplied by PV and V2G on total cost will be presented.

Table 14 show the KPIs for the apt cases. If comparing discharge in table 14 to discharge in table 12, it can be seen that the sum discharged increases significantly, in some cases more than doubling the amount. One outlier is PPM_V2G_PV compared to PPM_V2G_PV_apt, which only sees a lesser increase in energy discharged. This is likely due to the V2G potential of charging with solar energy or cheap nighttime hours to discharge at peak hours, which was already fully utilized. Meaning that increasing the V2G discharge would increase the peak loads of PPM_V2G_PV_apt, increasing the total cost. Hence, including the possibility of discharge to the apartments is not as valuable for this configuration.

Table 14: Key performance indicators for the apt-cases

Case	Total costs [NOK]	Sum imported [kWh]	Sum exported [kWh]	Peak load [kW]	Sum discharged [kWh]
EP_V2G_apt	939 988	759 931	0.00	293.03	33 191
EP_V2G_PV_apt	853 603	671 610	0.00	293.03	32 193
PPM_V2G_apt	909 971	758 209	0.00	120.63	18 828
PPM_V2G_PV_apt	833 023	670 086	0.00	120.60	19 491

Table 15 show the total cost reduction of the apt-cases. As seen from table 15, the objective value reduction is relatively small for all cases. However, the reduction is greater than when introducing V2G alone. It seems to vary little on the spot price region as the percentage reduction is comparable. It makes EV discharge more profitable as a whole. However, total cost reduction per kWh falls for all cases as the sum discharged increases.

Table 15: Case-wise cost reduction of enabeling energy flow from V2G and PV to apartment load

Case	Total costs [NOK]	Difference [NOK]	Percentage [%]
EP_V2G	942 224		
EP_V2G_apt	939 988	2 235	0.24
EP_V2G_PV	868 559		
EP_V2G_PV_apt	853 603	14 955	1.72
PPM_V2G	916 237		
PPM_V2G_apt	909 971	6 265	0.68
PPM_V2G_PV	851 959		
PPM_V2G_PV_apt	833 023	18 936	2.22

6.2 Grid burden

As in section 6.1, firstly, an overview of the grid burden impact of all the cases will be given before the classes of cases, and their impact on grid burden will be explored individually, in the order of grid tariffs, PV production, V2G and metering location.

Table 16 gives an overview of the key performance indicators of all the cases on grid burden impact, peak load, date and time, and the average daily peak hour. Peak load varies significantly between the cases, as seen from table 16. However, the difference is most definitely most significant between the EP- and PPM-cases in general. The peak date is described as December for the PPM cases, as the load is at its highest for several hours of December, with the peak being dictated by apartment electricity demand of 132.91 kWh the 31.12.2018 16:00-17:00.

The maximum peak load occurs for the case EP_V2G with 291.37, with the lowest peak occurring in PPM_V2G_PV_apt. The maximum peak occurs in this case because with energy pricing, there is no incentive to reduce the peak load, and through V2G, discharge is happening at afternoon peak hours, so there is a need for more nighttime charging. PPM_V2G_PV_apt has the minimum peak load, as it is incentivized through the price model, and V2G, PV and apt all allows for peak reduction, especially apt, as V2G can then be used to flatten the load peak of the apartment electricity load.

Table 16: Grid burden KPIs

Case	Peak load [kW]	Peak date [mm/dd/yyyy]	Peak hour [hh-hh]	Avg daily peak hour [hh:mm]
EP	289.18	22/01/2018	02-03	04:54
EP_PV	289.18	22/01/2018	02-03	07:00
EP_STC	218.93	09/01/2018	17-18	17:54
EP_V2G	291.37	14/03/2018	03-04	04:42
EP_V2G_apt	293.03	22/01/2018	02-03	04:54
EP_V2G_PV	289.99	22/01/2018	02-03	07:42
EP_V2G_PV_apt	293.03	22/01/2018	02-03	04:42
PPM	132.91	22/01/2018	02-03	01:18
PPM_PV	132.91	December	-	04:54
PPM_V2G	132.14	December	-	01:00
PPM_V2G_apt	120.63	December	-	00:18
PPM_V2G_PV	132.9	December	-	05:36
PPM_V2G_PV_apt	120.6	December	-	00:18

Figure 18 shows the daily average energy consumption, winter, and summer for the EP, EP_STC, and PPM-case. The trend for the controlled charging, as seen in figure 18, is to move the charging to nighttime. However, it is much more spread out for the PPM cases. As can be seen from both table 16, figure 30 and figure 18, the peak hours with the uncontrolled charging of the EP_STC-case occurs at the same time as the apartment electricity peaks. The EP case increases the peak load, while the PPM case keeps the night charging peak as high as the afternoon load peak to use the lower spot price while not increasing the peak per month penalty cost.

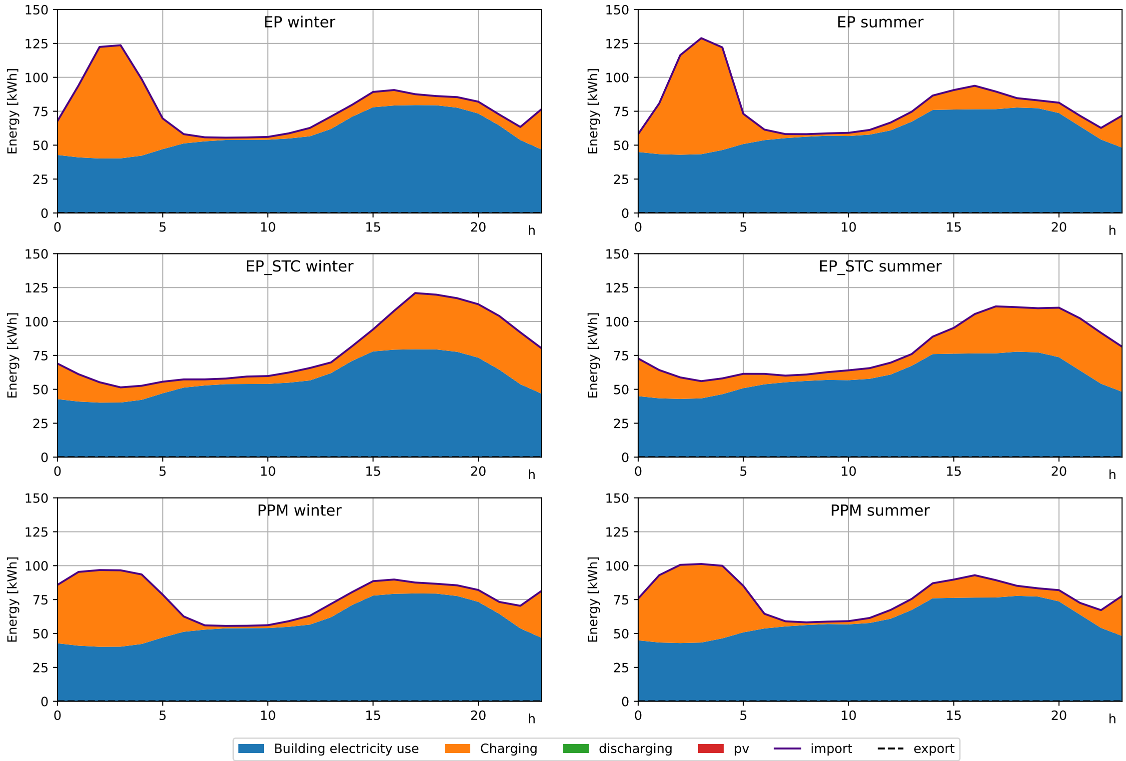


Figure 18: Average energy flow day profile for the base cases

6.2.1 Impact of grid tariffs models on grid burden

Figure 19 shows imported energy's electric load duration curve. As seen from figure 19, the duration curve for the EP and PPM cases are quite distinctively different for 2000 hours of the year. The standard EP and EP_OSL21 case is higher than PPM for around 1000 hours. The PPM curve is distinctive, with 12 plateaus corresponding to the monthly peaks. This is an effect of the optimization of having full information, knowing what will be the peak load each month, and then controlling the EV load up to this point for all other days of the month to fully utilize the lower spot prices when possible without increasing the peak per month penalty cost.

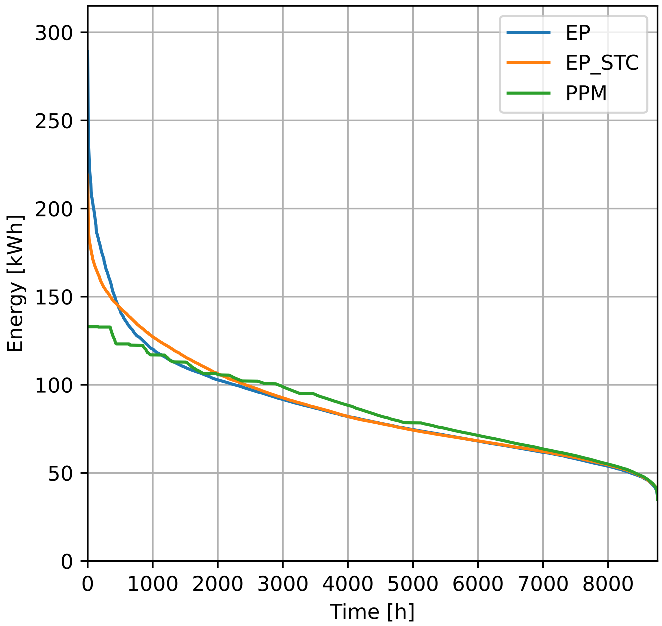


Figure 19: Duration curves of imported energy

Figure 20 shows the monthly peak load for the EP, PPM, V2G, and PV-cases. It shows the peak load difference between the EP and PPM cases and the relative stability of peak loads throughout the year. PV has a more significant impact on the peak loads of the EP-cases as more EV charging happens during daytime with the solar energy, so less charging is moved to nighttime. For PPM, the peak load is dictated by the apartment demand and the inflexible EV charging demand and is, therefore, more or less unaffected by the PV production. V2G has the opposite effect, increasing the peak loads of the EP-cases by increasing the charging demand and moving more charging to nighttime to discharge at the spot price peaks. V2G slightly reduces the peaks in the PPM cases by discharging during the afternoon peaks.

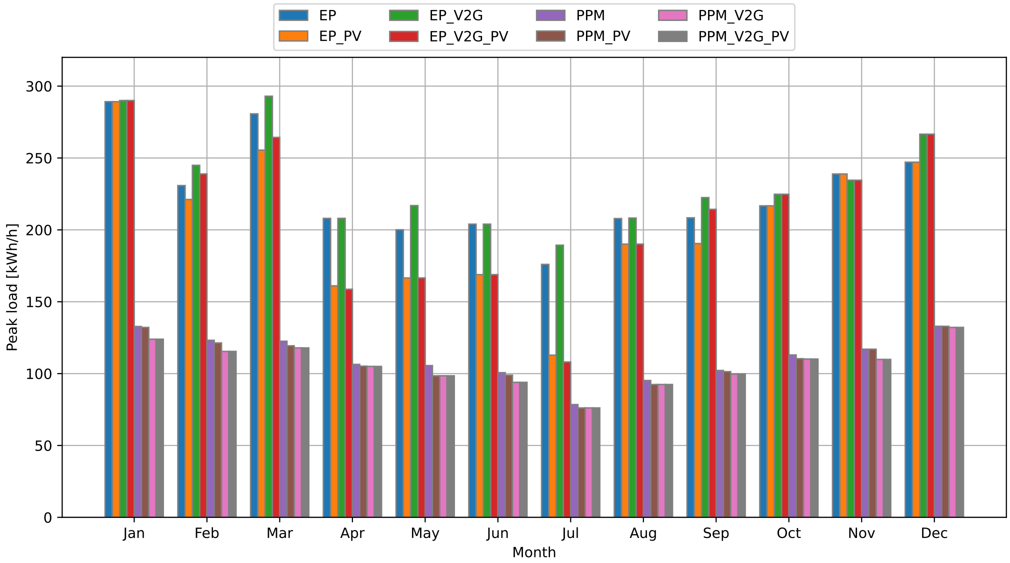


Figure 20: Peak load per month for EP, PPM, V2G and PV-cases]

6.2.2 Impact of PV production on grid burden

Figure 21 shows the average energy flow day profile for the PV cases for winter and summer. The purple line is the net import, and the black dashed line is the net export. During the winter months, the EV charging is moved, so all the produced solar energy is consumed, and non is exported for both EP and PPM. During the summer months, with higher PV production, a portion of the energy is exported when the production is highest as there is no available EVs to charge. However, a substantial amount of charging is moved to daytime, reducing the night peak for the EP-case, if compared with the EP-profile in figure 18

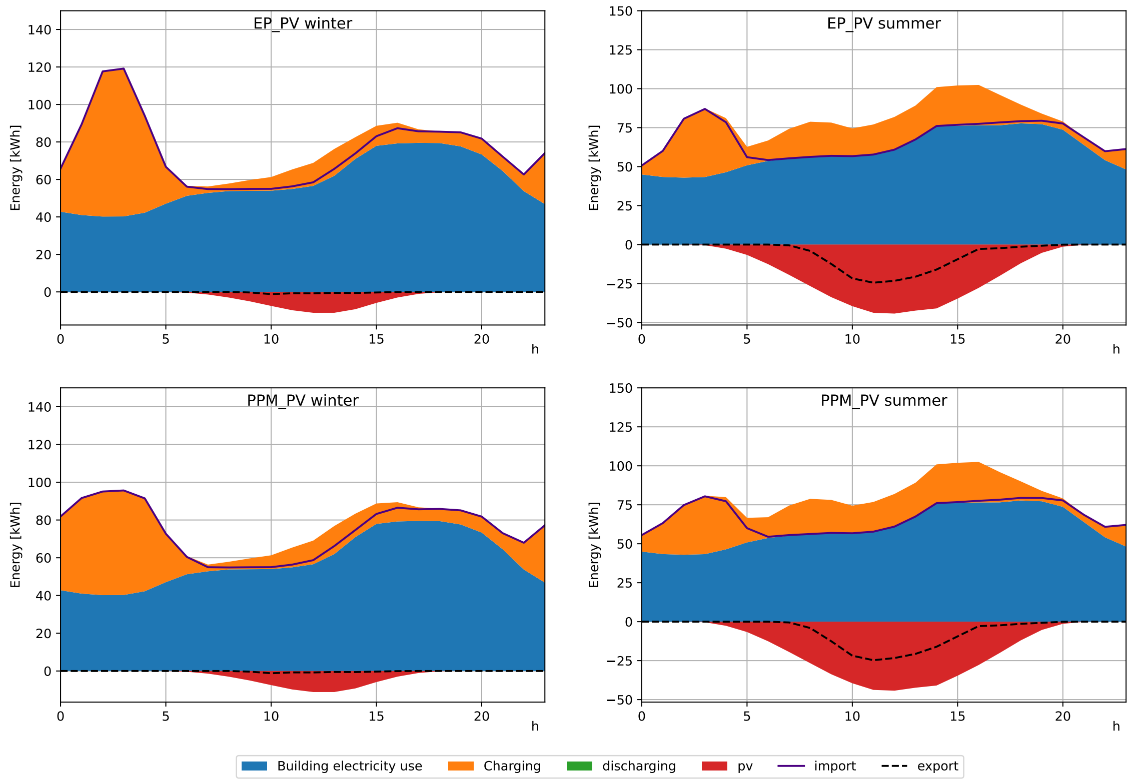


Figure 21: Average energy flow day profile for the PV cases

6.2.3 Impact of V2G on grid burden

V2G increases the total amount of energy imported. The amount of energy exported increases because of the round trip efficiency loss, leading to a 0.23 kWh energy demand increase for every kWh discharged.

Figure 22 shows average energy flow day profile for the V2G cases. The green area is the energy discharged by the EVs. There is a relatively low amount of energy discharged in general, so the effect on grid burden is seemingly not very noticeable. As seen in figure 22, the green area's average daily amount discharged is small. However, for the winter cases, it does occur at peak hours, slightly decreasing the after-work peak, which is the most expensive hours. However, for PPM_V2G during summer, in general, V2G is not used as the price differences are not high enough. This is evident when compared with PPM_V2G_PV summer, where the access to cheap electricity through PV production makes V2G operation profitable for a relatively large portion of the day, dividing the hours of PV production over the day.

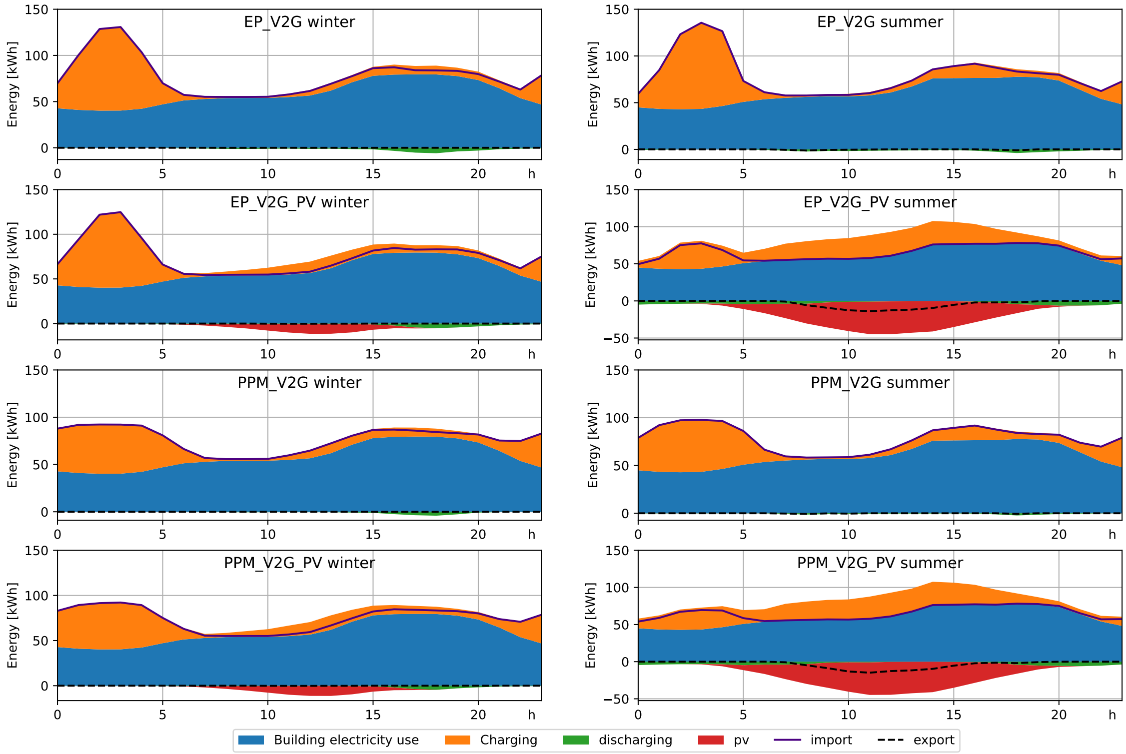


Figure 22: Average energy flow day profile for the V2G cases

6.2.4 Impact of apartment demand supplied by energy flow from PV and V2G on grid burden

Figure 23 Average energy flow day profile for the apt-cases. Energy flows from the PV panels and the EV batteries for electricity use in the apartments. There is more incentive to use V2G, as the apartment load peaks occurring at spot price peaks can be covered by V2G discharge. The discharge is used efficiently at times with the highest spot prices, while it is used for flattening the peaks for the PPM-cases, as seen before. There is close to zero export, with 100% of the energy produced, either by PV or V2G self-consumed. For the PPM-cases, the energy imported is stable throughout the day. The figure confirms what was seen in section 6.1.4, that there is only a slight increase in V2G discharge for the PPM_V2G-cases, as the potential to use cheap night hours is expended.

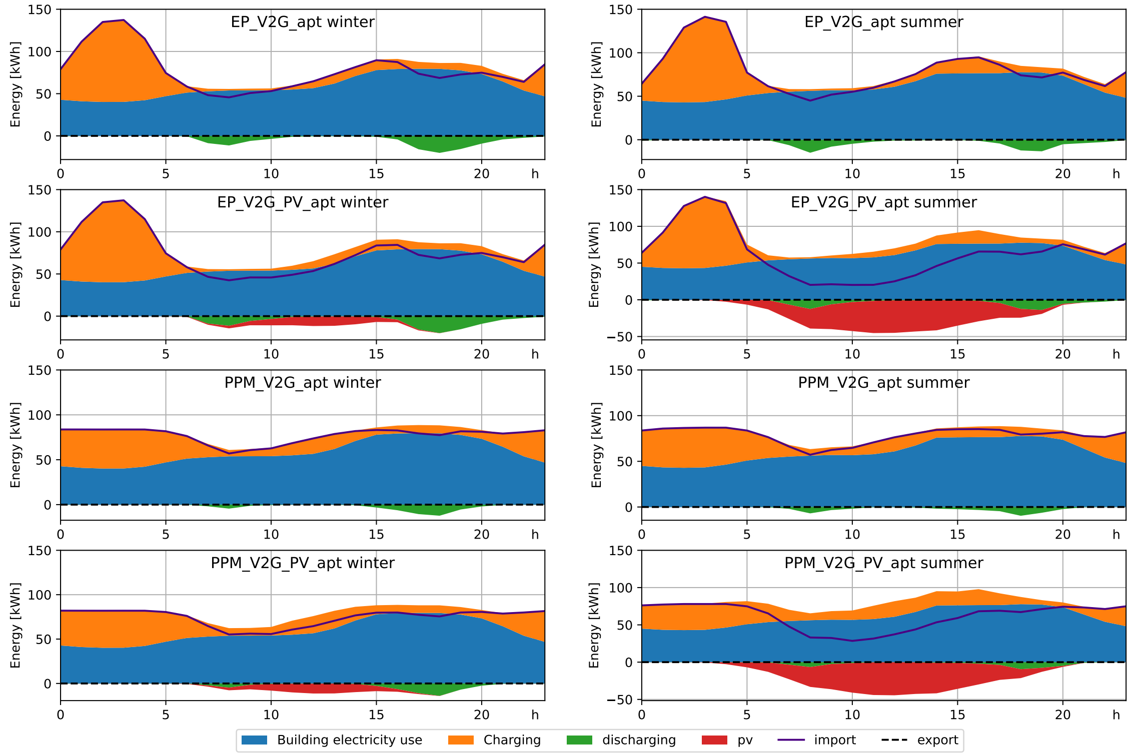


Figure 23: Average energy flow day profile for apt-cases

6.3 Sensitivity analysis - Spot prices from Oslo 2021

A sensitivity analysis was done with spot prices from Oslo 2021. As seen in figure 9 the prices from Oslo 2021 were, on average, higher, with a higher price variation. In general, the charging strategies are more or less unchanged, as peak hour times still occur at the same times of the day, and the PPM-cases are still dictated by the inflexible load peaks of the apartment load and inflexible EV charging. As seen in table 7 and 19 in the appendix, the OSL21 cases have a significantly higher objective function value, as the spot price was generally higher.

As can be seen from table 16 and 20, the peak for PPM and PPM_OSL21 is identical, and their duration curves are also more or less identical. Hence, the peak tariff tax is more or less unchanged between the two spot price regions, with spot price having a much higher percentage of the cost for the Oslo region, being almost doubled in most cases. The objective function value is about 30% higher for all cases. The main difference between the cases with spot prices from Trondheim 2018 and the aforementioned is the amount of energy discharged by V2G. The V2G-OSL21 cases will therefore be presented in detail here. More figures and tables with results from the OSL21-case can be found in the appendix.

Table 17 shows the key performance indicators for the V2G_OSL21-cases. Compared to the KPIs of the V2G-cases with spot prices from Trondheim 2018, seen in table 12, the sum discharged more than doubles for all cases, except PPM_V2G_PV_OSL21 which almost doubles. NOK per kWh discharged increases for all cases except PPM_V2G_OSL21. For EP_V2G_OSL21 compared to EP_V2G_OSL21, the increase in NOK per kWh discharged is 210%, from 0.138 NOK to 0.29 NOK. This is due to the higher spot price differences, increasing the profitability of the spot price arbitrage. Per EV, the sum discharged is still around 250-350 kWh per year or 5-7 kWh per week, hence not increasing battery stress notably.

Table 17: Overview of V2G KPIs for the OSL21-cases

Case	**Objective value [NOK]**	**Sum imported [kWh]**	**Sum exported [kWh]**	**Sum discharged [kWh]**	**NOK per kWh discharged**
EP_V2G_OSL21	1 272 043	764 161	4 825	28 225	0.29
EP_V2G_PV_OSL21	1 182 748	691 652	19 926	33 153	0.34
PPM_V2G_OSL21	1 249 907	761 686	3 778	16 329	0.52
PPM_V2G_PV_OSL21	1 168 999	691 226	20 260	26 824	0.37

Table 18 show the cost reduction of V2G per case. The absolute reduction is greater than the Trondheim 2018 spot prices, but the relative reduction is lower than 1%.

Table 18: Total cost reduction of V2G per case

	Objective value [NOK]	**Difference [NOK]**	**Percentage [%]**
EP_OSL21	1 280 308		
EP_V2G_OSL21	1 272 043	8 264.7	0.65
EP_PV_OSL21	1 193 988		
EP_V2G_PV_OSL21	1 182 749	11 238.6	0.94
PPM_OSL21	1 258 466		
PPM_V2G_OSL21	1 249 908	8 558.4	0.68
PPM_PV_OSL21	1 179 038		
PPM_V2G_PV_OSL21	1 168 999	10 038.8	0.85

For PPM, to reduce the peak per month penalty cost through V2G, the peak reduction must be sustained throughout the month to have an effect. Spot price signals are more effective at incentivizing peak discharge, which can be seen in figure 24, showing average energy flow day profiles for the V2G_OSL21-cases. For the EP-cases during the winter, where the spot prices are the most expensive, during the afternoon peak, almost all of the inflexible EV charging energy demand is supplied through V2G discharge instead of imported from the grid.

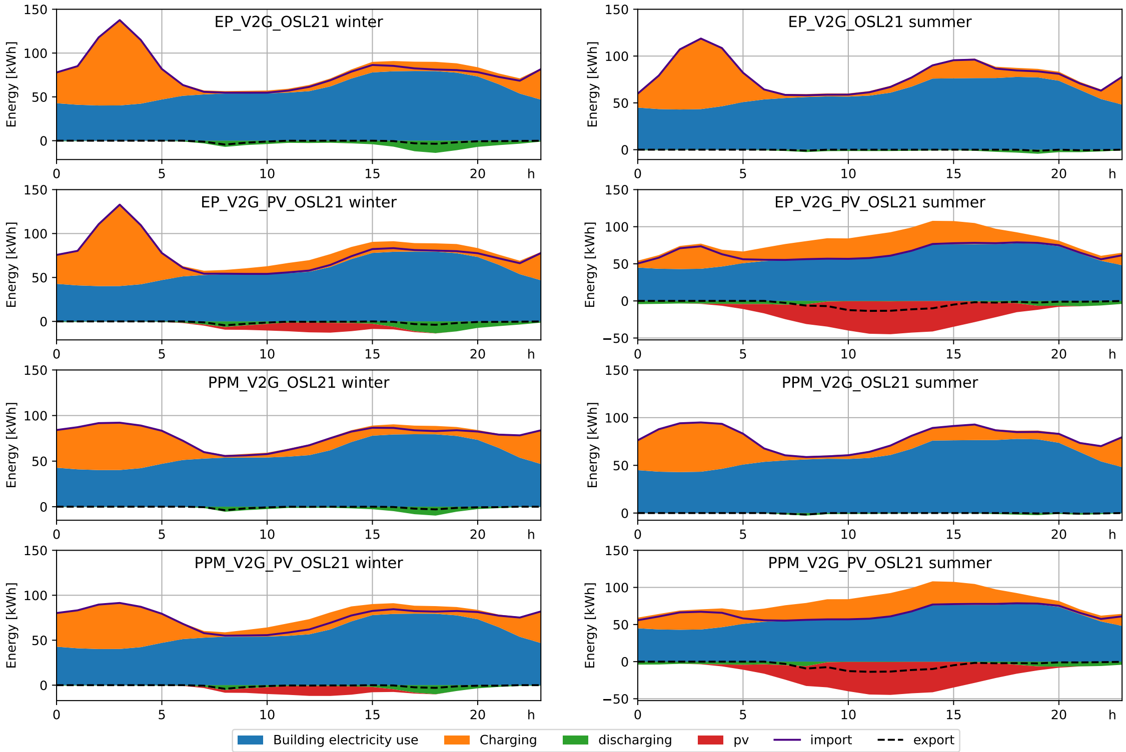


Figure 24: Average energy flow day profile for V2G-OSL21-cases

If looking at a specific week, especially for the prices from Oslo 2021, the discharge spikes are significantly higher as seen in figure 25 showing EV charging and discharging from 5th-15th of February, and correlates with price spikes. This week is chosen because of higher price variations. It also shows very clearly how most of the charging is being done at the price lows, both for the EP and PPM cases. However much more evenly spread out for PPM-cases. While the optimization for PPM spreads it evenly out to avoid the peaks, for the energy pricing, the optimization chooses the absolute cheapest hour, lumping the charging together, even though the price difference is minimal.

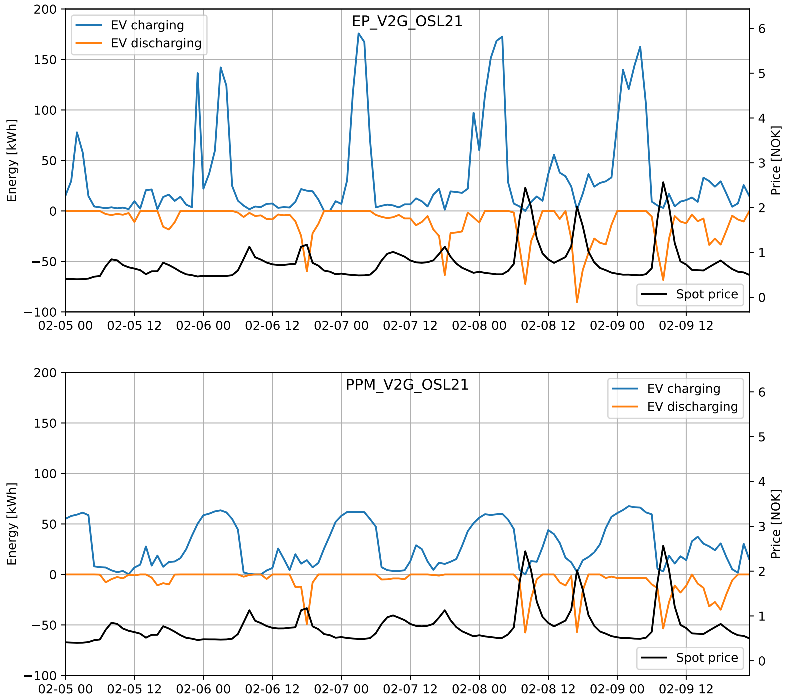


Figure 25: Charge and discharge a week in Oslo. Spot price on right y-axis.

6.4 Sensitivty analysis - Separated price model

A probable scenario is to have two separate energy meters for the apartment building and the garage, with energy pricing for the apartment buildings and peak per month pricing for the garage. The result of the controlled charging is shown in figure 26, where the EV charging is evenly spread throughout the day, with a dip during daytime for the non-EV cases, where there are fewer EVs connected. The downside is that the afternoon peaks are increased if comparing the peaks to the PPM-cases in 22. Because of the general flexibility of EV charging, V2G is more or less unused. For the PPM-cases for the Trondheim 2018 spot prices, the price difference is not high enough to make V2G discharge viable for energy arbitrage. The exception is for the non-sep PPM-cases with PV during summer, where the supply of solar energy makes V2G profitable.

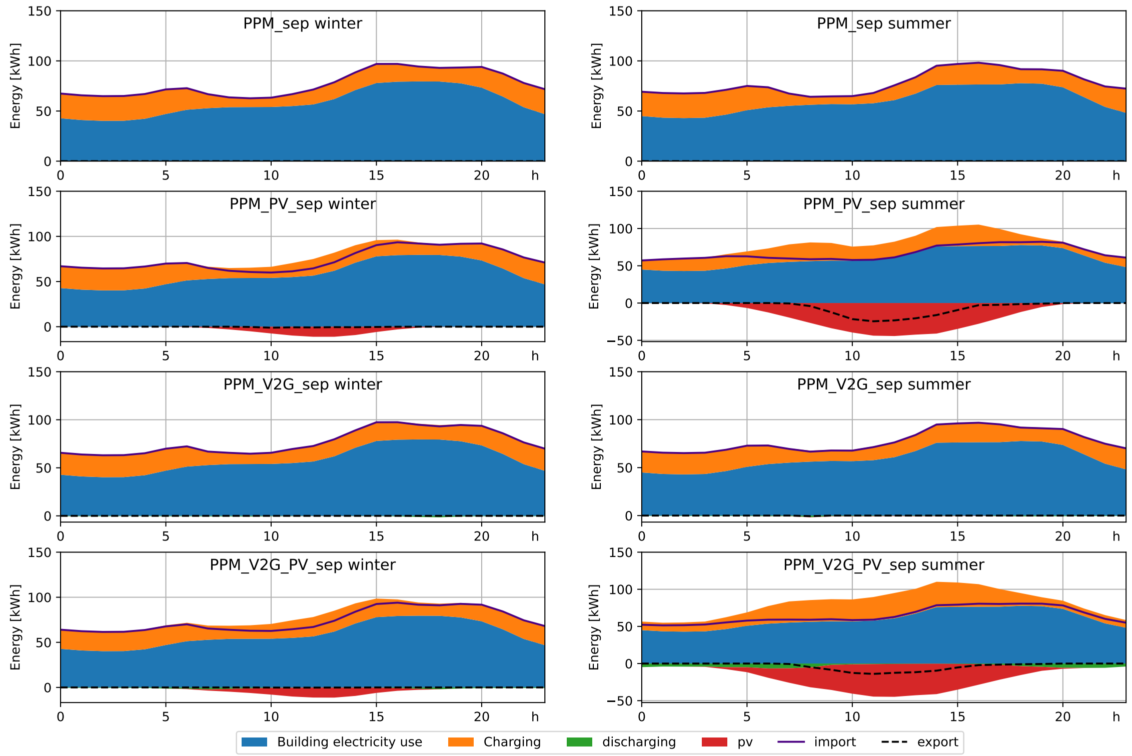


Figure 26: Average energy flow day profile for sep-cases

6.5 Increased EV charger limit to 10 kW pm the PPM_V2G_PV_apt-case

The largest portion of EVs has a charger limit below 10kW. The higher the charger limit, the more energy discharged, as there are more idle hours, and more can be discharged and charged when needed, giving more flexibility. Therefore a sensitivity analysis was done where all EVs had a charger limit of 10 kW. However, the battery capacity was kept the same. This was done for the PPM_V2G_PV_apt-case. The result was a decrease in total costs by 0.36%, an increase in EV discharge by 10%, and a reduction of peak load from 120 kW to 114 kW, or 5%. This is on par with the other case results, that for the PPM-cases, V2G is used most efficiently in terms of reducing cost when reducing the peak penalty cost. As EV discharge increases the charging demand at some point, there is a limit where the increased demand increases the peak loads. The sum discharged might have increased if battery sizes were also increased.

Figure 27 shows the sum discharged per EV plotted against time connected with the color of the dot representing the EV charger capacity. Blue dots show EVs with a charging capacity of less than 4 kW, green dots between 4 and 8 kW, and red dots above 8 kW. As expected, it shows a connection between the time connected and the sum discharged for each EV. There is also a clear connection between the charger limit and the sum discharged.

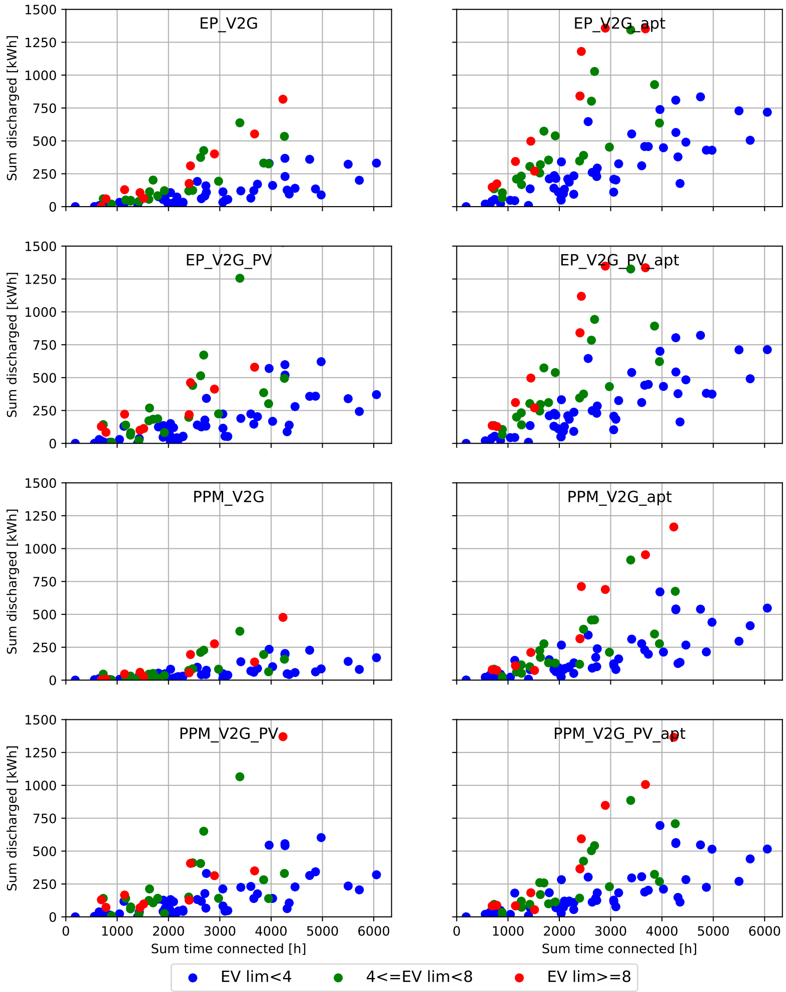


Figure 27: Scatter plot of sum discharged versus time connected per EV

6.6 Energy import restriction on the EP-case

When minimizing cost, the only way to reduce cost for the EP-cases is to move the charging to the hours with the lowest spot prices. An effect of this is that a triangle-shaped peak load is created at night time for most EP-cases as seen in figure 18, with a peak around 02:00-03:00. For the PPM-cases, on the other hand, the charging is spread more evenly between 00:00 to 05:00. Therefore, a sensitivity analysis was done to see the total cost of implementing an energy import restriction on the EP-case. An energy import restriction of 132 kW, the peak load of the PPM-case, was imposed. The result was an increase in the total cost of 340 NOK, or 0.036%. The peak load of the EP-case is 289 kW, so the restriction leads to a 54% decrease in peak load. This results in the price difference during night hours being minuscule. However, if not incentivized otherwise, a spot price optimizing algorithm will choose to move most of the charging to the absolute cheapest hour.

7 Discussion

In this section, the results and their implications will be discussed. The results show the optimal strategy given full information under the conditions of the cases. They show the potential of different EV charging strategies for an apartment block. In a real-life situation, the charging strategy will most likely have a lower output, and there are many limitations to this study as presented in the limitations in section 1.3. However, the results can be used as a guideline for the theoretical maximum potential of the charging strategies under similar conditions.

If not controlling the EV charging, with 70% EV penetration, the total costs will be high, especially with a peak per month grid tariff model. It will also lead to an increase in grid burden as the afternoon peaks are increased. Most EVs are stationary and connected to a charging station through the night and parts of the day, and implementing controlled charging could cut costs by up to 5.7% with a peak per month tariff model. The peak can be reduced by up to 39%, which completely negates a peak load increase from the EVs, with the peak load being the apartment electricity load. Hence, the grid burden reduction would, in the long term, further cut the costs of the residents and the DSO by removing the need for grid reinforcements due to increased peak loads.

The cases with energy pricing grid tariffs lead to peaks of up to 293 kW for Trondheim 2018 spot prices and up to 314 kW for Oslo 2021 spot prices. This is 34% and 44% higher than the peaks with uncontrolled charging, respectively. This is because the only control parameter is the spot price, and marginally cheaper hours are preferred in optimization because there is no incentive to even out the load. As seen from the sensitivity analysis of imposing a maximum import restriction, the increased spot price cost of flattening the EV charging to the levels of the apartment electricity peak load is 340 NOK or 0.036% of the total costs. As spot prices are the same within a price region, high penetration of controlled EV chargers that charge based on spot price could lead to overuse of these hours, increasing the grid burden. Therefore, controllable EV chargers must have implemented an incentive to flatten the load.

If not programmed to take into account self-consumption of solar energy in the control of the EV charging, almost all of the flexible EV charging will be moved to hours without solar energy production, as spot prices are at their minimum during nighttime. This increases the cost compared to self-consuming the produced energy. This effect is at its greatest during the weekends, as the EVs are connected to a greater extent during hours of PV production. Hence PV forecasting in an EV charging controller is important to increase self-consumption and decrease costs.

The most profitable V2G-case per kWh discharged was the case with peak per month tariff model and Trondheim 2018 spot prices and the same case with Oslo 2021 spot prices with a profit of 0.69 and 0.52 NOK/kWh discharged, respectively. These cases had lower amounts of energy discharged than the other V2G-cases, and a total cost reduction of 0.45% and 0.68%. Given the round trip charging efficiency of 77%, every kWh discharged from the EV battery leads to an energy demand increase of 0.23 kWh. With a peak per month tariff model, the V2G potential is lower as there is a cost associated with increasing the energy import to a point where the monthly peak load increases. On the other hand, there is an increased potential for cutting costs by discharging the EV batteries to decrease the monthly peaks. In these cases, the second effect dominated, and V2G cut total costs by more with the peak per month tariff model than in corresponding cases with energy pricing.

For most cases, the energy discharged from the EV batteries is, on average, below or around levels associated with negligible effect on battery capacity, 5 kWh per week. This does not rule out that there is some form of battery degradation. Mechanisms restricting battery discharge to only happen at certain price margins to limit V2G transactions with marginal gains could be effective but is not necessary if the battery degradation cost is possible to factor into the optimization.

When enabling apartment electricity demand to be supplied by discharge from the EVs, the cut in total costs more than doubled for all V2G cases, as the energy import during spot price peak hours and peak load could be decreased. The bottom line is that due to the Norwegian prosumer model, where the compensation for exporting to the grid is low compared to the taxes paid when importing energy, hence a charge/discharge cycle with grid export and import requires large profit margins to be viable. So V2G is more profitable when used to reduce imports at hours with high spot prices rather than exporting to the grid. The implication is that if planning for V2G, having an inflexible demand to supply is important for profitability.

V2G and solar energy production are seen to be a symbiotic combination, where the efficiency of both technologies is improved with the implementation of the other. V2G allows for storage of produced energy to discharge during peak hours in the morning and afternoon, rather than exporting to the grid at relatively low spot prices during the daytime. The V2G cases increase solar energy self-consumption by 10 percentage points, from 72% to 82%. It is also beneficial to be supplied by solar production, as it decreases the cost of charging and hence increases the profit from discharge. Combining V2G with solar energy production is, therefore, a valid measure if wanting to increase efficiency. However, other energy storage methods might be more efficient.

8 Conclusion

The thesis answers how different grid tariff models, bidirectional charging with V2G, solar energy production, and energy meter locations impact the total cost and grid burden for an apartment block in Risvollan with 117 apartments and 70% EV penetration.

The grid tariff model significantly impacts the optimized charging profiles of EVs. Having a peak per monthly penalty tariff model leads to a decrease in maximum peak load 39% lower than with uncontrolled charging, and the increased peak load burden is negligible compared to having 0 EVs, thereby removing the need for grid capacity reinforcements due to higher EV penetration. Solely having energy pricing tariffs lead to an increase in the maximum peak of up to 44% compared to uncontrolled charging, causing stress on the grid, which would demand costly grid reinforcements. A peak per month tariff model gives the most significant incentive to implement controlled charging, cutting the total costs by up to 5.7%.

Controlled EV charging increases the effectiveness of solar energy production, as the flexibility of the EV charging allows for a higher degree of self-consumption, decreasing the total costs and grid burden. Using the EVs as energy storage with bidirectional charging further increases the effectiveness of the solar panels, increasing the yearly self-consumption to 82%, from 72% without bidirectional charging.

The amount of energy discharged by the EVs was generally low, but it occurred at the morning and afternoon peaks, thereby cutting costs and grid burden. The maximum income per kWh discharged from the EV is 0.69 NOK, occurring for the case with peak per monthly tariffs, spot prices from Trondheim 2018, and no PV, and the discharge only supplying the other EVs or for grid export. The energy discharged was used to supply the inflexible charging demand at the afternoon peaks, thereby reducing the total costs by 0.45%. The amount discharged on average per EV was far below what is considered to cause more than negligible capacity reduction on the EV batteries.

Enabling apartment electricity demand to be supplied by discharge from the EVs and solar energy production increases the efficiency of both, as the synergy of PV and EV discharge supplies the morning and afternoon peaks of the apartment electricity demand. The compensation for grid export is so low that measures to self-consume instead of exporting are beneficial. Having a separated energy meter for the apartments and the garage, with peak per month tariffs, leads to a flat charging profile over the day due to the flexibility of the EV charging. However, when aggregated with the apartment electricity load, it leads to an overall increase in the peak load. This suggests that looking at EV charging load and apartment electricity load together can decrease the grid burden.

8.1 Future work

Future work should try to implement dynamic optimization, replacing the full information model used in this thesis. For the peak per month tariff, peak load is kept low dynamically throughout the month, instead of being a given throughout the month as the model knows the lowest possible load peak.

It could be interesting to look more at user behavior in future work, studying at how effective the optimization works given user inputs and logical rules restricting the charging control algorithm and EV energy discharge.

The temperature affects battery health and charging efficiency, and future work could consider this. Future work should also include the cost of battery degradation for a more realistic EV discharge output.

Because the EV measurement data was not linked to the specific apartments, it was not possible to look at the effect of controlled EV charging on a single household, but only on aggregated levels for the apartment block. Future work should look at optimizations on the individual household level and look at this effect when aggregating the individual optimization in a neighborhood or apartment block, as single homes will not have the same possibility to coordinate charging for multiple EVs at the same time.

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Appendix

Table 19: Cost breakdown for OSL21 cases

Case	Fixed Cost [NOK]	Spot price cost [NOK]	Export income [NOK]	Prosumer compensation [NOK]	Grid Tax [NOK]	Energy transport tax [NOK]	Peak tariff tax [NOK]	VAT [NOK]	SUM [NOK]
EP_STC_OSL21	183 500	604 570	0.00	0.00	133 605	125 397	0.00	261 768	1 308 840
EP_OSL21	183 500	582 948	0.00	0.00	132 983	124 813	0.00	256 061	1 280 307
EP_PV_OSL21	183 500	547 278	-14 023	-701	121 838	114 353	0.00	241 742	1 193 987
EP_V2G_apt_OSL21	183 500	564 480	-17	-0.87	134 374	126 119	0.00	252 118	1 260 575
EP_V2G_OSL21	183 500	584 126	-12 402	-620	134 339	126 086	0.00	257 013	1 272 043
EP_V2G_PV_apt_OSL21	183 500	512 534	-33.40	-1.67	118 839	111 538	0.00	231 603	1 157 980
EP_V2G_PV_OSL21	183 500	545 023	-21 476	-1 073	121 592	114 122	0.00	241 059	1 182 748
PPM_STC_OSL21	183 500	604 570	0.00	0.00	133 605	37 999	103 635	265 827	1 329 138
PPM_OSL21	183 500	585 033	0.00	0.00	132 986	37 823	67 429	251 693	1 258 466
PPM_PV_OSL21	183 500	548 893	-14 314	-715	121 889	34 667	66 303	238 813	1 179 037
PPM_V2G_apt_OSL21	183 500	577 637	-20.41	-1.02	133 585	37 993	61 181	248 474	1 242 350
PPM_V2G_OSL21	183 500	587 941	-9 647	-482	133 904	38 084	64 600	252 007	1 249 907
PPM_V2G_PV_apt_OSL21	183 500	524 930	-66	-3.31	118 140	33 600	58 229	229 600	1 147 931
PPM_V2G_PV_OSL21	183 500	547 591	-19 727	-986	121 517	34 561	64 600	237 942	1 168 999

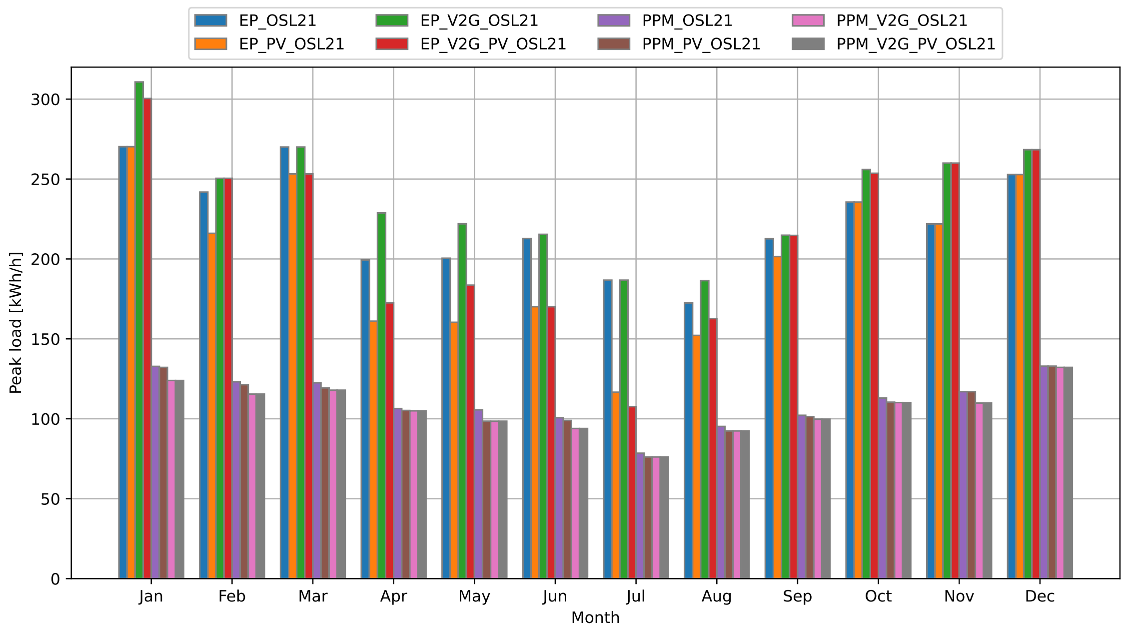

Figure 28: Peak load per month for the OSL21-cases

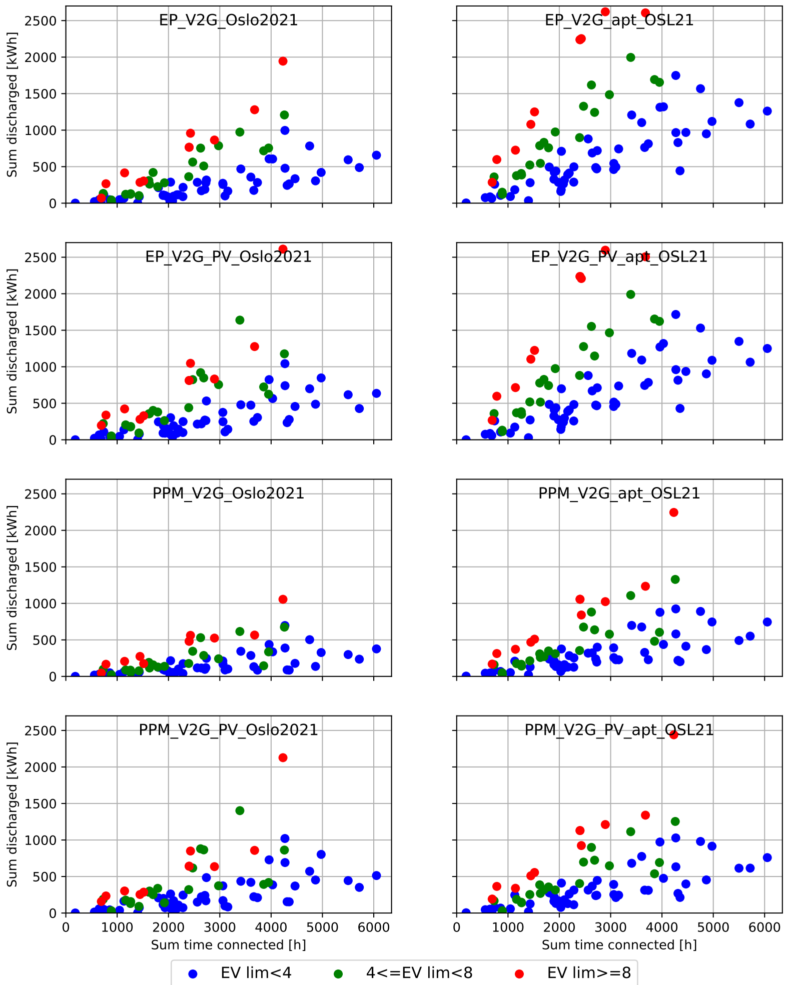

Figure 29: Scatter plot of sum discharged versus time connected per EV for OSL21-cases

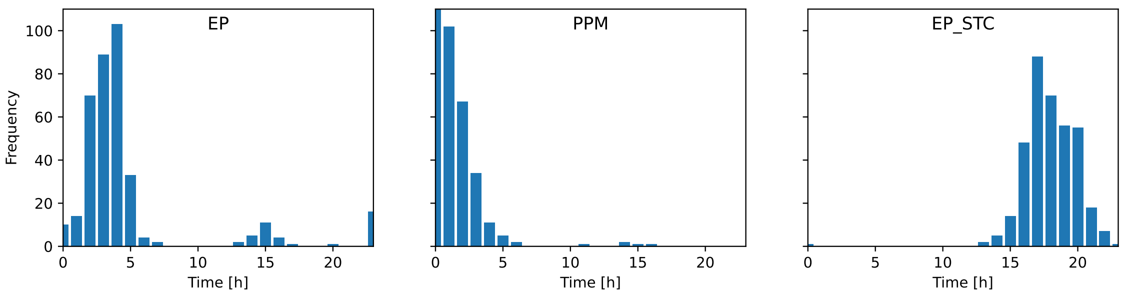

Figure 30: Frequency of peak hours over the day

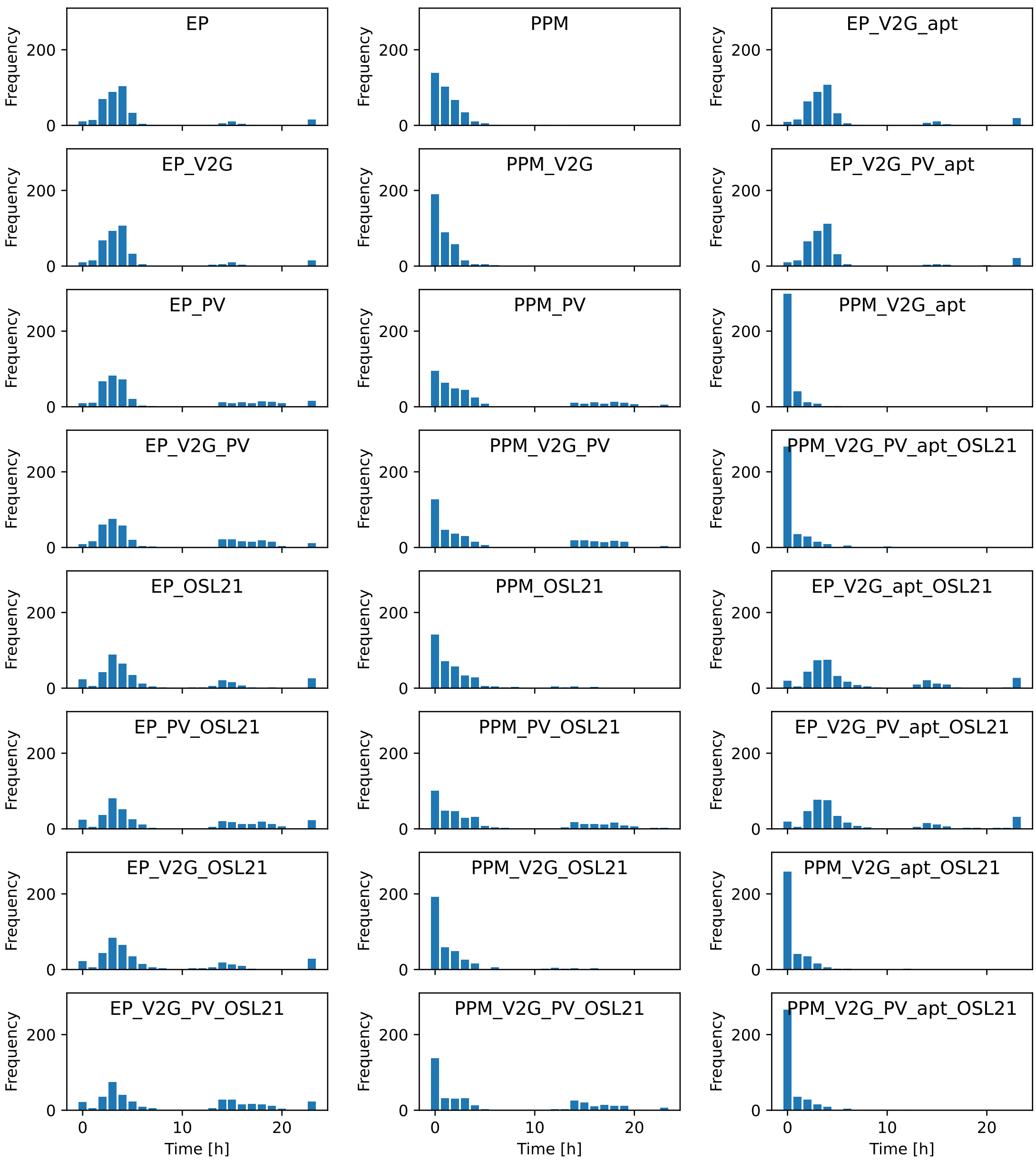

Figure 31: Bin count of daily peak hour occurrence over the year

Table 20: Grid burden KPIs

Case	Peak load [kW]	Peak date [mm/dd/yyyy]	Peak hour [hh-hh]	Avg daily peak hour [hh:mm]
EP_OSL21	270.22	17/01/2018	03-04	06:33
EP_PV_OSL21	270.22	17/01/2018	03-04	08:10
EP_V2G_apt_OSL21	314.56	22/01/2018	03-04	06:51
EP_V2G_OSL21	310.70	22/01/2018	03-04	06:36
EP_V2G_PV_apt_OSL21	314.56	22/01/2018	03-04	06:43
EP_V2G_PV_OSL21	300.39	22/01/2018	03-04	08:45
PPM_OSL21	132.91	December	-	02:42
PPM_PV_OSL21	132.91	December	-	05:31
PPM_V2G_apt_OSL21	130.09	December	-	00:43
PPM_V2G_OSL21	132.14	December	-	01:32
PPM_V2G_PV_apt_OSL21	129.89	December	-	00:47
PPM_V2G_PV_OSL21	132.14	December	-	05:42

Table 21: Key performance indicators for the apt-cases

Case	Objective value [NOK]	Sum imported [kWh]	Sum exported [kWh]	Peak load [kW]	Sum discharged [kWh]
EP_V2G_apt_OSL21	1 260 575	764 362	8.17	314.56	70 021
EP_V2G_PV_apt_OSL21	1 157 980	675 990	20.46	314.56	68 504
PPM_V2G_apt_OSL21	1 242 350	759 870	8.67	130.09	32 584
PPM_V2G_PV_apt_OSL21	1 147 931	672 017	43.80	129.89	35 198

Table 22: Case-wise cost reduction of implementing combined metering point

Case	Objective value [NOK]	Difference [NOK]	Percentage [%]
EP_V2G_OSL21	1 272 043		
EP_V2G_apt_OSL21	1 260 575	11 468	0.90
EP_V2G_PV_OSL21	1 182 748		
EP_V2G_PV_apt_OSL21	1 157 980	24 768	2.09
PPM_V2G_OSL21	1 249 907		
PPM_V2G_apt_OSL21	1 242 350	7 557	0.60
PPM_V2G_PV_OSL21	1 168 999		
PPM_V2G_PV_apt_OSL21	1 147 931	21 067	1.80

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