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Arbitrage Trading Opportunities with Bidirectional Charging

Optimizing Charging Costs by Exploiting Electricity Price Fluctuations in Norway

William Woie and Imre Tøllefsen Søndrol

Supervisor: Endre Bjørndal and Mette Bjørndal

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Norwegian School of Economics

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William Woie

Imre Tøllefsen Søndrol

Abstract

The Norwegian government has established ambitious climate goals, with the electrification of society playing an essential role in achieving them. Specifically, the electrification of the transportation sector is deemed crucial. However, local and geopolitical factors have led to record-high electricity prices in Norway, undermining the benefits of electrification. Consequently, there is an increased urgency to adopt technologies that provide incentives for electrification.

This thesis focuses on adopting bidirectional charging in Norway, specifically exploring the potential for electric vehicle owners to capitalize on arbitrage opportunities using this technology compared to smart charging. Bidirectional charging allows electric vehicles to take advantage of price fluctuations in electricity markets by utilizing the energy storage capabilities of the EV battery. The analysis is conducted through an optimization model that captures EVs' bidirectional charging behavior in the NO5 Norwegian power market, where the objective is to minimize charging costs. The thesis examines three simplified behavior patterns representing Norwegian driving habits and includes a scenario analysis considering various input parameters.

The obtained results show that bidirectional charging offers advantages over smart charging and unmanaged charging in terms of accumulated cost savings. The annual cost savings when utilizing bidirectional charging range from NOK 415 – NOK 1,275 in 2022 and NOK 176 – NOK 625 in 2021. The main finding is that substantial volatility in day-ahead prices is a prerequisite for the economic benefits of bidirectional charging to be perceptible, and the magnitude of the economic benefits increases with higher day-ahead prices during periods of high volatility. Results from the scenario analysis show that arbitrage opportunities increase by investing in a larger battery capacity and changing the current grid tariff model. In contrast, a higher charging capacity does not show cost benefits to the same extent, as the increasing cost of the capacity component of the current grid tariff outweighs any potential arbitrage gains from utilizing higher charging capacities. Lastly, the electricity support package introduced by the Norwegian government compromises the full potential of bidirectional charging. This subsidy eliminates the essential price volatility necessary for bidirectional charging, thus eradicating incentives for intelligent technologies like bidirectional charging.

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List of Abbreviations

AC	Alternate current
A	Ampere
AMPL	A Mathematical Programming Language
DC	Direct current
DER	Distributed Energy Resources
DSO	Distribution system operator
EV	Electric Vehicle
Km	Kilometer
Kr	Norwegian krone
kW	Kilowatt
kWh	Kilowatt per hour
MWh	Megawatt per hour
NOK	Norwegian krone
NVE	The Norwegian Water Resources and Energy Directorate
TSO	Transmission system operator
V2B	Vehicle to Business
V2G	Vehicle to Grid
V2H	Vehicle to Home
V2L	Vehicle to Load

1. Introduction

Europe's renewable energy sector was experiencing remarkable growth characterized by increased production of clean energy sources. Simultaneously, the utilization of coal-fired power plants was dwindling, leading to reduced CO2 emissions from power generation – a positive trend in the right direction.

At the same time, the European energy market was influenced by a rare combination of local and geopolitical factors that affected consumers. The opening of the Nord Stream 2 cable was postponed, Europe struggled to fill up its gas reserves, and there was an extreme demand for liquefied natural gas (LNG). Following a dry autumn in 2021, Norway's hydro reservoirs were tapped by using the flexibility in the multi-year magazines to produce a relatively large amount of electricity. Then came winter, with low snowfall, and in February 2022, war broke out in Europe. Nord Steam 2 was not approved, and the EU sanctioned everything they could from Russian goods except gas - they could not manage without it.

Gas prices rose to record levels, and Norway experienced an electricity crisis with record prices and high price variations in 2022. The average price in the NO5 bidding zone in 2022 was NOK 1.93, over 19 times the average price in 2020[1] and over seven times the average price in the period 2015 – 2020[2] (Nord Pool, 2023). Due to the high prices, Norwegian consumers have reduced consumption, and the Norwegian industry has scaled-down production[3]. But, even though the market has been exposed to turbulence, the energy transition must continue to reduce CO2 emissions.

Electrification of the transport sector is a vital part of this energy transition. Replacing fossil fuel-powered vehicles with electric vehicles (EVs) reduces reliance on fossil fuels and decreases greenhouse gas emissions. However, EVs increase the reliance on electricity, and the upward trajectory of electricity prices presents a potential deterrent to the willingness to transition the transportation sector fully.

On the other hand, advancements in battery technology and new charging systems have made EV charging more convenient. The advent of fast charging systems has decreased charging

[1] Average price of NOK 0.097
[2] Average price of NOK 0.262
[3] Elkem (2022) & Hydro (2022)

time significantly, while smart charging[4] has enabled the charging process to be more efficient as one can charge when the electricity prices are at the lowest. Results from research conducted by Enger & Nøstvik (2022) show that an EV would preferably charge at night to minimize charging costs with smart charging.

Further development of smart charging has resulted in the technology of bidirectional charging. This technology can revolutionize how we use EVs by allowing them to consume electricity and serve as a source of electricity for the grid (Vitra Ltd, 2022). Today, researchers widely acknowledge that the advancement of bidirectional charging technology holds significant potential for EV owners to capitalize on arbitrage trading opportunities and generate additional revenue [5].

This thesis aims to contribute to the ongoing research about bidirectional charging by exploring the potential benefits an EV owner can achieve with the technology. By maximizing economic benefits from an owner's perspective, the following research question is answered:

Can bidirectional charging offer potential arbitrage benefits to an EV owner?

The research question is answered by creating an optimization model considering an EVs bidirectional charging behavior in the NO5 Norwegian power market. The technology can exploit price fluctuations in the market by utilizing the storage opportunities in an EV battery.

The remainder of the thesis is divided into eight chapters. Chapter 2 provides background information on key concepts and other academic research on the topic. Chapter 3 presents a description of the optimization model, and Chapter 4 presents the mathematical formulation of the model. Chapter 5 describes the various data inputs used in the model. Chapter 6 presents and discusses the results, while Chapter 7 discusses the model's limitations and potential future research. Finally, the thesis concludes in Chapter 8.

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[4] Smart charging allows the EV owner to monitor, manage and restrict the use of their charging devices remotely to optimize charging (Vitra Ltd, 2019).

[5] Arbitrage trading refers to an investment strategy where one buys and sells an asset in different markets to take advantage of a price difference and generate a profit (Stobierski, 2021).

2. Background

This chapter provides an overview of the research question by introducing relevant background information. The chapter is divided into three sections. The first section focuses on practical information about EVs, charging components, and the current market situation in Norway. The second section presents an overview of the Norwegian energy market, including the market structure, the potential for renewables, and the impact of battery storage. The final section summarizes previous research on the topic of arbitrage trading with bidirectional charging.

2.1 Electric Vehicles

EVs are fully or partly powered by an electric engine (US Department of Transportation, 2022). Fully electric vehicles are, in practice, referred to as Battery Electric Vehicles (BEVs) and are solely powered by an electric engine. Plug-in Hybrid Electric Vehicles (PHEVs) are another type of EV, but in contrast to a BEV, PHEVs are powered by a gas engine with an electric engine as support. The PHEVs electric engine can be charged externally with a charging unit. On the other hand, a hybrid electric vehicle (HEV) has an electric engine that assists the gas-powered engine without the possibility of charging the electric engine with a charging unit. In the following chapters, only BEVs are considered, and the BEVs are referred to as EVs.

2.1.1 Charging strategies

Unmanaged charging

EVs need more time to charge the battery with electricity than petrol and diesel cars need to fill the tank. Instead of filling within minutes, an EV must be connected to a home charger or a public charging station to receive energy, which takes considerably longer. The most common EV charging strategy is an unmanaged charging strategy, where the vehicle charges from the time it is plugged into the charger unit until it is disconnected or the vehicle is fully charged (Buvik et al., 2019). This strategy only considers the users' preferences concerning when the battery needs to be charged.

Smart charging

In the past years, the new technology of smart charging has emerged. Smart charging allows the EV owner to monitor, manage and restrict the use of their charging devices remotely to optimize charging (Vitra Ltd, 2019). Smart charging relies on a real-time connection between an EV, a charging unit, and a charging operator. This connection enables the owner to increase or decrease charging power automatically when needed—for example, charging when the day-ahead prices are at the lowest, resulting in reduced electricity costs.

Bidirectional charging

Vehicle manufacturers have further developed the technology of smart charging to bidirectional charging. Bidirectional charging refers to two-way charging, meaning charge and discharge (Vitra Ltd, 2022). Bidirectional charging is further divided into different use cases based on where the electricity is pushed back; Vehicle-to-Grid (V2G), Vehicle-to-Load (V2L), Vehicle-to-Home (V2H), and Vehicle-to-Business (V2B).

V2G is the technology that enables energy to be pushed back to the electric grid (Vitra Ltd, 2022). The vehicle’s battery will charge and discharge based on different market signals, such as electricity prices. As renewable energy continues to develop with the energy transition, V2G can help tackle balancing problems in the energy market by providing congestion management, which can increase energy efficiency and reduce grid volatility (Drechny & Jóźwiak, 2019). V2G increases robustness in the electric grid rather than creating capacity problems.

V2L allows EVs to charge smaller electrical devices, while V2H and V2B enable the EV to power a home or business (Thai, 2022). These technologies are typically used when a distributed energy resource (DER) is installed at a home or business. DERs are small power generation units located on the consumer's side (AEMC, 2022), and they generate electricity to supply the home or business with power. If there is any excess energy, it can be sent back to the EV to be stored. Instead of relying on a separate permanent battery system, the EV's battery acts as an energy storage device for the DER system.

The benefit of this technology is that it helps reduce energy consumption during times of high demand, since it allows energy usage to be shifted to more favorable times. Additionally, EVs equipped with V2H and V2B technology can serve as backup systems, ensuring electricity supply in the event of a blackout. Essentially, the EV becomes a flexible energy resource for homes or businesses.

The bidirectional charging technology, though, has constraints. First, the technology degrades the battery faster because of the extra charging cycles that deliver electricity back to the grid (McKenzie et al., 2017). The research found that the batteries lost 5% to 9% more of their initial capacity after 18 equivalent months of bidirectional charging compared to unidirectional charging, but the loss varies between EV models and battery specifications. The loss results from higher usage of the battery's capacities, and the discharging frequency impacted the capacity loss.

Second, there has currently not been implemented a regulatory framework for bidirectional charging, neither by the EU nor the Norwegian government (EASE, 2019). Kern et al. (2020) argue that the essential issue is whether bidirectional chargeable EVs are classified as storage devices and, consequently, what additional fees may be required to discharge an EV. Third, the technology depends on a home charging unit or a public station that allows discharging. Today, such charging units are limited; only a few charging operators have developed charging units that enable this technology.

Finally, one also needs a vehicle that has adopted bidirectional charging. Currently, only a limited number of EVs offer bidirectional charging (Britto & Krannich, 2022). As of 2021, only Nissan and Mitsubishi have EVs capable of bidirectional charging in a V2G perspective, while a few other manufacturers, such as Hyundai, Ford, and MG, have incorporated V2L. Volkswagen announced that they are working to adopt bidirectional charging in their EVs; however, it is still unsure what type of use case and when the technology will be incorporated into their vehicles.

2.1.2 Charging specifications

EV charging stations use alternating current (AC) or direct current (DC) charging (Evbox, 2022). Power from the electric grid is AC, but EV batteries only accept DC. At some point, then, the current is converted. This conversion takes place inside or outside of the EV. DC charging allows the converter to be significantly larger as it is located outside the vehicle. As a result, higher charging capacity can be achieved. Such chargers are often public at gas stations or other designated areas. These fast chargers can deliver with a capacity of up to 350 kW. However, only a limited amount of EVs on the market can receive electricity with a higher capacity than 150 kW.

There are two options when charging an EV with AC power: using a designated charging unit or an ordinary socket. An AC charger is the charging unit used at home (Wallbox Chargers, 2023). In this case, the electricity conversion happens inside the vehicle, which results in lower charging capacity. On the other hand, an ordinary socket's charging capacity depends on the electric fuse installed in the household and can only deliver a maximum capacity of 2.3 kW[6]. As a result, the charging time can range between 8-40 hours, depending on the fuse and the EV's battery capacity (Strøm, 2013).

The charging time can decrease significantly by utilizing a home charging unit that can charge with a higher capacity. The 230V IT system is the standard distribution system for electricity in Norway (Oslo Economics, 2019). Consequently, it limits the charging capacity for most households to a maximum of 11 kW, depending on the installed fuse. With a 16A fuse, the charging capacity can be a maximum of 3.7 kW, while a 32A fuse is needed to charge up to 11 kW. In Norway, all new electrical installations follow the standard European 400V TN distribution system, which enables a charging capacity of up to 22 kW for home charging (Oslo Economics, 2019). There are mainly four maximum charging capacities that can be delivered in Norwegian households[7], as presented in Table 2.1 (Elbilgrossisten, 2022).

	Charging Cable Capacity	**Max Charging Capacity**			
Nominal voltage	**Fuse / phase**	**3.7 kW**	**7.4 kW**	**11 kW**	**22 kW**
230V / IT	16A / 1-phase	X			
	32A / 1-phase	X	X		
	16A / 3-phase	X			
	32A / 3-phase	X	X	X	
400V / TN	16A / 3-phase	X		X	
	32A / 3-phase	X	X	X	X

Table 2.1 – Maximum charging capacities in Norwegian homes (Elbilgrossisten, 2022)

[6] Disregarding efficiency loss.
[7] Disregarding efficiency loss.

The charging capacity depends on the factors: charging unit specifications, local distribution system, electric current, charging cable capacity, and EV-specific components. The charging capacity is limited by the weakest link of the five factors.

The capacity achieved when discharging the EV depends on the same factors as when charging but is typically lower due to EV-specific limitations (Thai, 2022). For example, the MG ZS can only discharge with a maximum capacity of 2.2 kW, the Nissan Leaf with a maximum capacity of 3.6 kW, and the Ford F-150 Lightning with a maximum capacity of 9.6 kW (Edelstein, 2022). Also, there are only a few charging units available on the market that offer bidirectional charging. These units provide a charging capacity of up to 22 kW but only a discharging capacity of up to 11 kW.

2.1.3 Cost of home charging units and smart charging

Investing in a home charging unit requires a significant capital investment. There are over 30 different models on the Norwegian market, and the price starts at approximately NOK 6,000[8] (Elbilgrossisten, 2023). Charging units with a charging capacity of 22 kW starts at approximately NOK 7,000. As mentioned in section 2.1.1, charging units that offer bidirectional charging are more limited. The Norwegian technology company Zaptec recently announced that their new Zaptec Pro charger allows for bidirectional charging (Zaptec, 2022). This charger is, however, intended to be used in housing cooperatives (Borettslag) and is designed to manage several vehicles at a time. Therefore, the price of this charger is significantly higher than a standard home charger, starting at NOK 15,875[9].

Whether an EV can be charged smartly depends on the technical compatibility between the power supplier and the EV brand. Some power suppliers include smart charging as part of their power subscription, while others offer it as an additional subscription. The cost of this extra subscription varies among suppliers, ranging from NOK 29 to NOK 100 per month. Additionally, Zaptec has also incorporated a free smart charging function called Eco Mode in their charging unit model Zaptec Go. This allows an EV owner to charge smart regardless of the power supplier or the subscription. Regarding bidirectional charging, no power suppliers currently offer subscriptions for this particular type of charging.

[8] Additionally, costs for installation and cables will accrue.
[9] The lowest price found per May 20, 2023 was NOK 15,875 (Ledonline, 2023).

2.1.4 Demand for electric vehicles in Norway

In the past decade, there has been a rapid growth in the number of EVs in Norway (SSB, 2023). In 2010, the household fleet consisted of 2,068 EVs. In 2022, 79% of all new cars sold were EVs, resulting in an EV fleet of 599,169 vehicles. The growth makes the current share of EVs in Norway 20.5% of the total household fleet. It also makes Norway the country with the highest amount of EVs per capita globally (Ministry of Transport, 2021). In contrast, the share of total gasoline and diesel vehicles has decreased, as Figure 2.1 illustrates.

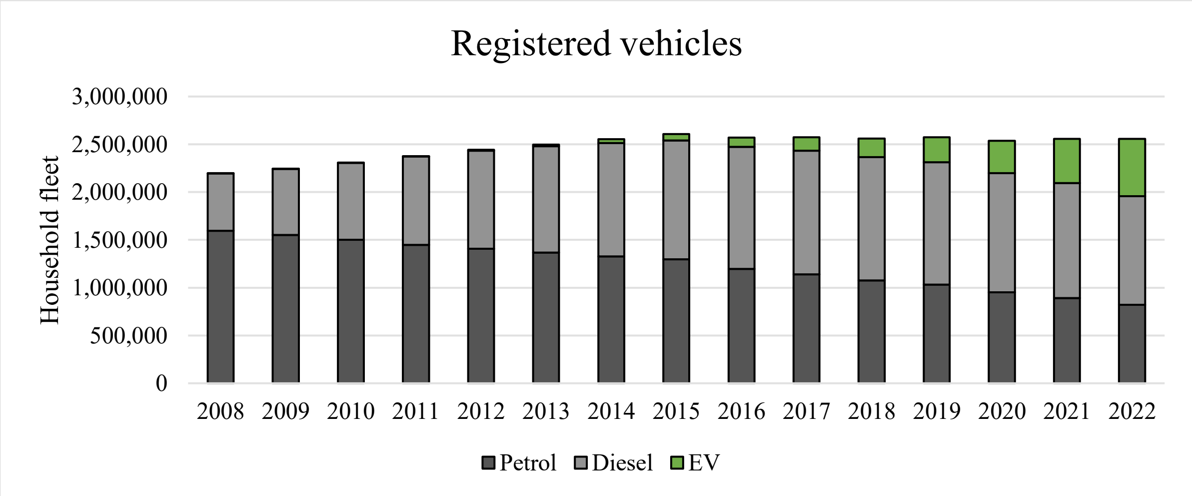


Figure 2.1 – Registered vehicles in Norway (SSB, 2023)

The widespread adoption of EVs in Norway has been facilitated by a series of policy measures implemented over the past decade. According to Fearnley et al. (2015), national policies that address the purchase price of EVs are the most effective in incentivizing consumers to buy zero-emission vehicles. Norway implemented such measures as exemption from import tax and VAT, and a national policy that exempted EVs from annual road tax. Galbusera (2019) and Figenbaum & Kolbenstvedt (2016) highlight that among various local policies promoting EV adoption, the exemption from toll road charges has proven to be the most influential in incentivizing consumers to purchase EVs. Conversely, other policies, such as access to bus lanes and free public parking, have not yielded the same consumer incentives.

Recently, EV taxation rules and incentives have experienced resistance. The Norwegian government has tightened up several of EV owners' benefits, such as introducing VAT on EVs on the part of the purchase exceeding NOK 500,000, increasing the re-registration rate, increasing on-off registration tax, and increasing road toll (Kalstad & Laugaland, 2022).

Despite that the EV benefits are being reduced, the Norwegian Parliament still has a national goal to reduce emissions from transportation, and by 2025 all new cars sold should be zero-emission vehicles (Ministry of Transport, 2021). In addition, the EU has also banned the sale of new petrol and diesel cars from 2035, making it likely that the share of EVs in the European Economic Area will rise (European Parliament, 2022). Statista (2022) projects the Norwegian EV market to increase to approximately 248,000 new sales in 2027, which reflects an approximately 70% increase from 2022 sales, and an average of 16% increase annually. Figure 2.2 displays the market outlook for total EVs sold per annum.

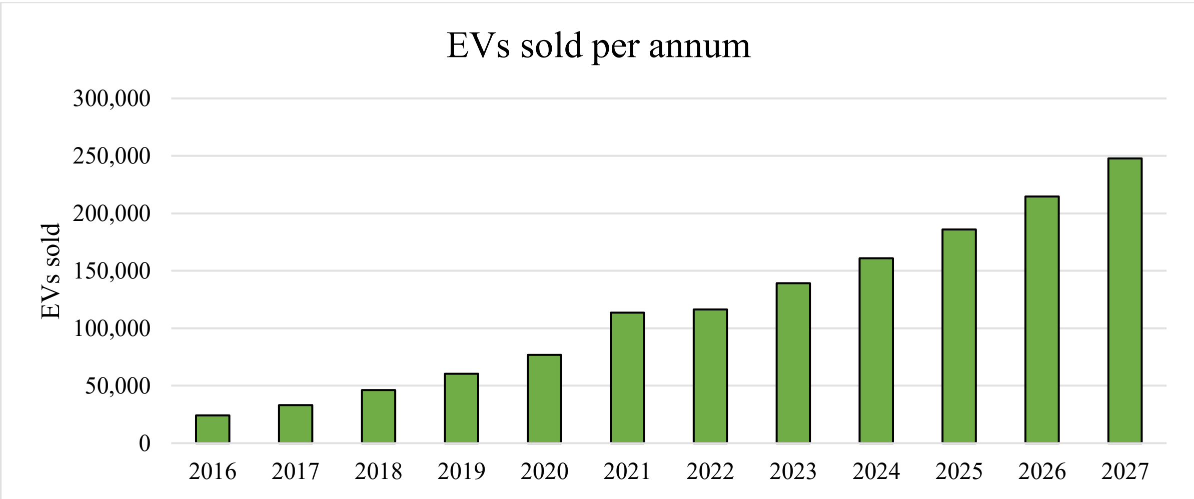


Figure 2.2 – EVs sold per annum in Norway (Statista, 2022)

2.1.5 Impact on the electric grid

In 2019, Buvik et al. estimated that an EV fleet of 1,5 million vehicles would consume 4 TWh of electricity annually, thereby increasing Norway's total energy consumption by 3%. Eggum et al. (2016) from the Norwegian Water Resources and Energy Directorate (NVE) found that while the average grid burden from EV charging is low, it can cause local overloads in areas where grid capacity is already limited, which may require significant investments in grid infrastructure such as transformers and cables in the distribution network. To address this issue, NVE suggests that demand-shifting systems, such as smart charging and bidirectional charging, could alleviate the challenges that local grid systems face due to EV charging. By optimizing charging to reduce peak hour demand, both grid burden and costs for EV owners could be reduced.

2.2 The Norwegian Power Market

The power system in Norway is market-based, meaning that electricity price is set through market mechanisms. However, these market mechanisms are strongly influenced by regulations enforced by the Norwegian Energy Regulatory Authority (RME)[10] (Energy Facts Norway, 2022). This regulatory framework helps ensure the efficient and reliable functioning of the electricity sector in Norway.

The Norwegian power market is closely integrated with the neighboring countries Sweden, Denmark, and Finland, forming a joint Nordic power market (Energy Facts Norway, 2022). This integration involves the participation of the financial market Nord Pool and interconnectors, which facilitate the exchange of electricity between these countries. Furthermore, Norway is connected to the broader European energy market through direct interconnectors to Germany, the UK, and the Netherlands. Additionally, there are direct transmission lines to Russia and indirect connections to Poland and the Baltic states (Energy Facts Norway, 2022). These interconnections enable the flow of electricity across borders, enhancing energy cooperation and facilitating the efficient utilization of resources within the European energy market.

2.2.1 Price formation

In the Norwegian electricity market, electricity prices are influenced by supply, demand, and transmission capacity. While market forces play a role in determining prices, the Norwegian market operates under a combination of competitive and regulated mechanisms to ensure stability and security of supply.

In this market, prices are determined through a combination of factors, including the marginal cost of production, available supply, and demand. While the marginal cost represents the cost of producing an additional unit of electricity from the cheapest available energy sources, it is essential to note that other factors, such as long-term contracts, regulatory interventions, and renewable energy subsidies, can also impact electricity prices. The Norwegian electricity market strives to balance efficiency and reliability by incorporating competitive market

[10] RME is organized as a separate and independent unit in NVE's organization.

dynamics and regulatory measures. This approach ensures the most efficient use of resources while maintaining a secure and stable electricity supply.

Norway's high trading capacity with other countries means that its electricity prices are influenced by the production costs of thermal power plants, particularly the prices of coal, natural gas, and emission allowances (Energy Facts Norway, 2022). Price variability in the Nordic region can also be affected by fluctuations in water inflow to storage reservoirs due to the significant amount of hydropower in Norway[11] and Sweden. When water inflow is high, prices decrease, and vice versa. The same applies to wind power, which is a growing renewable industry. Due to the limited capacity of the electric grid to equalize differences, energy availability can vary between different regions in Norway's weather-based energy system (Statnett, 2022). The grid network is divided into five bidding zones to ensure system operation and signal scarcity or surplus.

Figure 2.3 – Bidding zones in Norway (Statnett, 2022)

2.2.2 Wholesale and end-user markets

Norway's power market consists of two segments: the wholesale market and the end-user market (Energy Facts Norway, 2022). The wholesale market, operated by Nord Pool and other power exchanges, is auction-based and encompasses the day-ahead market, where contracts

[11] In 2021, 88% of Norway's power production came from hydro power, while 9% came from wind power (NVE, 2020).

for delivering physical electricity hour-by-hour the following day are traded; the intraday market, which allows for continuous trading up to the delivery hour, and the balancing market, which ensures grid balance. On Nord Pool, energy producers, brokers, energy companies, power suppliers, and large industrial customers engage in trading. Statnett, Norway's transmission system operator (TSO), oversees the balancing market to ensure proper functioning.

In the end-user market, consumers purchase electricity from either power suppliers or the wholesale market (Energy Facts Norway, 2022). In Norway, consumers can select from three types of contracts: spot price, variable price, and fixed price. Spot price contracts are priced according to market rates set by Nord Pool, with an additional markup, and are adjusted hourly. Variable price contracts are tied to market developments but have a shorter-term guarantee, with price adjustments made two weeks in advance and following the spot price with a slight delay. Fixed-price contracts offer a consistent rate for up to three years.

2.2.3 Regulations of the power grid

Norway's power grid operates on three levels: the transmission grid, the regional grid, and the distribution grid. The majority of consumers are connected to the regional or distribution grid, which according to EU legislation, are considered distribution systems (NVE, 2018). These distribution systems are subject to extensive controls by the Norwegian government, implemented through RME to prevent exploitation (Energy Facts Norway, 2019). This regulatory framework ensures that the distribution system operators (DSOs), which operate in a natural monopoly, adhere to specific regulations and guidelines.

The Norwegian government aims to maintain a rational and socially beneficial electricity grid[12]. The regulation of DSOs follows a monopolistic structure, with direct and incentive-based regulations in place. These regulations aim to ensure the efficient operation, utilization, and development of the grid in a manner that benefits society as a whole. Direct regulation ensures necessary investment in the grid, maintenance, operation, sufficient capacity, and supply quality, while incentive-based regulation is through a revenue cap (Energy Facts Norway, 2019). This cap allows for revenues that cover grid operation costs and provides a reasonable return on invested capital, incentivizing DSOs to find cost-effective ways to meet

[12] Regulated to protect consumer from the DSOs to use monopoly power.

their requirements. The annual revenue cap is set for each DSO by NVE based on a yardstick formula of 40% cost recovery and 60%[13] cost norm resulting from benchmarking exercises (Langset & Nielsen, 2021).

Grid tariffs

Electricity consumers in Norway are required to pay grid tariffs to their local DSOs. The grid tariff is intended to cover the costs associated with operating and maintaining the grid within each DSO's area (NVE, 2018). NVE sets the general guideline principles for the tariffs, which states that the prices must be fair, non-discriminatory, and based on the relevant conditions of the local grid.

In July 2022, the Norwegian government introduced a new grid tariff model encouraging consumers to spread their electricity consumption throughout the day. Although the specific grid tariff model may vary depending on the DSO, they must be based on two factors: Load and Consumption (NVE, 2018).

The load factor, a fixed component, is determined by the maximum load and should cover customer-specific costs and a portion of the fixed costs related to grid operation. Moreover, the fixed component should be differentiated according to power, i.e., customers requiring high capacity will have to pay more than those requiring less (NVE, 2022a).

The consumption factor, a variable component, is determined by electricity consumption (NVE, 2018) and based on the marginal cost of transmission losses (Energy Facts Norway, 2019). Although the variable component is typically set higher than the marginal cost, estimated to be around NOK 0.05 per kWh, DSOs must evaluate how the variable component should vary over time based on the grid's load. This evaluation considers factors such as demand patterns and variations in electricity consumption.

By adjusting the variable component, DSOs can effectively manage the grid's operation and ensure its reliability. This regulation helps to ensure that the grid operates effectively, covers operational costs, and maintains a stable and secure electricity supply (Energy Facts Norway, 2019).

[13] 70% starting from 2023.

In addition to the grid tariff, electricity customers in Norway must pay VAT, electricity tax, and a fee to the Energy Fund (ENOVA) (Strøm, 2019).

2.2.4 Potential for renewables in Norway

Norway primarily relies on renewable energy sources for its electricity generation. The annual electricity production in Norway varies per annum, but on average, it is estimated to be 156 TWh (NVE, 2023). In 2021, approximately 88% of Norway's power production came from hydroelectric power, while 9% came from wind power and around 2-3% from thermal sources (NVE, 2020). The high proportion of renewable energy production positions Norway with the highest share in Europe (Energy Facts Norway 2021).

Despite Norway's impressive renewable energy production, the country has set ambitious climate targets. The goal is to reduce greenhouse gas emissions by 55% by 2030 and transition to a zero-emission society by 2050 (Energy Norway, 2021). To achieve these targets, the electrification of society plays a crucial role. By increasing the use of electricity in various sectors, such as transportation and heating, Norway can reduce its reliance on fossil fuels and significantly contribute to achieving its climate objectives.

DNV estimates that Norway requires additional 45 TWh of annual electricity production by 2030 to ensure sufficient supply due to the electrification (Kippe, 2022). This production needs to come from renewable energy resources to comply with climate goals, increasing the pressure to continue the development of renewable energy resources. NVE (Henriksen et al., 2020) estimates a realistic potential for an additional 22.7 TWh of hydropower, while the remaining production gap must come from other renewable sources such as solar and wind.

Renewables Norway (former Norwea) estimated a potential of 30 TWh of land-based wind power annually (Hovland, 2019), while the Norwegian government has set a goal of allocating areas for 130 TWh of offshore wind production on the Norwegian continental shelf by 2040 (Tande, 2022). Solar power has also seen increased utilization in Norway, with higher electricity prices and support from ENOVA driving growth (NTB, 2022). A recent study found significant potential for solar power on Norwegian rooftops and facades, agricultural land out of operation, car parks, and closed landfills (Mørk, 2022).

Even though most of Norway’s energy production comes from green sources, the distinctive challenge of renewable energy is intermittency. Norway has a significant advantage in hydropower as it has a remarkable ability to store energy, but with the predicted increase in other renewable sources, challenges for the electric grid may arise.

2.2.5 The impact of renewables on the electric grid

Gas and coal-fired power plants have been used in Europe to generate continuous electricity (Eurostat, 2023). These plants can modulate their production based on demand, providing a certain degree of flexibility for the TSOs to respond to voltage and frequency disturbance fluctuations. Similarly, hydropower can also be used to store energy and provide electricity during periods of low rainfall or water flow. Norway has a large reservoir capacity for hydropower, allowing for smoothing production over several periods depending on market conditions. In fact, Norway has half of Europe's reservoir storage capacity, with over 75% of its production capacity being adjustable (Energy Facts Norway, 2022).

However, the increasing use of intermittent energy sources such as wind and solar power has made it more challenging to maintain balance on the grid. These sources are unpredictable, making it hard to predict the frequency and voltage they will produce. As a result, it is uncertain whether intermittent energy sources will generate enough electricity during peak consumption periods, while production may exceed consumption at other times. In extreme cases, grid congestion caused by periods of high wind may require wind turbines to be shut down, leading to less efficient production of (potential) energy.

Prosumers

Traditionally, the power grid has been designed to deliver electricity from power plants to consumers (NVE, 2021). The plants generate electricity at high voltages and then reduce the voltage for distribution. However, this approach is changing as more households generate their own electricity[14] using renewable sources such as photovoltaic systems, where excess electricity is sent back to the grid.

[14] In Norway the increase of households with a solar photovoltaic system increased from 2,500 in 2019 to 6,100 in April 2021 (SSB, 2021).

Customers who both purchase and produce electricity are referred to as prosumers. While prosumers pay a standard grid tariff for electricity consumption from the grid, they do not pay a grid tariff for electricity delivered to the grid (BKK, 2022b; Elvia, 2022). To send excess electricity back to the grid, prosumers must enter into an agreement with a power supplier that manages both production and consumption. Furthermore, DSOs are required to connect with prosumers and receive their electricity (Langset & Nielsen, 2021). Prosumers producing less than 100 kW are exempt from the fixed generation fee, even if the DSO must reinforce the grid to receive power (NVE, 2022b).

However, the prosumer scheme has created challenges for DSOs. While research indicates that the grid can handle distributed energy resources (DERs), the increased number of solar cells may strain some areas of the grid's voltage quality standards. This strain is mainly due to capacity problems in the transformer and high voltage values (Tveiten, 2019). Despite the required significant investment, NVE believes establishing a connection between DERs and the grid is critical.

2.2.6 Battery storage of electricity

As society transitions to renewable energy, batteries will play a crucial role (European Commission, 2016). Batteries enable us to store excess electricity generated from renewable sources like solar and wind power, ensuring a stable and efficient power grid. Battery storage also helps smooth out fluctuations in electricity supply by acting as reserves in balancing markets, improving energy efficiency, and facilitating renewable energy integration into the grid (European Commission, 2016).

Recent advancements in battery storage technology, particularly lithium-ion batteries, have made them more cost-effective and efficient (European Commission, 2016). However, the cost of battery storage is still relatively high, making it challenging for households and businesses to justify the investment (Statkraft, 2022).

In addition to grid-scale applications, batteries enable households to store surplus energy from local energy resources. By adding battery packs to their power systems, households can save excess energy instead of selling it back to the grid at a potentially low price. Furthermore, EV batteries can be used as home energy storage, eliminating the need to purchase additional batteries for home electricity systems, and can protect against short-term power outages. This development has prompted research into bidirectional charging technology, offering EV owners a flexible way to utilize more of their EV's potential.

2.3 Literature Review

The concept of bidirectional charging was introduced decades ago, with a substantial amount of research conducted on the concept; however, in recent years, the technology has been nascent. Aghajan-Eshkevari et al. (2022) have divided the studies into three categories depending on the research objectives of bidirectional charging. These categories are economic, environmental, and power system improvement. Figure 2.4 displays the structure of the different research categories.

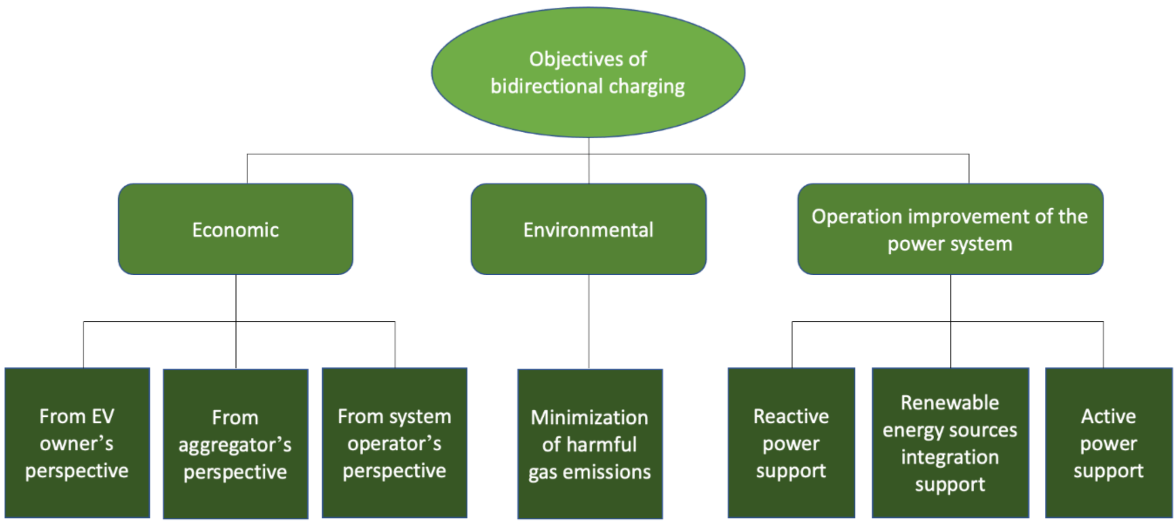


Figure 2.4 – Research categories of bidirectional charging (Aghajan-Eshkevari et al., 2022)

In recent years, technology companies and vehicle manufacturers have launched pilot projects to investigate the actual effects of the technology. The pilot projects have an extensive range of different focuses, among other things, how the EV can act as an energy reserve for the balancing markets, how bidirectional charging along with distributed energy resources can facilitate a more intelligent use of the electric grid, and how arbitrage trading can incentivize consumers to enable bidirectional charging in their EV. In this section, the thesis will focus on literature regarding arbitrage trading, which falls under the EV owners' perspective.

Kempton and Letendre (1997) first introduced how EVs can be a new power source for electric utilities. The study used a technical and economic analysis method to analyze the grid's and vehicle owner's benefits based on EV configurations, driving requirements, and electric utility demand conditions. The idea of this bidirectional charging concept was that the vehicle would have a two-way computer-controlled connection to the grid. The battery from the EV should then be fed to the grid for load-leveling purposes. The study's results showed that EVs would be considered attractive to power systems regarding the benefits of flattening peak hour prices when energy storage was considered. For the EV owner, the model was based on the utilities providing incentives in the form of capital payments for access to the stored energy in the EV. If these payments were higher than the costs associated with discharging an EV, especially costs related to wear and tear on the battery, it would be economically beneficial for the EV owners to agree with utilities to allow for discharge.

More recent research by Kern et al. (2020) presents a mixed integer linear, rolling horizon optimization model to investigate revenue potentials for bidirectional chargeable vehicles in the German spot market. The authors present a model to minimize the charging cost while discharging at maximum revenue. The model uses an aggregated EV pool consisting of commuters and non-commuters. Charging is done at home, at work, or in public, all based on data from driving behaviors in Germany. The electricity prices included additional charges for purchased energy to reflect the regulatory framework. The model is designed to minimize charging costs while allowing for transactions in the intraday market. The authors present results that show that the revenue potential gives EV owners clear incentives to participate in bidirectional charging. However, the revenue depends on the parameters such as the EV pool, driving behavior, and regulatory framework. Non-commuters are believed to have the highest possibility for revenue, as the vehicle will be more connected to the grid than a commuter EV. The authors further investigate the potential in other European countries and show that the revenue potential depends on how the energy market is structured and how volatile electricity prices are.

Kern et al. (2022) have further researched the revenue opportunities with bidirectional charging when implementing it in a smart house fitted with a photovoltaic system. They propose an optimization model with linear and mixed-integer linear programming. First, they present the optimization model considering V2H exclusively before allowing for arbitrage trading when V2H and V2G are combined. The analysis includes three scenarios: unmanaged, smart, and bidirectional charging. The objective of both models was to minimize the household's electricity costs. The authors found that including a bidirectional chargeable EV in a smart home configuration and only allowing for V2H leads to a 25% - 35% reduction in electricity costs for a household with an unmanaged charging EV. However, the cost reduction depends on household size, as larger houses with higher power demand enable more efficient discharging of the EV. In the model where V2H and V2G are combined, they find even higher potential for cost reductions and show that arbitrage trading complements V2H in the winter months due to less photovoltaic generation.

Baker et al. (2022) have a different approach to arbitrage trading with bidirectional charging. They researched the potential for energy arbitrage to be a temporal and spatial arbitrage, meaning they looked at utilizing the EV as a mobile storage device. The authors present a single-stage mixed integer linear stochastic optimization model where the EV can charge/discharge at the two predetermined geographical locations of San Marcos and Austin in the US. The objective is to minimize the charging cost, maximizing the profit from arbitrage trading. For simplicity reasons, they assume the EV can only travel once per day between the two locations and only travel if there is an arbitrage opportunity. Traffic behavior is implemented by using Google Maps traffic features. The EV configurations are equal to a Tesla Model S; however, the charging and discharging capacity was set to 50 kW. The results show that the ability to minimize cost and achieve profitability highly depends on if there exists perfect information. When the EV knows when price peaks occur and the most optimal traffic conditions exist, the model generates a high profit compared to the stochastic case. The stochastic case still produces profitability but to a lower extent. The findings also showed that the EV conducted both spatial arbitrages by traveling to a location with higher electricity prices but also performed temporal arbitrage once parked at the destination by continuously charging and discharging.

The research mentioned above shows that an efficient amount of reliable data has been conducted to investigate bidirectional charging's economic potential from an EV owner's perspective. This thesis, therefore, aims to contribute to the ongoing research by focusing on an EV's bidirectional charging behavior in the NO5 Norwegian power market.

3. Problem description

This thesis aims to investigate the potential arbitrage benefits of bidirectional charging and determine how the various parameters affect profitability. A mathematical optimization model is presented in Chapter 4. The objective is to minimize charging costs, and the model strives to achieve a high level of realism through ex-post optimization. To accomplish this, it is crucial to develop mathematical representations of driving behavior that accurately reflects real-world patterns. The model incorporates input data from EV-specific components; however, the model is subject to simplifications.

The primary emphasis of this thesis centers on the years 2022 and 2021 due to the escalating electricity prices that triggered a national electricity price crisis in Norway. In addition, the period spanning 2015 – 2020 is examined, incorporating average prices on an hourly basis in the model.

3.1 Specifications

This thesis explores the cost optimization of bidirectional charging when an electric vehicle is connected to a home charger. As there is currently no established regulatory framework for bidirectional charging, this study assumes that the EV owner is a prosumer with their power supplier. Moreover, the study excludes other electricity usage within the household from its analysis.

Norwegian electricity prices from the NO5 bidding zone are obtained to investigate the arbitrage opportunities in the NO5 market. The charging cost is determined by multiplying the amount of electricity charged by the day-ahead price, adding the applicable VAT, and incorporating the grid tariff fees. Due to the prosumer scheme, earnings from discharging are exempt from the grid tariff fee[15] and VAT. Therefore, discharging is only subject to the electricity price at the time of discharge multiplied by the amount discharged.

The electricity received by charging is stored in the battery and used to power the vehicle when driving. The battery capacity varies with different EV models and influences the storage

[15] Both the variable and fixed (capacity) component.

possibilities and driving range of the EV. The state of charge (SOC) is the amount of energy available in the EV battery at a specific time and is determined by the interaction between charging, discharging, and energy consumption when driving. The SOC cannot exceed the battery capacity limit nor be negative.

The EV must be connected to a home charger when charging or discharging. As written in section 2.1.1, home charging allows for four maximum charging capacities[16]. The model ensures that the total amount of electricity the charging unit delivers does not exceed its maximum capacity in kW. When the EV is connected to the charging unit, the EV is available and can freely charge or discharge. The SOC of the battery will change depending on the optimization. It may increase, decrease, or remain the same. The model ensures that a minimum amount of electricity is stored in the EV's battery before departure.

Energy losses will occur when charging, discharging, and storing electricity due to heat conversion and transmission loss (Apostolaki-Iosifidou et al., 2017). It is difficult to estimate the exact loss and time of loss. Therefore, a simplification is incorporated in the model where the loss is added to the charging process. Adding efficiency loss makes the model more realistic, as there is a need for more energy to load the battery fully. However, the model is simplified by not considering battery degradation, as the degradation varies between EV models and battery specifications.

The EV can function as a battery storage system that is always connected to the grid; however, this is unrealistic. Using an EV only as a storage system would be highly unprofitable due to the high investment costs. Instead, the model will consider three different behavior patterns of EV usage. The daily energy consumption when driving is calculated based on the average daily EV consumption, and the model ensures that the SOC of the battery decreases correspondingly to the consumption.

[16] Se Table 2.1

3.2 Behavior patterns

The thesis investigates three different behavior patterns that are simplifications of driving behaviors in Norway on a weekly average. Therefore, long periods where the EV can be available or unavailable are not considered. A base case and two alternative driving patterns are presented in the following sections. The base case will be used as default in the scenario analysis.

3.2.1 Base case

The base case investigates a behavior pattern where the EV owner has one day of home office a week and where the EV is used to and from work the other weekdays. After the covid-19 pandemic, more employers have offered their employees the benefit of working from home.

3.2.2 High availability

In this behavior pattern, the EV owner takes public transport to and from work, and the EV is only used for errands some evenings a week and in the weekends. As many people use public transportation to work, the EV stands unused most of the time, resulting in high availability for bidirectional charging.

3.2.3 Low availability

The last behavior pattern investigates the profitability of bidirectional charging when the EV is used daily for work, in addition to some evenings a week and in the weekends. The EVs availability is low and consumption is high.

4. Model

This chapter explains the mathematical formulation of the model used to minimize the cost of bidirectional charging.

4.1 Model introduction

Optimization is the art of making good decisions. It provides us with a set of tools, mainly from computer science and mathematics, which are applicable in virtually all fields, ranging from medicine to EV charging (Neri, 2018). An optimization model is a translation of the key characteristics of the problem one is trying to solve. The model consists of three elements: the objective function, decision variables, and constraints (IBM, 2022), where the goal often is to determine the maximum or minimum value of a complex equation (Kelso, 2015).

The model used in this thesis solves a deterministic optimization problem. The deterministic method is used because the model has a well-defined objective goal and a precise measure of what constitutes an optimal solution. The model and its requirements are described using binary relationships, and the model will explore the entire solution space and evaluate all possible solutions to find the best one.

The optimization model and the model data are implemented and solved in AMPL using the CPLEX solver. AMPL is a mathematical programming language that facilitates experimenting with formulations and simplifies using suitable solvers to solve the resulting optimization problems (Gay et al., n.d.).

4.2 Sets

The goal of this thesis is to minimize charging costs on an annual basis by utilizing hourly price data. Table 4.1 presents the sets included in the model. The set D contains days of the year, and set D_i contains the days in a given month $i \in I$. Set T contains the hours in a day from 1 to 24, and set I represents the twelve months. Set J incorporates the six levels of the grid tariff.

Set	Description	Values
D	Days	{1,365}
D_i	Days in month *i*	
T	Hours in a day	{1,24}
I	Months	{1,12}
J	Levels in the grid tariff	{1,6}

Table 4.1 – Model sets

4.3 Parameters

Table 4.2 presents the model parameters, their brief description, and corresponding units of measure.

Parameter	***Description***	***Unit***
$p_{t,d}$	Spot price in the day-ahead market in hour *t* on day *d*	NOK
$e_{t,d}$	Variable cost of the grid tariff in hour *t* on day *d*	NOK
VAT	Applicable VAT	%
$q_{t,d}$	Equal to 1 if the EV is available for bidirectional charging in hour *t* on day *d*, zero otherwise	
s	Maximum discharging capacity	kW
w	Loss when charging	%
max	Maximum SOC	kWh
$SOC_{departure}$	Departure SOC	kWh
$f_{t,d}$	EV consumption in hour *t* on day *d*	kWh
k_j	Charging capacity at level *j*	kW
h_j	Fixed monthly cost of grid tariff at level *j*	NOK

Table 4.2 – Model parameters

Parameters $p_{t,d}$, $e_{t,d}$, and *VAT* represent the price components of the model. Parameter $p_{t,d}$ contains day-ahead prices for every hour of every day of the applicable year and parameter $e_{t,d}$ contains the corresponding variable cost of the grid tariff. *VAT* is the applicable VAT at the time of charging. Parameter $q_{t,d}$ states the availability of the EV to bidirectional charging and is equal to 1 if the EV is available to bidirectional charging in hour *t* on day *d*, and zero otherwise. Parameter s is the maximum discharging capacity of the model, and units are given in kW. Parameter w represents the losses occurring in the charging process. The model is simplified to recognize losses when charging, not discharging.

Parameter max represents the maximum SOC of the battery in the model, and $SOC_{departure}$ is the amount of electricity the battery must store before departure. How much the EV consumes when driving in given by parameter $f_{t,d}$. Parameter k_j states the charging capacities constrained by the current grid tariff, and parameter h_j gives the corresponding fixed monthly cost of the grid tariff at level j.

4.4 Decision Variables

Decision variable	Description	Type
$x_{t,d}$	Amount of electricity retrieved from the grid in hour t on day d	Continuous
$y_{t,d}$	Amount of electricity sent back to the grid in hour t on day d	Continuous
$SOC_{t,d}$	State of charge of the EV's battery at the end of hour t on day d	Continuous
$z_{i,j}$	Indicates whether level j is used (1) in month i, or not (0)	Binary

Table 4.3 – Model's decision variables

Table 4.3 display the model variables. The model is subject to three decision variables every hour, every day of the applicable year. The EV can either retrieve $x_{t,d}$ electricity from the grid or send $y_{t,d}$ electricity back to the grid. The decision variable $SOC_{t,d}$ varies in accordance with the first two and, in addtiotion to consumption, and displays the battery capacity status at any time. Variable $z_{i,j}$ is a binary variable that takes the value 1 if level j of the grid tariff is used in month i, or 0 if not.

4.5 Objective Function

$$min \sum_{t\in T,d\in D} p_{t,d} \cdot x_{t,d} \cdot (1+VAT) + \sum_{t\in T,d\in D} e_{t,d} \cdot x_{t,d} + \sum_{i\in I,j\in J} h_j \cdot z_{i,j} - \sum_{t\in T,d\in D} p_{t,d} \cdot y_{t,d} \tag{4.1}$$

The objective function, 4.1, aims to minimize the charging cost, considering the day-ahead prices and the grid tariff. It is done by price arbitrage; the EV charges when the price is low and discharges when it is high.

The first part of the objective function calculates the cost of charging, which is determined by multiplying the amount charged by the electricity price at the time of charging and applying the applicable VAT %. The second part incorporates the variable cost of the grid tariff when charging. The third part incorporates the fixed component of the grid tariff and is measured by the sum of each month's cost. Finally, the fourth part considers the revenue earned by discharging electricity back to the grid, calculated by multiplying the amount discharged by the electricity price at the time of discharge.

4.6 Constraints

The model constraints are developed to create a realistic interaction between using the EV as a vehicle and as a tool to balance the electric grid, considering realistic features of the bidirectional charging and the battery's health. The following sections will explain the model constraints.

4.6.1 Charging

$$x_{t,d} \leq q_{t,d} \cdot \sum_{j \in J} k_j \cdot z_{i,j} \qquad \forall\, t \in T, d \in D, i \in I \qquad (4.2)$$

$$x_{t,d} \geq 0 \qquad \forall\, t \in T, d \in D \qquad (4.3)$$

In theory, the maximum charging capacity is limited by the home charging unit's charging capacity, the EV's availability, and the maximum charging capacity the EV can receive. However, in practice, the charging capacity should be optimized subject to which level of the capacity component is optimal due to the increasing cost of higher charging capacities. Constraint 4.2 limits the maximum charging capacity each month by multiplying the charging capacity k at level j with the binary variable $z_{i,j}$, deciding which maximum charging capacity is optimal for the given month. The EV must be connected to the grid before a charging process can occur, which the parameter $q_{t,d}$ accounts for. Constraint 4.3 limits the possibility of negative charging.

4.6.2 Discharging

$$y_{t,d} \leq s \cdot q_{t,d} \qquad \forall\, t \in T, d \in D \qquad (4.4)$$

$$y_{t,d} \geq 0 \qquad \forall\, t \in T, d \in D \qquad (4.5)$$

The potential electrical output of an EV is restricted by both the discharge capacity of the home charging system and the accessibility of the EV, which is the underlying basis for constraint 4.4. Furthermore, Constraint 4.5 dictates that a negative amount of electricity cannot be discharged from the EV.

4.6.3 Capacity component

$$\sum_{j=1}^{6} z_{i,j} = 1 \qquad \forall\, i \in I \qquad (4.6)$$

Each month, EV owners are subjected to the capacity component of the grid tariff. To ensure that EV owners are subject to only one specific capacity component per month, constraint 4.6 is in place, which comprises the binary variable $z_{i,j}$.

4.6.4 State of charge

$$SOC_{t,d} = SOC_{t-1,d} + x_{t,d} \cdot (1-w) - y_{t,d} - f_{t,d} \qquad \forall\, t \in T, d \in D\colon t > 1 \qquad (4.7)$$

$$SOC_{1,d} = SOC_{24,d-1} + x_{1,d} \cdot (1-w) - y_{1,d} - f_{1,d} \qquad \forall\, d \in D\colon d > 1 \qquad (4.8)$$

$$SOC_{1,1} = SOC_{start} + x_{1,1} \cdot (1-w) - y_{1,1} - f_{1,1} \qquad \forall\, t = 1, d = 1 \qquad (4.9)$$

In order for the model to operate effectively, it is imperative to maintain continuous monitoring and tracking of the SOC of the EV battery. Constraints 4.7 and 4.8 maintain the relationship between bidirectional charging, EV consumption, and inventory constraints. Specifically, Constraint 4.7 tracks the SOC of the battery on an hourly basis by adjusting it to potential battery operations, such as charging, discharging, or consumption. The model accounts for energy losses during these operations by incorporating a loss factor *w* in the charging process. Constraint 4.8 performs a similar function to Constraint 4.7 but focuses on tracking the SOC when entering a new day. Constraint 4.9 states the charging process during the first hour of the model.

$$SOC_{t,d} \leq max \qquad \forall\, t \in T, d \in D \tag{4.10}$$

$$SOC_{t,d} \geq 0 \qquad \forall\, t \in T, d \in D \tag{4.11}$$

Constraints 4.10 and 4.11 keeps the bidirectional charging process limited to a SOC interval between 0 and the useable capacity, which is the minimum and maximum SOC of the model.

$$SOC_{t-1,d} \geq SOC_{departure} \cdot (q_{t-1,d} - q_t) \qquad \forall\; d \in D, t \in T{:}\, t > 1 \tag{4.12}$$

$$SOC_{24,365} \geq SOC_{departure} \qquad \forall\; t = 24, d = 365 \tag{4.13}$$

While constraints 4.4 and 4.5 limit the amount discharged to be between 0 and *s*, constraint 4.12 guarantees that the threshold amount is reached before departure. Finally, Constraint 4.13 ensures that the threshold amount is maintained during the year's last hour.

5. Data

This chapter will present and describe the data input incorporated in the optimization model. The data used in the model can be divided into four categories: cost components, charging and discharging components, EV-specific components, and driving patterns.

5.1 Cost components

The total cost of EV charging is a function of the day-ahead prices, VAT, and the grid tariff.

5.1.1 Day-ahead prices

The optimization model incorporates day-ahead prices for the NO5 bidding zone, obtained from Nord Pool's FTP server (2023) and converted from NOK/MWh to NOK/kWh in Excel before being implemented in AMPL. Table A.1 in the appendix provides an extract of the day-ahead price structure.

The model uses the respective day-ahead price data to examine the implementation of bidirectional charging for 2022, 2021, and the period 2015 – 2020. For the period 2015 – 2020, the average hourly day-ahead prices per hour are used. The day-ahead prices obtained from Nord Pool exclude electricity taxes and fees; thus, the current VAT rate of 25% in Norway is added to the day-ahead prices when charging. It is important to note that the price paid by a consumer also includes a surcharge, but this is not considered in the study as it varies depending on the power supplier.

Seasonality

Seasonality refers to patterns in electricity prices within years. Figure 5.1 compares the average day-ahead price of 2022, 2021, and the period 2015 – 2020 on hourly variations, with 2021 prices belonging to the secondary y-axis. For 2022 and 2021, the price varies similarly depending on the time of day for both years. The prices were, on average, higher in 2022 compared to 2021, hence a secondary y-axis. Electricity demand tends to be higher when households use electricity for heating and cooking, among other things. As a result, electricity prices are typically higher in the morning and when people return home from work, while they are lower during midday and at night. The figure also displays how low, on average, the electricity prices were in 2015 – 2020 compared to recent years.

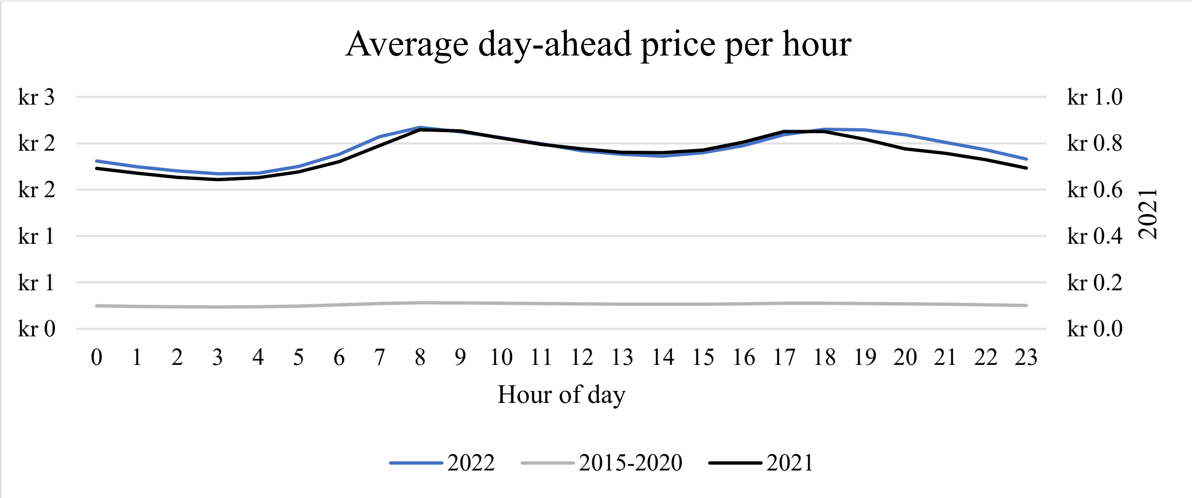


Figure 5.1 – Average day-ahead prices per hour

Figure 5.2 considers the seasonality occurring on a weekly variation, with 2021 prices belonging to the secondary y-axis. There is a noticeable difference between weekdays and weekends, with spikes often being prominent and the average price being lower on weekends than on weekdays. The price difference between weekdays and weekends is significant in 2022. However, in 2021, the price on Sundays tends to be as high as on weekdays.

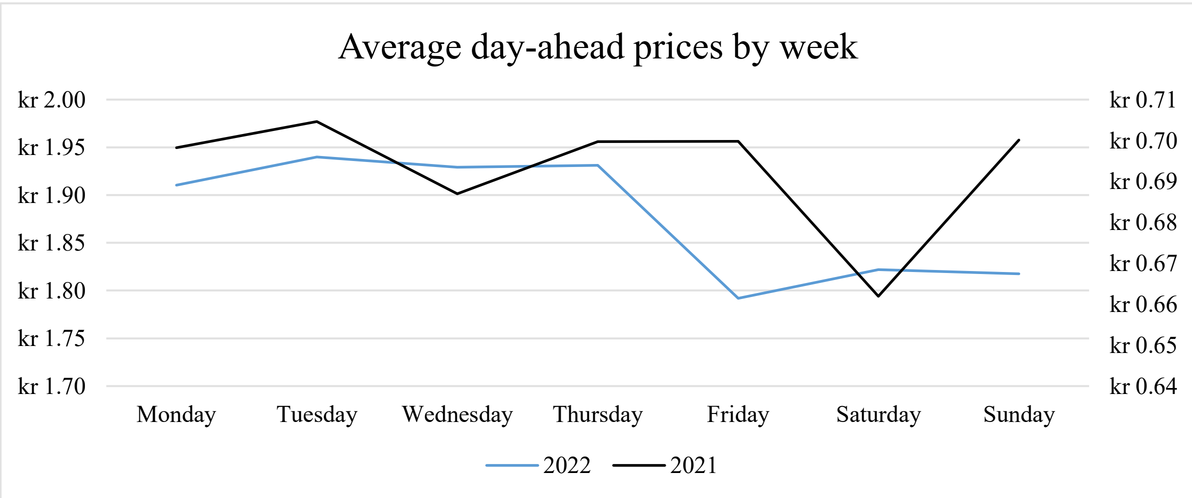


Figure 5.2 – Average day-ahead prices by week

In 2021, the average electricity consumption in Norway was 23,000 kWh per household (Ulvin, 2022), over three times the European average of 7,000 kWh. The high difference is because of topographical and climatic conditions. In addition, Norwegian buildings are more reliant on electricity for heating compared to other European countries that rely on gas. Electricity prices, therefore, tend to deviate depending on the season. Typically, winters are cold, resulting in increased heating demand, which increases electricity prices. During the summer, there is less demand for heating, decreasing electricity prices. This trend is illustrated in Figure 5.3 below, where the hourly mean for the period 2015 – 2020 is used to analyze the seasonality in prices. The seasonal mean is provided by dividing the yearly periods into summer, spring, fall, and winter[17].

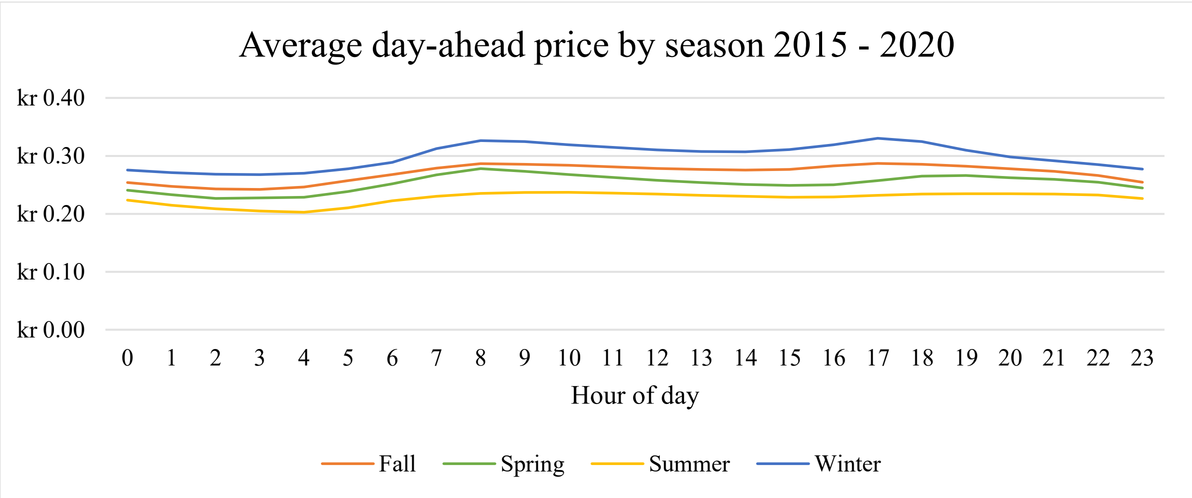


Figure 5.3 – Average day-ahead price by season 2015 – 2020

By comparing the seasonal trend for the electricity prices in 2022 and 2021 with 2015 – 2020, the seasonal trend for the years deviates from the reasoning above, as illustrated in Figure 5.4 and 5.5.

[17] Dember, January, and February are considered winter; March, April, and May are considered spring; June, July, and August are considered summer; September, October, and November are considered fall.

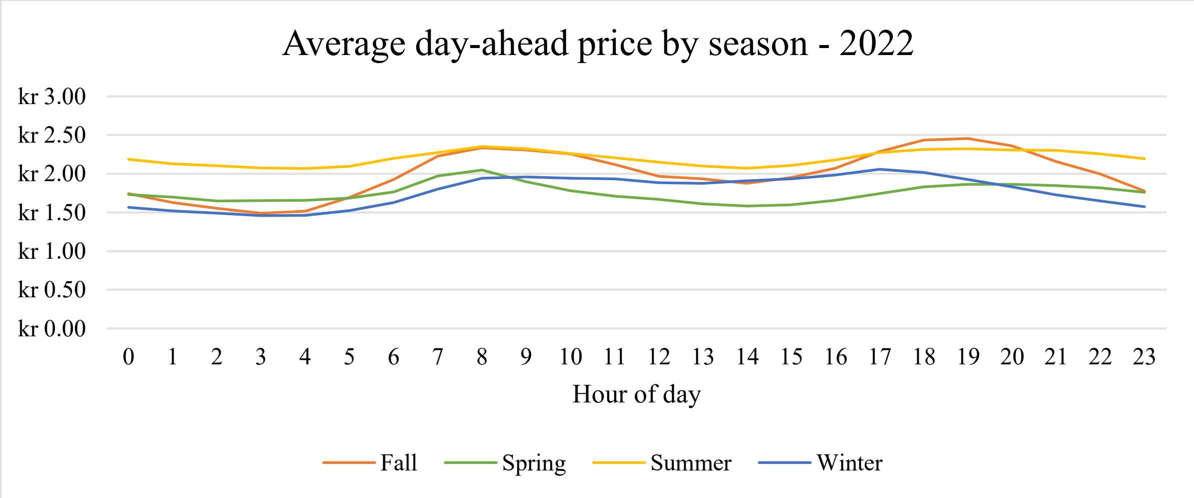


Figure 5.4 – Average day-ahead price by season in 2022

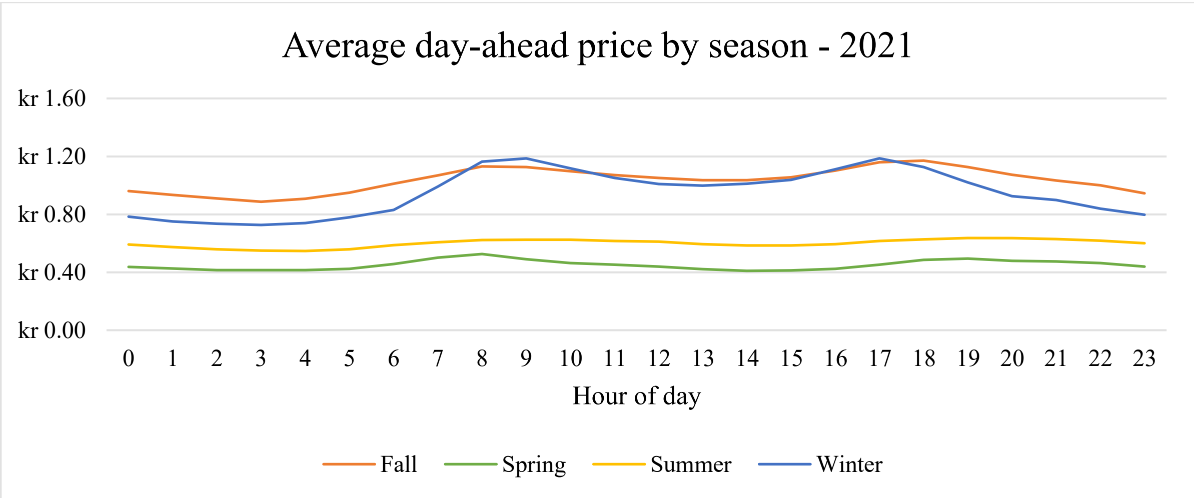


Figure 5.5 – Average day-ahead price by season in 2021

Figure 5.4 clearly illustrates that the summer period had the highest average electricity price in 2022, while the fall had higher average prices than the winter. Depending on the time of the day, spring also had higher prices than winter. This deviation in seasonal trends can be explained by the energy crisis that began in the autumn 2021, which led to an increase in electricity prices, and they were, on average, significantly higher than between the years 2015 to 2020. In 2021, spring was the period with the lowest average prices, while fall had, on average higher prices than winter. Notably, the average price in 2021 for all periods was higher than the corresponding average prices from 2015 – 2020. This difference can result from fluctuations in water inflow to storage reservoirs, but research also suggests that the increased gas prices and the opening of the interconnectors to the UK and Germany in 2020 and 2021, respectively, might have caused higher prices in southern Norway (Volue, 2022).

Volatility

As mentioned in the previous section about price seasonality, the prices in 2022 were, on average, significantly higher than in 2021 and 2015 – 2020. Table 5.1 shows that the day-ahead prices for 2022 were also significantly more volatile than in previous years.

Year	Lowest price	25% quantile	75% quantile	Highest price	St. Dev
2022	0	1.329	2.138	7.820	1.092
2021	0	0.459	0.951	6.125	0.481
2015 – 2020	0	0.235	0.286	0.461	0.039

Table 5.1 – Summary statistics of the day-ahead price data

Figure 5.6 compares the standard deviation per day in the respective years, confirming that most days' prices have been more volatile in 2022. It is also evident that the volatility in the average day-ahead prices per day in the period 2015 – 2020 was close to zero.

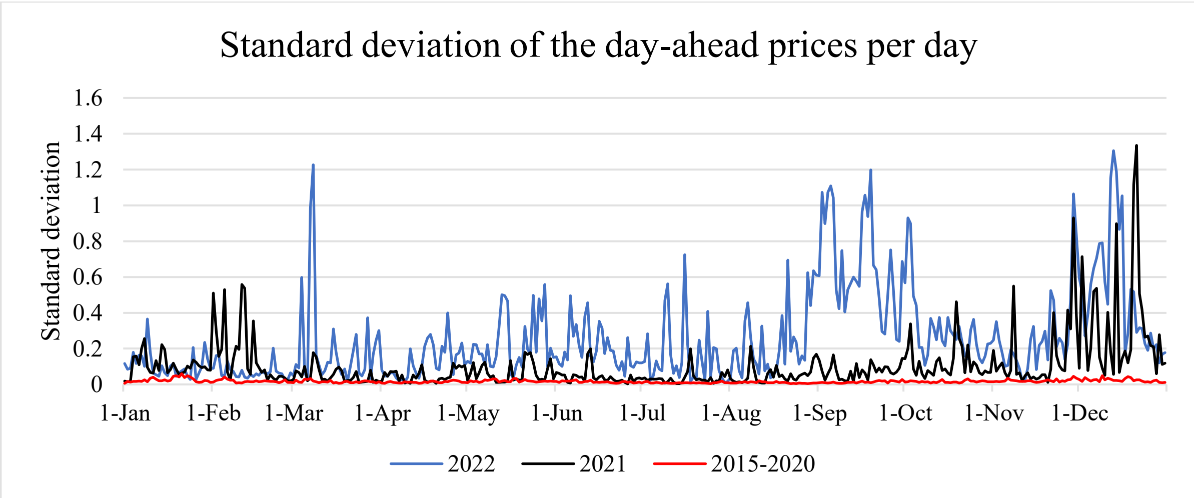


Figure 5.6 – Standard deviation of the day-ahead prices per day

5.1.2 Grid tariffs

The grid tariff refers to the cost incurred by consumers for the transportation of electricity to their homes. Further details on this concept are explained in section 2.2.3. Notably, BKK, the largest grid operator in the NO5 bidding zone, provides tariff prices that serve as inputs in this model. Additionally, a section in the scenario analysis considers both an old and a proposed grid tariff.

Current grid tariff

The current grid tariff pricing model comprises two main components: a variable component and a fixed component. The variable component is calculated based on the total electricity consumption (kWh) and time of consumption. The cost per kWh during weekends (Saturday, Sunday, and public holidays) and at night (between 10 pm to 6 am) is lower than during weekdays in the daytime.

The fixed component or so-called capacity component is determined by the monthly maximum charging capacity (kW), which is calculated by the average of the three highest daily maxes per hour within one calendar month. The capacity component is calculated based on the highest charging capacity recorded within a given month to simplify the model. The rate of this component is determined in a step-based model, with each step corresponding to a specific rate. This capacity-based price model incentivizes electricity consumers to distribute the load on the electric grid more evenly throughout the day. Table 5.2 presents the current grid tariff in prices.

Variable component (incl. taxes and fees):

Daytime weekdays	Night and weekends
0.499 NOK/kWh	0.399 NOK/kWh

Capacity component (incl. taxes):

Level	Monthly max (kW)	Monthly cost
Level 1	0-2	NOK 125
Level 2	2-5	NOK 206
Level 3	5-10	NOK 350
Level 4	10-15	NOK 494
Level 5	15-20	NOK 638
Level 6	20-25	NOK 781

Table 5.2 – Current grid tariff in numbers (BKK, 2022a)

The variable component of the current tariff includes consumption tax, ENOVA fee, and VAT. Table 5.3 display the value of these fees for 2022. It is important to note that these prices may vary per year.

Description	Value
Consumption tax	0.1541 NOK/kWh
ENOVA fee	0.01 NOK/kWh
VAT	25%

Table 5.3 – Costs included in the variable component (BKK, 2022a)

Scenario – Old grid tariff

The old grid tariff model also consisted of a variable and fixed component (capacity component) as the current grid tariff but with fewer aspects. The variable component was solely based on the total amount of electricity used (kWh), with no regard for the time of consumption. The capacity component had a fixed price, regardless of how much electricity was consumed simultaneously or in total. Table 5.4 presents the costs of the old grid tariff.

Variable component (incl. taxes and fees):	
0.430 NOK/kWh	
Capacity component (incl. taxes):	
Monthly	**Annual**
NOK 239.58	NOK 2,875

Table 5.4 – Cost of the old grid tariff (BKK, 2022a)

The variable component of the old grid tariff includes consumption tax, ENOVA fee, and VAT. Table 5.3 illustrates the applicable values.

Scenario – Proposed tariff

The new grid tariff implemented by NVE 1st of July 2022 was introduced to incentivize consumers to spread consumption throughout the day. We find two problems with the current grid tariff. First, the variable tariff prices, which depend on the day and time, do not sufficiently incentivize individuals to modify their consumption patterns due to the minimal deviation in pricing. Secondly, the current grid tariff discourages high consumption regardless of the capacity on the grid due to the capacity-based fixed price model. Even though the grid capacity is high, consumers must still limit their charging capacity (kW) to avoid reaching the next level of the capacity component.

We present a proposed grid tariff model, assuming it is aligned with revenue cap regulations[18]. The proposed tariff in Table 5.5 aims to discourage consumption during periods of low capacity. Figure 5.1 shows that prices are highest in the morning and evening, indicating that the grid's capacity is low in these periods. The widened price differentials would incentivize consumers to refrain from consuming during periods of high tariffs while penalizing non-compliance. The capacity component is set equal to the old grid tariff model. By doing this, consumption is not punished when grid capacity is high. It enables consumers to take advantage of periods of high grid capacity, such as at night, to utilize a higher charging capacity and charge their electric vehicles more quickly when electricity prices are lower.

As in the two other tariff models, the proposed grid tariff also includes consumption tax, ENOVA fee, and VAT.

Variable component (incl. taxes and fees):

06:00-10:00 & 15:00-21:00	**10:00-15:00**	**Night and weekends**
0.800 NOK/kWh	0.300 NOK/kWh	0.200 NOK/kWh

Capacity component (incl. taxes):

Monthly	**Annual**
NOK 239.60	NOK 2,875

Table 5.5 – Proposed grid tariff in prices

5.1.3 Electricity support package

Since December 2021, the Norwegian government has provided an electricity support package to help households manage the high electricity prices. The support package is a subsidy covering a percentage[19] of the average monthly price that exceeds 0.70 NOK/kWh, excluding VAT (Huseierne, 2022). The Norwegian government has proposed to change the support from

[18] See section 2.2.3.

[19] For December 2021 – 55%, January 2022 to August 2022 – 80%, for September to December 2022 – 90%, and January 2023 until the end of 2024 – 90% (Given that the proposal is adopted) (Huseierne, 2022).

September 1st, 2023. From this date and throughout 2024, the subsidies are proposed to be calculated hourly instead of a monthly average. With this change, the electricity subsidy will reflect the individual's consumption and not be based on the average price in the price range for the current month as in the past.

The subsidy is proposed to cover 90% of the price that exceeds 0.70 NOK/kWh, excluding VAT. It means that if the day-ahead price is 1 NOK/kWh, the support becomes:

$$90\% \cdot (1\ \mathrm{NOK/kWh} - 0.7\ \mathrm{NOK/kWh}) = 0.27\ \mathrm{NOK/kWh}$$

The price the consumer pays before VAT is:

$$1\ \mathrm{NOK/kWh} - 0.27\ \mathrm{NOK/kWh} = 0.73\ \mathrm{NOK/kWh}$$

5.2 Charging and discharging components

In Norway, 77% of EV owners have a charging unit at home (Norsk Elbilforening, 2021). As the rate of home charger units has grown in the past years, the model assumes that a home charging unit is installed at home in the optimization model. As mentioned in section 2.1.2, four maximum charging capacities can be delivered depending on five factors: the local distribution system, electric current, charging cable capacity, the EVs specifications, and charging units' specifications. The standard distribution system in Norway is a 230V IT earthing system, which allows for a maximum capacity of up to 11 kW with a 32A fuse. For this reason, the maximum charging and discharging capacity in the base case is set to 11 kW, assuming the EV and charging unit can charge and discharge up to this capacity[20].

To further investigate the potential for arbitrage trading, it is relevant to explore all the possible capacity levels regarding the local distribution system. For the scenario analysis, an assumption is made that the distribution system, charging cable, and EV can handle a capacity up to 22 kW. Figure 5.6 summarizes the maximum amount of kW the EV can charge and discharge in various cases.

[20] As mentioned in section 2.1.2, there are only a few EVs and charging units available on the market that offer bidirectional charging. The charging units provide a charging capacity of up to 22 kW but only a discharging capacity of up to 11 kW, while the current EVs can only discharge up to 9.6 kW.

Scenario	Charging (kW)	Discharging (kW)
Low	3.7	3.7
Medium	7.4	7.4
Base Case	**11**	**11**
Future	22	22

Table 5.6 – Maximum charging and discharging capacities

Section 3.1 states that the optimization model will also consider an efficiency loss when charging. Apostolaki-Iosifidou et al. (2017) found that the loss would vary between 12% to 36%, while more recent research by Reick et al. (2021) found the loss varying between 12.79% to 20.42%. The efficiency loss varies with the vehicles tested, the charging units used, and the charging cables. In this model, the efficiency loss is assumed to be 15%, corresponding with Reick et al.

5.3 EV specific components

The EV-specific components in the base case are used to reflect the Tesla Model Y. This is due to its popularity in Norway. In June 2022, the sales of Tesla Model Y amounted to 17% of total new car sales in Norway (OFV, 2022). The EV-specific components of the Tesla, presented in the following sections, were found in the EV database (EV Database, 2022). It is important to note that the Tesla Model Y does not contain V2G technology and cannot charge with a charging capacity higher than 11 kW with a home charging unit. Despite this, as the current most popular EV model, its specifications are used as a benchmark in the optimization model.

5.3.1 Battery capacity

Tesla's battery is the base case for this analysis, and three other capacities are examined in the scenario analysis[21]. Total capacity refers to the theoretical amount of energy the EV battery can hold; however, car manufacturers typically reserve approximately 10% as a buffer resulting in a usable capacity of 90%. The reservation is to ensure the EVs battery last longer,

[21] See Table 2.1.

as fully charging a battery has proven to degrade the battery faster (Ryan, 2021). Therefore, the model uses the usable capacity as the maximum SOC.

The minimum possible SOC of the battery is zero. This SOC is not a desired situation since there should always be some electricity in the battery when a drive is necessary. A departure amount is set to 20% of the total capacity for the base case and the low case, 15% for the high case, and 10% for the future case. Table 5.7 presents the total capacity, maximum SOC, and departure SOC in absolute numbers[22]. To summarize, the battery's SOC will at any point in time be between 0 and the maximum SOC of the battery, and a certain amount of electricity should always be present when it is time to drive.

Scenario	Total capacity (kWh)	Max SOC (kWh)	Departure SOC (kWh)
Low	62	58	12.4
Base case	**82**	**75**	**16.4**
High	120	107.8	18
Future	202	180	20.2

Table 5.7 – Battery capacities

5.3.2 EV consumption

In this instance, EV consumption refers to the amount of electricity consumed per kilometer (km) driven, while the behavioral patterns define the distance driven[23]. EV consumption has been simplified in two ways: an assumed fixed consumption per km and a fixed amount consumed every driven hour.

EV consumption is affected by various factors, including the vehicle's speed, the operator's driving style, the climate in which the EV is operated, and the conditions of the road on which it travels. As a result, it is not easy to estimate a single, perfect measure of energy consumption that can be used in an optimization model. Table 5.8 presents the real-world energy use of the Tesla Model Y in some situations. "Cold weather" consumption is based on -10°C and with the use of heating, while "Mild weather" is based on 23°C and no use of air conditioning. *Highway* is based on a constant speed of 100km/h, while *City* is based on a city drive

[22] The battery capacities in cases "Low" and "High" are based on Volkswagen ID.3 Pro Performance and Mercedes EQS 450+. These vehicles are used for realistic reasons. The study also examines future EV battery capacity, as battery technology is constantly improving.
[23] See section 3.2.

experience. This thesis uses the combined mild weather consumption of 0.149 kWh/km. Of the situations in Table 5.8, this situation is most comparable to the route conditions and climate in the NO5 bidding zone.

Cold Weather	**kWh/km**	**Mild Weather**	**kWh/km**
City	0.179	City	0.118
Highway	0.238	Highway	0.185
Combined	0.205	**Combined**	**0.149**

Table 5.8 – Real energy consumption of Tesla Model Y

The average driving distance for EVs in Norway was 12 772 km in 2021, which amounts to 34.99 km per day (SSB, 2021). The average driving distance per day is multiplied by the average energy consumption per km to calculate the average daily demand in kWh per km. The model uses the average daily demand as a consumption parameter per trip. For example, in the base case, an approximately 35 km trip is modeled to and from work. This trip amounts to a consumption of 5.2 kWh[24] each way.

Table 5.9 displays the kWh per km, average daily demand incorporated in the base case, and the values incorporated in the scenario analysis in section 6.2.

Scenario	**kWh per km**	**Average daily demand (kWh)**
High consumption	0.2	7
Base case	**0.149**	**5.2**
Low consumption	0.125	4.4
Future consumption	0.1	3.5

Table 5.9 – EV Consumption

[24] 34.99 km · 0.149 kWh/km.

5.4 Behavior patterns

This section presents the driving patterns introduced in section 3.2 in numbers. The data in the parameters $g_{t,d}$ and $f_{t,d}$ differ with the EVs availability in the driving patterns' and EV consumption. The weekly data structure of these parameters is attached in the appendix[25].

5.4.1 Base case

The base case behavior pattern investigates the charging cost when the EV is unavailable for bidirectional charging four weekdays from 7 am until 5 pm[26]. It is assumed that a one-hour drive each way is necessary.

5.4.2 High availability

In this behavior pattern, the EV is unavailable for bidirectional charging on Tuesdays and Thursdays from 6 pm until 10 pm with an expected total driving time of one hour, and on Saturdays between 11 am and 5 pm with an expected total driving time of two hours.

5.4.3 Low availability

The EV is unavailable from 7 am until 5 pm Monday to Friday, with a corresponding one-hour drive in the morning and afternoon. Tuesday and Thursday, the EV is unavailable from 6 pm until 10 pm with an expected drive of one hour. On Saturdays, the EV is unavailable from 11 am until 5 pm with a scheduled drive of two hours. Finally, on Sundays, the EV is unavailable from 12 noon until 4 pm, with an expected drive of one hour.

[25] See Table A.2-7.
[26] Which day of the week the EV owner should have home office, is optimized ex post in AMPL. The results show a clear trend towards having home office on Fridays for 2022 and 2021. The model is therefore implemented with home office on Fridays, making the EV available for bidirectional charging.

5.5 Summary of data inputs and EV availability

The following table summarizes the data inputs used as the base case regarding the EV-specific components.

Description	Value
Initial SOC	75 kWh
Max SOC	75 kWh
Departure SOC	16.4 kWh
Min SOC	0 kWh
Average daily demand	5.2 kWh
Max charging capacity	11 kW
Max discharging capacity	11 kW
Efficiency loss	15%

Table 5.10 – Summary of data inputs in base case

Table 5.11 presents an overview of the EV's availability for bidirectional charging, and Table 5.12 displays the total hours per week the EV is available for bidirectional charging within the three behavior patterns.

	Weekdays	**Weekends**
Base case	*Unavailable Monday - Thursday, 4 days a week, 7 am to 5 pm*	*Available*
High availability	*Unavailable Tuesdays & Thursdays from 6 pm to 10 pm*	*Unavailable Saturdays from 11 am to 5 pm*
Low availability	*Unavailable 7 am to 5 pm* *Unavailable Tuesdays & Thursdays from 6 pm to 10 pm*	*Unavailable Saturdays from 11 am to 5 pm* *Unavailable Sundays from 12 noon to 4 pm*

Table 5.11 – Overview of EV availability

Behavior Pattern	Hours
Base case	128
High availability	157
Low availability	104

Table 5.12 – Total hours available for bidirectional charging per week

6. Results

This chapter will present the model results. Section 6.1 assesses the three behavior patterns before a scenario analysis is presented in section 6.2.

Before assessing the profitability of bidirectional charging, it is prudent to establish the benefits of smart charging on its own. Figure 6.1 illustrate the accumulated cost of charging in 2022, contrasting a scenario where the EV is limited to charging only on Tuesday and Thursday evenings with the base case without bidirectional charging. This is done by changing the input in parameter $q_{t,d}$ to make the EV available for charging Tuesday and Thursday evenings between 5 pm and 10 pm. The visual representation demonstrates significant cost advantages associated with smart charging. The total charging cost in the forced evening pattern is NOK 9,269, while for smart charging, NOK 6,074.

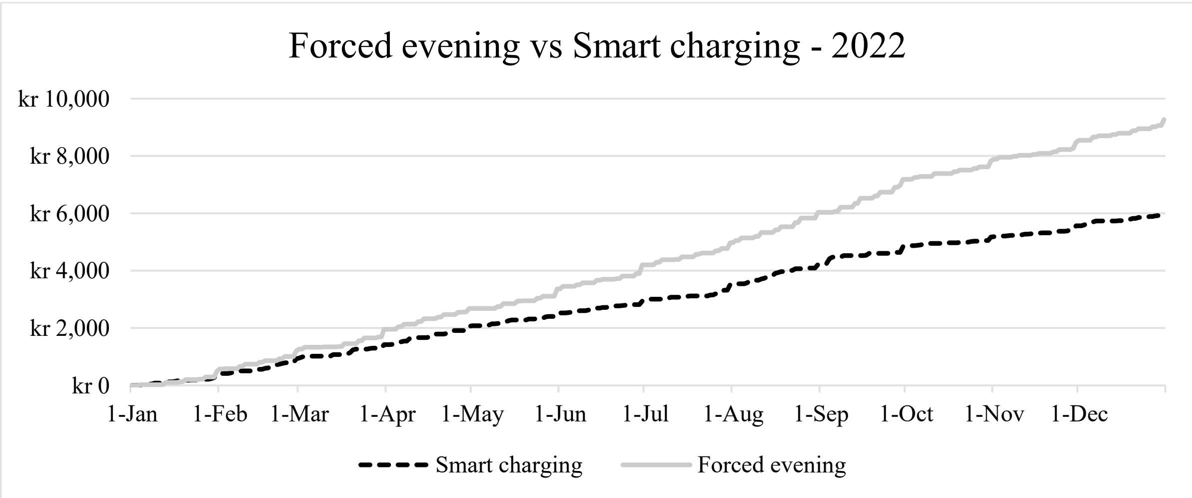


Figure 6.1 – Forced evening vs Smart charging – 2022

6.1 Bidirectional charging vs. Smart charging

Fundamentally, it is essential to consider the cost difference between bidirectional and smart charging. This section aims to determine if charging with V2G technology is economically beneficial compared to smart charging. The model is modified for smart charging by replacing constraint 4.5 with constraint 4.14, which prevents discharging.

Removed:

$$y_{t,d} \geq 0 \qquad \forall\, t \in T, d \in D \qquad (4.5)$$

Replaced by:

$$y_{t,d} = 0 \qquad \forall\, t \in T, d \in D \qquad (4.14)$$

6.1.1 Base case

2022

Figure 6.2 depicts the cumulative cost trend for bidirectional and smart charging in 2022[27]. The graph illustrates an initial period of overlapping cost trajectories until September when the cost differential becomes more pronounced.

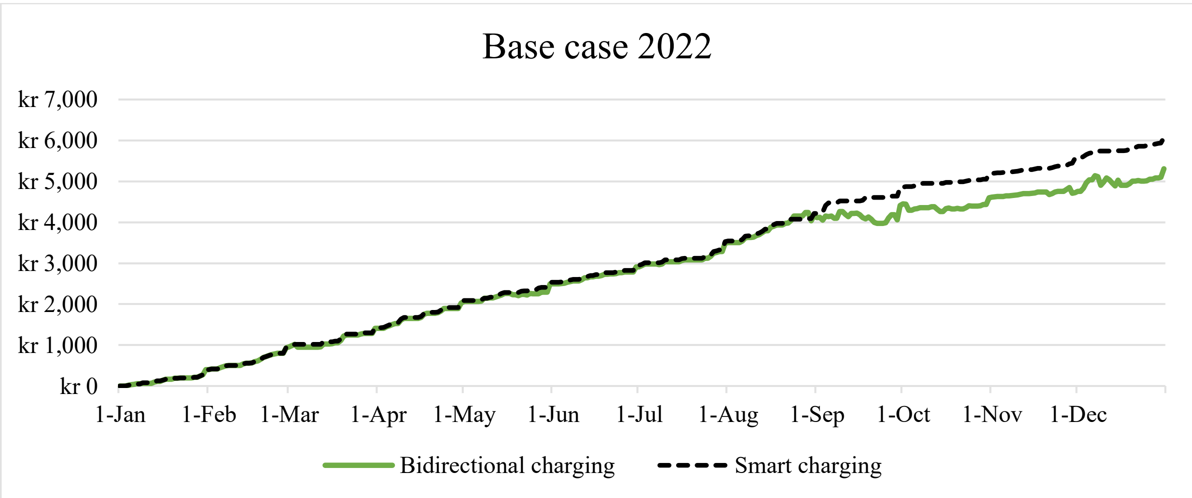


Figure 6.2 – Base case 2022

Despite the observed increase in cost differential favoring bidirectional charging, there are instances where the utilization of bidirectional charging results in a higher capacity component level of the grid tariff relative to smart charging. This is evident in Figure 6.3, where some months exhibit high capacity components for bidirectional charging, especially in September. Since the capacity component is calculated at the end of each month, the component is

[27] Includes all costs of charging.

visualized at the end of the corresponding month[28]. By utilizing a higher capacity component, the EV can charge more electricity when the price is relatively low.

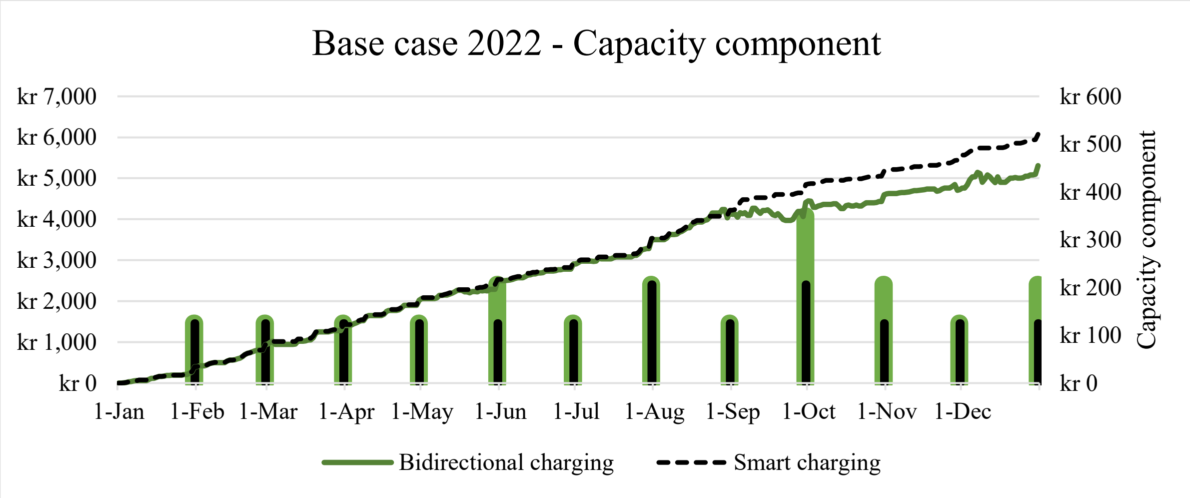


Figure 6.3 – Capacity component in the base case, 2022

Upon comparison of the amount charged in Figure 6.4, a resemblance to the capacity component is observed. The charging trends are almost parallel until divergence becomes evident in September. An observed increase in electricity charged with bidirectional charging is expected, as this process involves two outgoing sources: charging and discharging. In total, 3,841 kWh are charged with bidirectional charging, while 2,476 kWh are charged with smart charging.

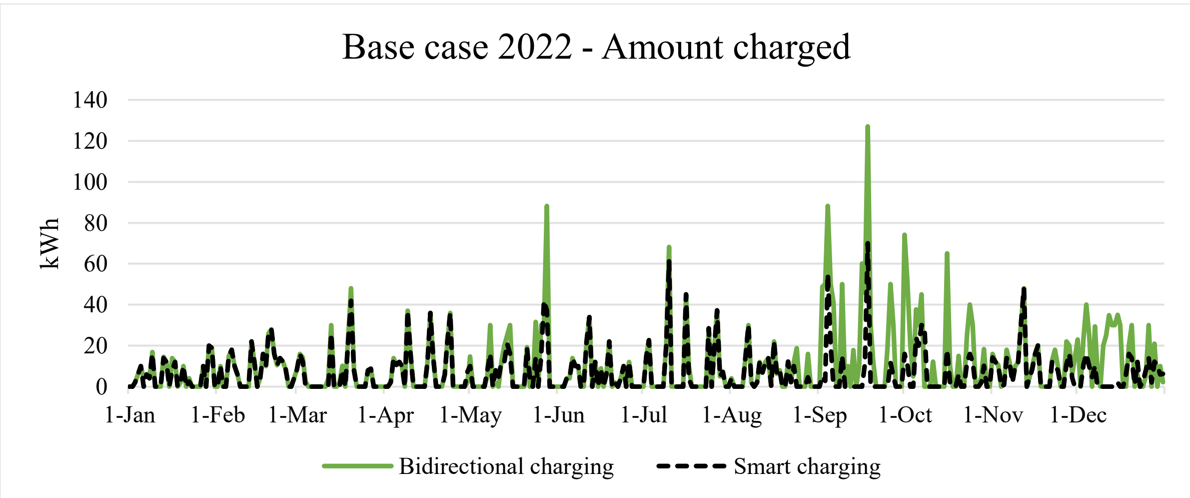


Figure 6.4 – Amount charged 2022

[28] This refers to all figures showing accumulated costs including visualization of capacity component.

Figure 6.5 reveals that the EV charges at nighttime on weekdays when the average day-ahead prices are lowest[29]. However, on weekends, it charges at night- and daytime due to the availability for charging and relatively low prices.

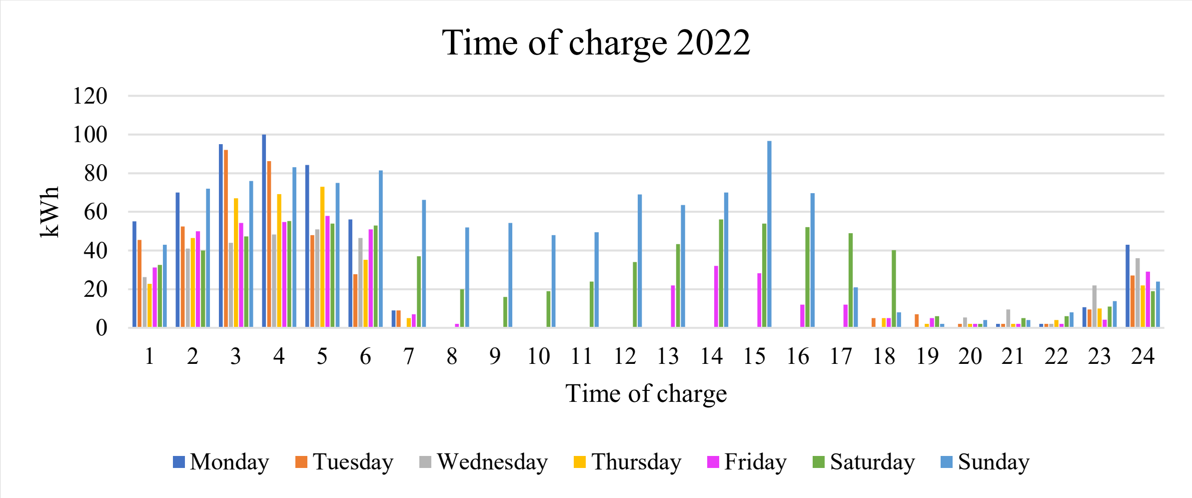


Figure 6.5 – Time of charge, base case 2022

Figure 6.6 presents the amount discharged in 2022. The graph indicates sporadic instances of discharging at the beginning of the year, but it appears that the EV is not discharging regularly until the latter part of September and throughout the remainder of the year.

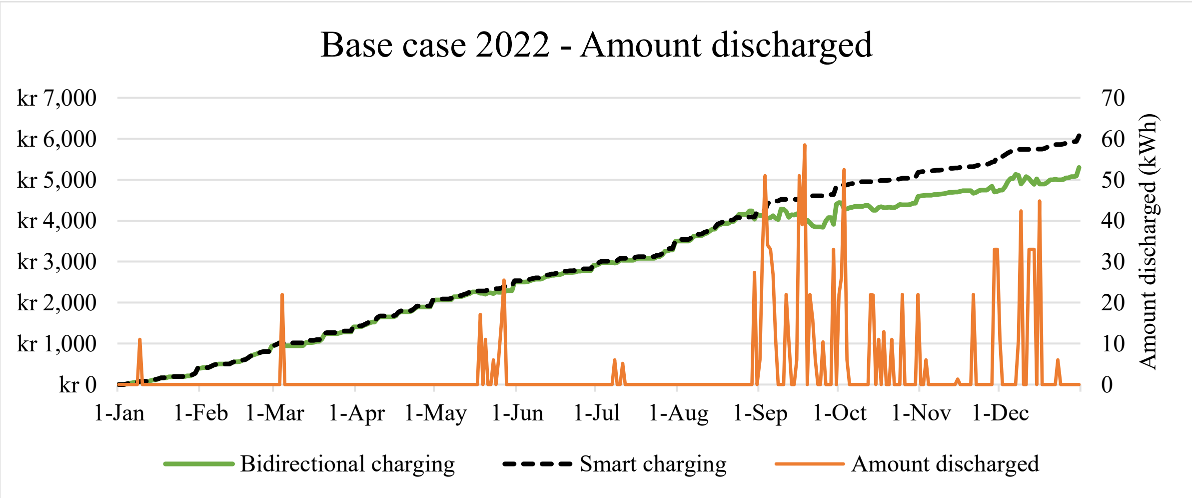


Figure 6.6 – Amount discharged 2022

Upon further examination in Figure 6.7, it can be deduced that a significant portion of discharging activities occurs from 5 pm to 9 pm, coinciding with, on average, higher day-ahead prices as depicted in Figure 5.1. The results also show that the EV mainly discharges

[29] See Figure 5.1 and Figure 5.2.

during the daytime on weekends, with the highest discharge amounts observed on Fridays when the EV owner works from home. This is the opposite of the charging behavior, indicating that the EV is utilizing the price differences daily.

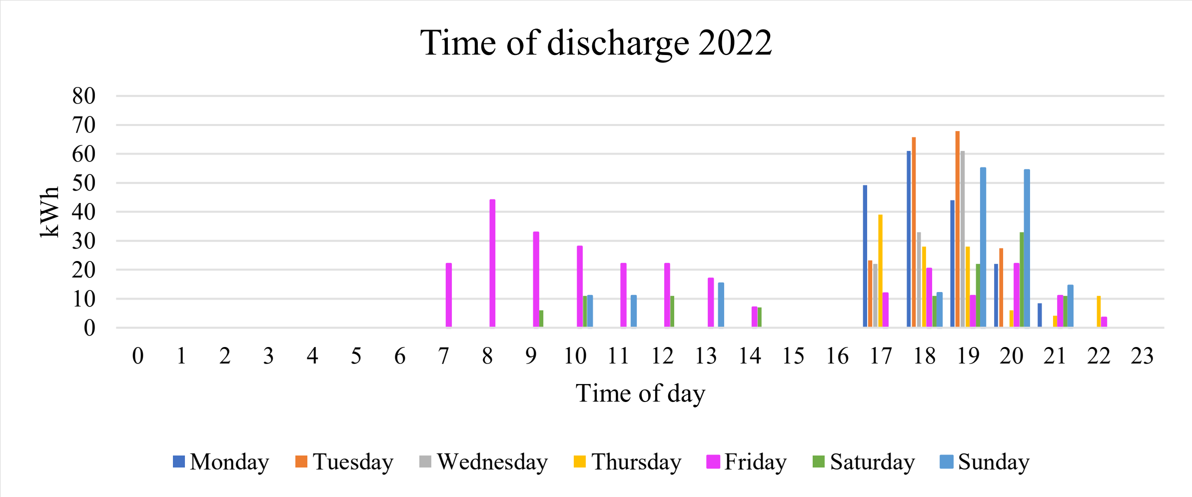


Figure 6.7 – Time of discharge, base case 2022

The delayed initiation of bidirectional charging activities until September can be attributed to the information in Figure 6.8. Specifically, for bidirectional charging to be economically justifiable, there needs to be sufficient volatility in day-ahead prices. The higher the volatility and day-ahead prices, the greater the profitability of bidirectional charging. Hence, it can be inferred that the observed delay in bidirectional charging was due to inadequate market conditions for optimal economic viability.

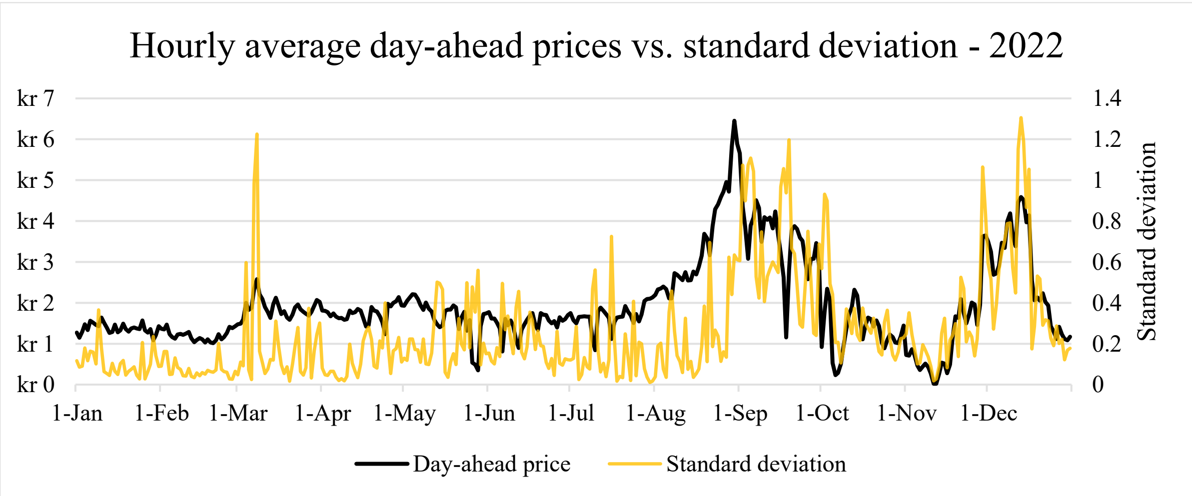


Figure 6.8 – Hourly average day-ahead prices vs. standard deviation, 2022

2021

In 2021, a comparison of the base case scenario with smart charging in Figure 6.9 revealed an overlapping cost trend throughout the year. However, bidirectional charging appears to have pushed down costs in February, after which cost development remained parallel until December. Subsequently, there was a noticeable increase in cost deviation, and bidirectional charging became more economically beneficial. Notably, the grid tariff capacity component was at its lowest level all year with both technologies.

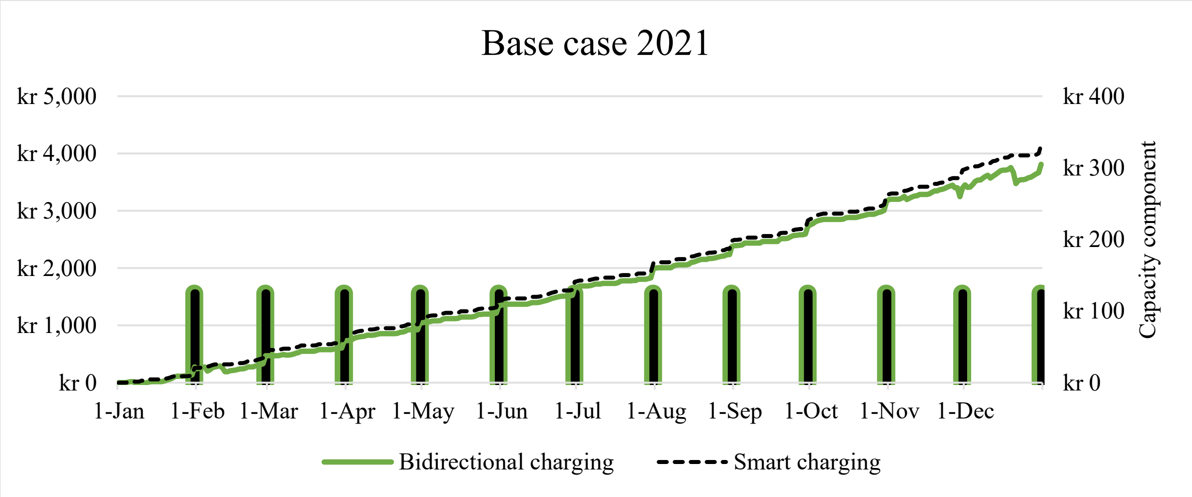


Figure 6.9 – Base case 2021

Figure 6.10, depicting the amount discharged, explains the observed cost push-down in February and the subsequent cost reduction in December. The graph illustrates that discharging only occurred at the start and end of the year, with the bulk of discharging activities occurring in February and December. Mostly, there was no discharging throughout the year, accounting for the parallel cost development.

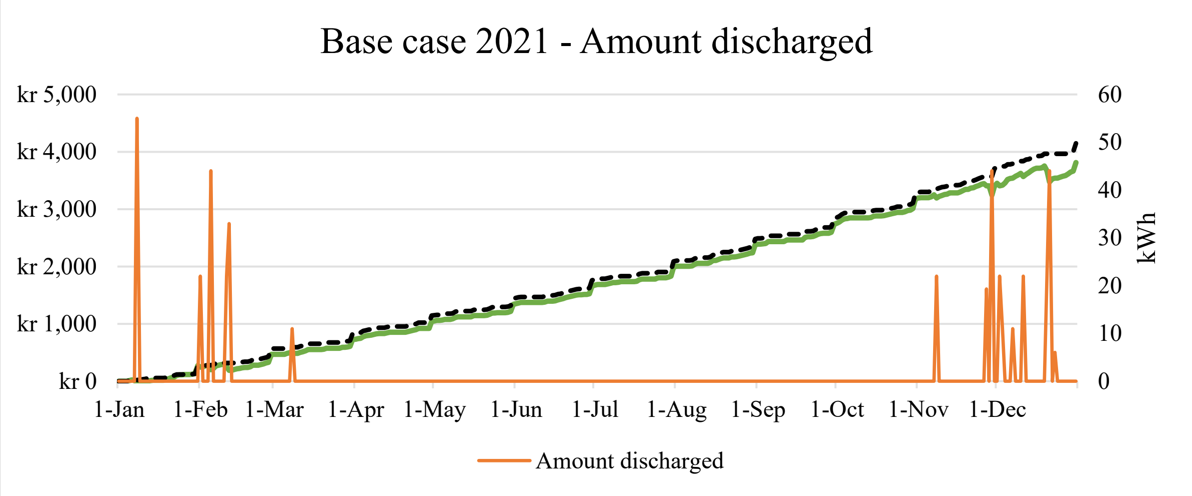


Figure 6.10 – Amount discharged in 2021

Upon examining Figure 6.11, it can be observed that the majority of the discharging activity occurred from 5 pm to 8 pm. This coincides with the period of highest prices, as indicated in Figure 5.5. Notably, the EV is observed to discharge during the daytime only on Fridays, when the EV owner works from home.

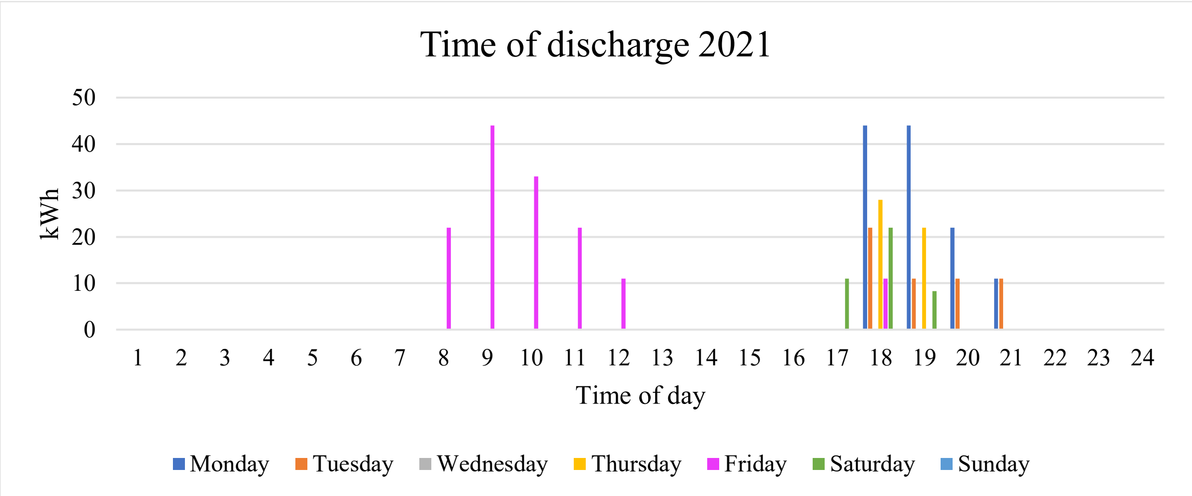


Figure 6.11 – Time of discharge, base case 2021

Figure 6.12 explains the observed pattern of bidirectional charging occurring primarily at the start and end of the year, with a lack of activity for most of the year. During these periods, the volatility of the day-ahead price increased, resulting in economic benefits for EVs to be used as tools for price arbitrage. Conversely, for most of the year, the volatility of the day-ahead price remained stable, creating an environment where bidirectional charging was not viable. The increased cost reduction in December confirms the 2022 conclusion that the higher the day-ahead prices, the greater the cost savings achievable through bidirectional charging when the volatility is high.

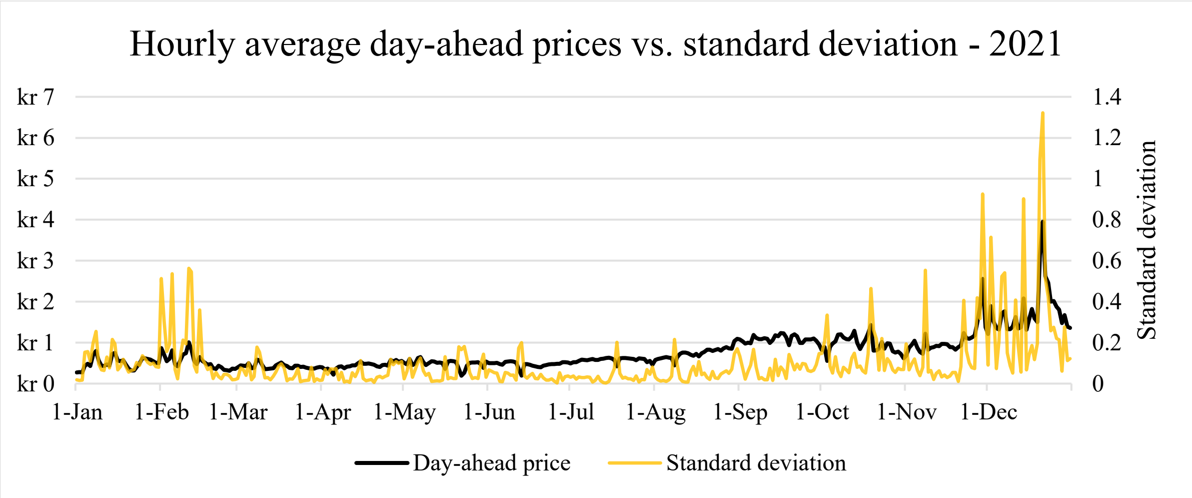


Figure 6.12 – Hourly average day-ahead prices vs. standard deviation, 2021

2015 – 2020

For the period 2015 – 2020, the base case scenario in Figure 6.13 reveals no deviation between smart charging and bidirectional charging – with no kWh being discharged. As a result, the cost trajectory remains parallel from start to end, with no economic benefits to be gained from bidirectional charging relative to smart charging. Consequently, this scenario occurs at the lowest level of the capacity component each month.

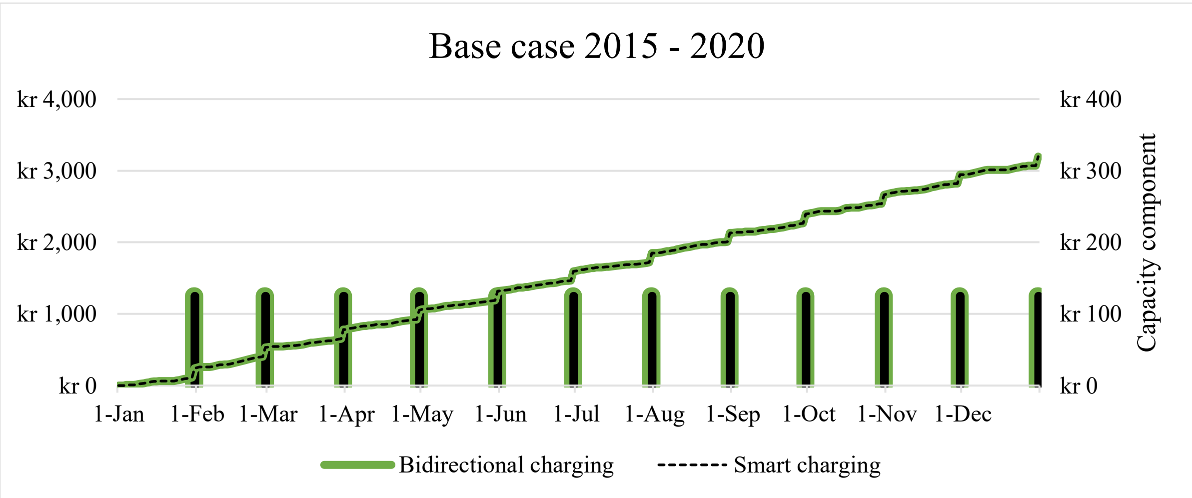


Figure 6.13 – Base case 2015 – 2020

Figure 6.14 illustrates the average day-ahead price and standard deviation for the given period, revealing that the day-ahead price remained stable, with an average close to zero. This finding confirms that bidirectional charging requires spikes in volatility to be economically viable. It highlights the importance of considering the volatility of electricity prices in the decision-making process for the deployment of bidirectional charging infrastructure, as it is a critical factor in determining the feasibility of such systems.

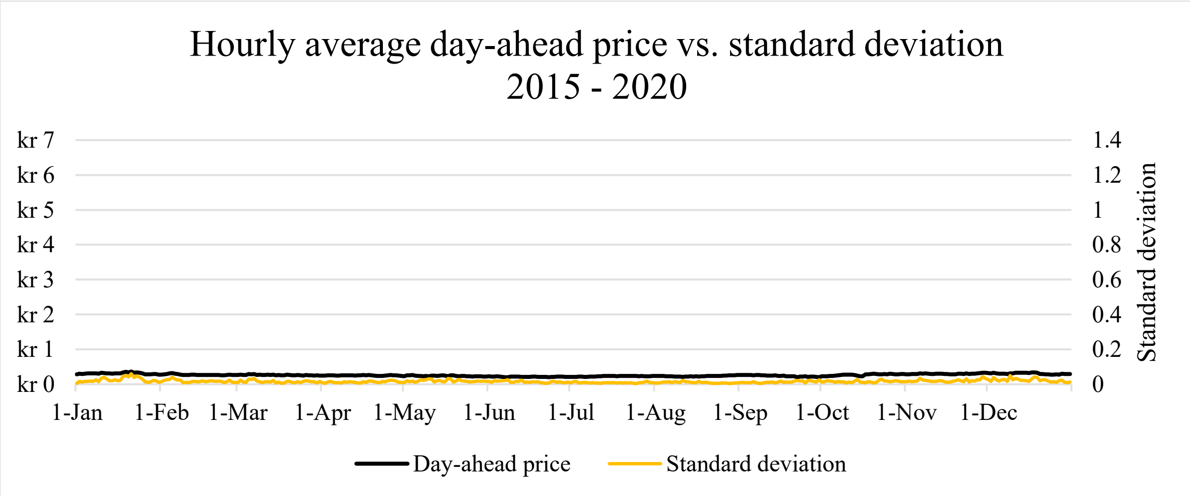


Figure 6.14 – Hourly average day-ahead prices vs. standard deviation, 2015 – 2020

Base case summary

	V2G	Smart charging	%	Amount discharged
2022	NOK 5,307	NOK 6,074	- 12.63%	1,161 kWh
2021	NOK 3,812	NOK 4,147	-8.08%	410 kWh
2020 - 2015	NOK 3,195	NOK 3,195	0%	0 kWh

Table 6.1 – Total costs in base case

Table 6.1 presents the total cost of charging each year with this base case behavior pattern. In 2022, the EV owner could save NOK 767 by utilizing bidirectional charging instead of smart charging. This amount equals a cost reduction of 12.63%. Compared with the forced evening pattern, the total cost savings amount to NOK 3,962[30] for 2022. For 2021, the cost savings

[30] $\text{NOK } 9{,}269 - \text{NOK } 5{,}307 = \text{NOK } 3{,}962$

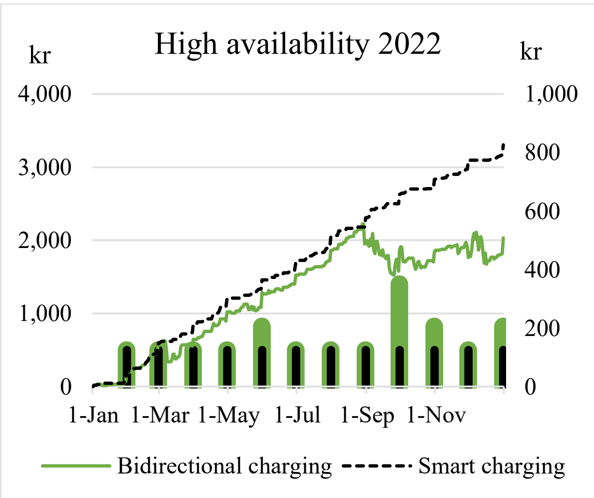
were lower, amounting to NOK 335 for the entire year. This amount equals a cost reduction of 8.08%.

6.1.2 High availability

The behavior pattern “high availability” entails a higher availability of the EV for bidirectional charging and a reduction in electricity consumption from driving compared to the base case scenario. This increased availability makes the EV more suitable for exploiting price fluctuations and provides greater opportunities for using the EV as a flexible tool for balancing the electric grid.

2022

Figure 6.15 displays the cost patterns for 2022 with high availability. The cost patterns are similar to the base case, with the most significant cost reduction occurring from September onward but with more noticeable cost differences. Additionally, there is an apparent cost reduction in March, with costs staying parallel until September, after which they diverge. Figure 6.16 depicts the discharging behavior with high availability, and it is apparent that the EV is utilizing bidirectional charging more frequently, resulting in higher arbitrage opportunities for the EV owner. The increased availability of the EV for bidirectional charging enables the owner to exploit price fluctuations to a higher degree and gain more significant cost benefits.



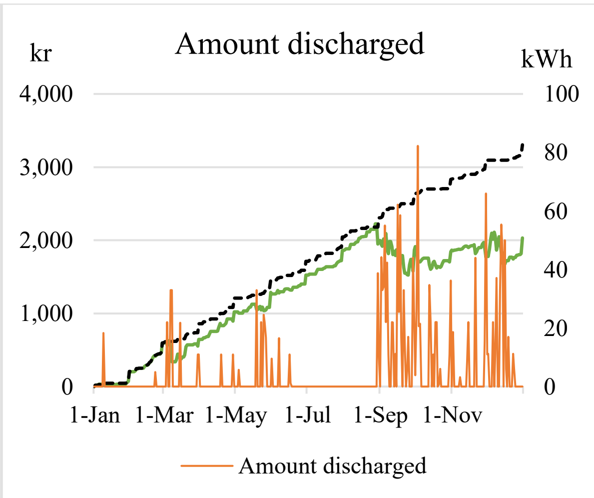
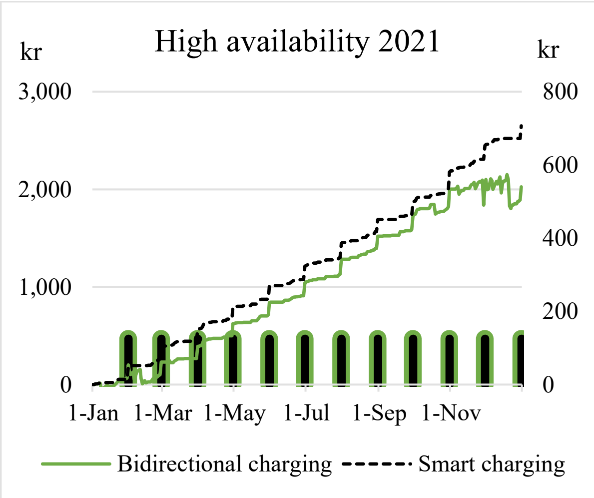


Figure 6.15 – High availability 2022

Figure 6.16 – Amount discharged 2022

2021

The results for bidirectional charging with high availability in 2021 show similar cost developments as in the base case scenario, but to a greater extent, see Figure 6.17. However, it is worth noting that the EV continues to use a charging capacity below 2kW, resulting in the lowest level of the capacity component each month. The discharge behavior in 2021, as shown in Figure 6.18, is still limited to the beginning and end of the year but with a higher frequency of discharging than in the base case.



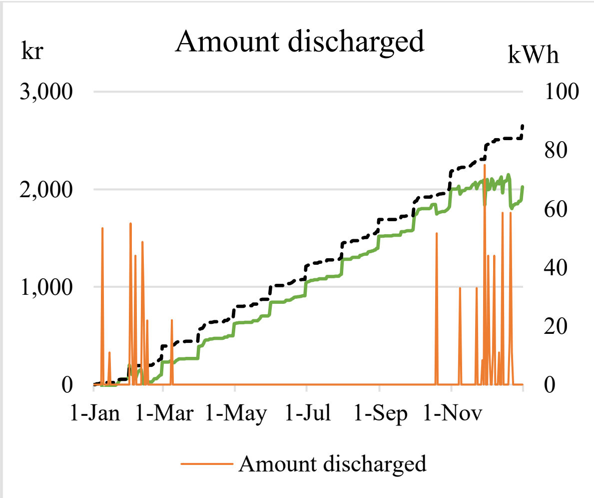


Figure 6.17 – High availability 2021 **Figure 6.18** – Amount discharged 2021

2015 – 2020

During the period 2015 – 2020, despite the high availability for bidirectional charging, no kWh was discharged as it was not economically beneficial. The total charging cost in this pattern is lower than the base case since the EV drives less and hence needs less electricity to be functional[31].

[31] Total cost pattern is displayed in Figure A.1 in the appendix.

High availability summary

	V2G	Smart charging	%	Amount discharged
2022	NOK 2,029	NOK 3,304	- 30.98%	1,799 kWh
2021	NOK 2,025	NOK 2,650	- 23.58%	770 kWh
2020 – 2015	NOK 2,316	NOK 2,316	0%	0 kWh

Table 6.2 – Total costs with high availability

Table 6.2 presents the total cost of charging each year with the high availability pattern. In 2022, the EV owner could save NOK 1,275 by utilizing bidirectional charging instead of smart charging. This amount equals a cost reduction of 30.98%. For 2021, the cost savings were lower, amounting to NOK 625 for the entire year. This amount equals a cost reduction of 23.58%.

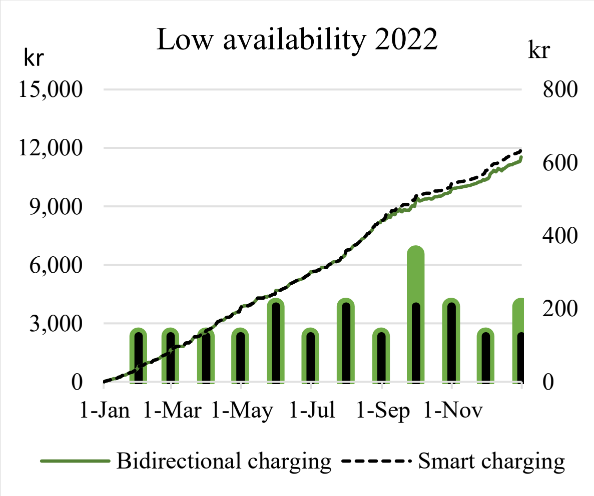
6.1.3 Low availability

The behavior pattern "low availability" entails a lower availability of the EV for bidirectional charging and an increase in electricity consumption through driving compared to the base case scenario, which causes costs to be generally higher. This decreased availability makes the EV less suitable for exploiting price fluctuations and provides fewer opportunities for using the EV as a flexible tool for balancing the electric grid.

2022

Figure 6.19 illustrates that the cost patterns are quite parallel between bidirectional charging and smart charging in 2022, with bidirectional charging showing some cost advantages towards the end of the year. The figure also displays the utilization of higher charging capacities for several months for both technologies. The lower availability prompts the EV to charge more effectively – with higher capacities (kW) – when favorable pricing conditions arise.

As shown in Figure 6.20, the amount discharged is only noticeable towards the end of 2022, except for a single instance in May where the EV exploited a significant price drop. This suggests that the EV requires high volatility over an extended period to effectively leverage bidirectional charging when the availability is low, as evidenced by the EV not discharging at the start of the year despite a brief period of high volatility.



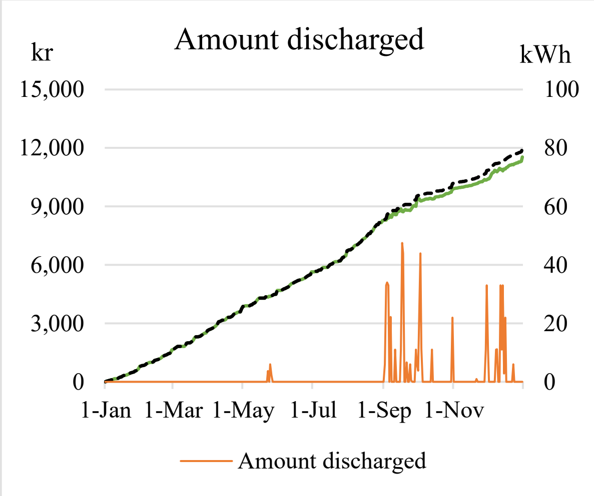
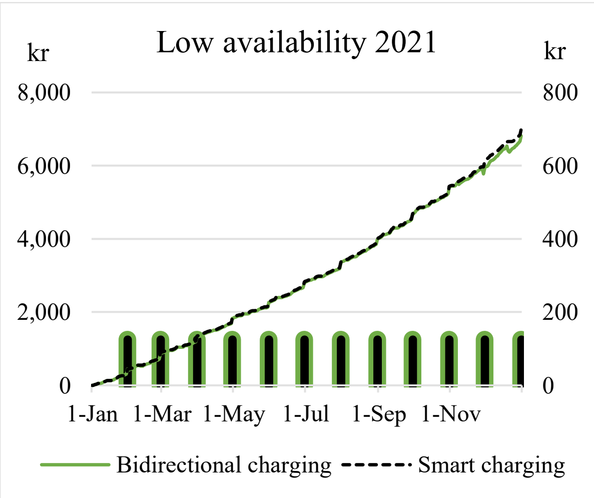


Figure 6.19 – Low availability 2022

Figure 6.20 – Amount discharged 2022

2021

The cost pattern for 2021 with low availability, in Figure 6.21, displays parallel cost patterns until a slight deviation appears towards the end of the year, with the capacity component steady at the lowest level. Figure 6.22 shows that the discharging behavior is similar to that of the base case, although with a lower frequency and a smaller quantity of electricity discharged.



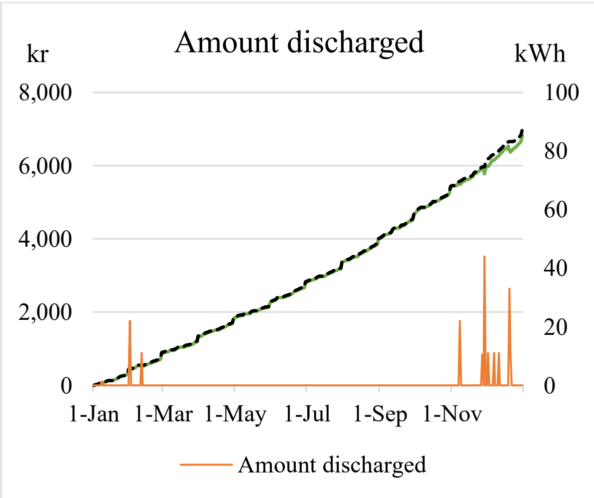


Figure 6.21 – Low availability 2021

Figure 6.22 – Amount discharged 2021

2015 – 2020

During the period 2015 – 2020, no electricity was discharged when the EV had low availability for bidirectional charging. Lower availability due to more driving results in higher costs than in the base case. Hence the need for more electricity to be functional[32].

Low availability summary

	V2G	Smart charging	%	Amount discharged
2022	NOK 11,536	NOK 11,951	- 3.47%	584 kWh
2021	NOK 6,816	NOK 6,992	- 2.52%	188 kWh
2020 - 2015	NOK 4,785	NOK 4,785	0%	0 kWh

Table 6.3 – Total costs with low availability

Table 6.3 presents the total charging cost each year with the low availability pattern. In 2022, the EV owner could save NOK 415 by utilizing bidirectional charging instead of smart charging. This amount equals a cost reduction of 3.47%. For 2021, the cost savings were lower, amounting to NOK 176 for the entire year. This amount equals a cost reduction of 2.52%.

6.1.4 Summary of behavior patterns

Bidirectional charging offers advantages over smart charging in terms of accumulated cost savings as it can send electricity back to the grid, thereby transforming the EV into a valuable tool in the balancing markets. However, it is imperative to note that substantial volatility in day-ahead prices is a prerequisite for the economic benefits of bidirectional charging to be perceptible. This is seen when investigating the total cost between the years and the amount discharged. Furthermore, the magnitude of the economic benefits increases with higher day-ahead prices during periods of high volatility. It is also noteworthy that bidirectional charging becomes more economically advantageous with higher availability, as this gives the EV owner more time to engage in the trading of electricity, thereby creating additional arbitrage opportunities.

[32] Total cost pattern is displayed in Figure A.2 in the appendix.

6.2 Scenario analyses

In the following sections, different scenario analyses are conducted to examine how sensitive the profitability of bidirectional charging is to changes in parameter values, all else equal[33].

6.2.1 Scenario 1 – Battery capacity

This section aims to examine the battery capacity's influence on bidirectional charging, all else equal. A larger battery capacity enables EVs to charge more electricity when the price is low and sell more electricity when the price is high. In addition, the possibility for longer time intervals between each charging period. The battery capacities used in this scenario are displayed in Table 5.7. To ensure unbiased scenarios regardless of the initial SOC of the battery, the high and future scenarios commence with the base case initial SOC of 75 kWh. The low case scenario begins with an initial SOC of 58 kWh, representing the maximum SOC for that particular scenario.

2022

The graphical representation in Figure 6.23 depicts the cost trends associated with varying battery capacities in 2022. The data reveals that a larger battery capacity offers greater cost benefits, particularly during periods of sustained volatility in the day-ahead prices. Such price fluctuations were observed in September and the first half of December[34]. Therefore, the cost-benefit analysis of battery capacity should be considered in light of the specific market conditions and the period under scrutiny.

[33] The scenarios for the period 2015 – 2020 have also been completed and are available in the appendix section A.2 Results 2015 – 2020. This is because none of the scenarios resulted in discharging of any kWh, indicating that investing in bidirectional charging infrastructure during this period would not be economically justifiable.
[34] See Figure 6.8.

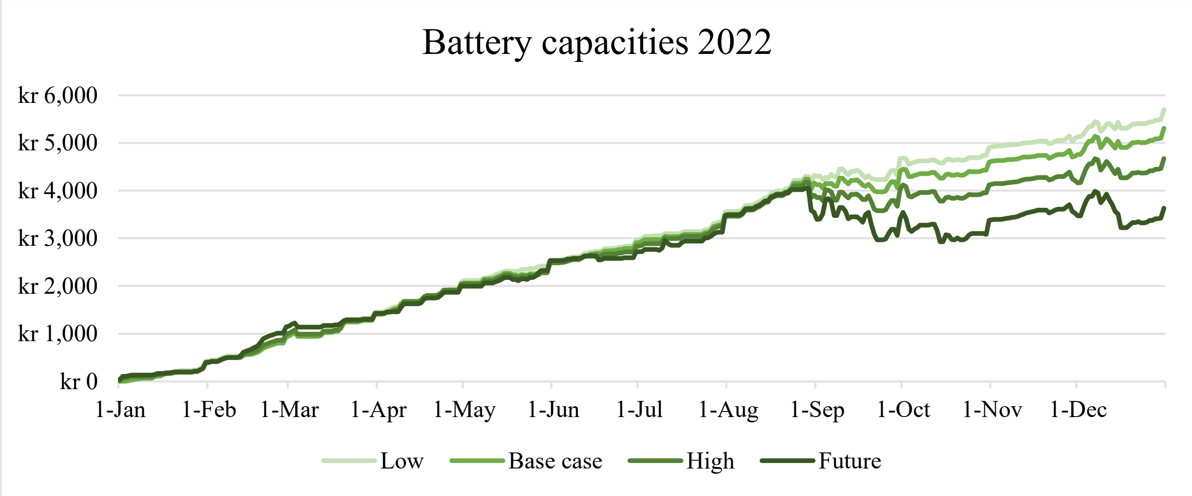


Figure 6.23 – Scenario battery capacities 2022

Based on the results illustrated in Figure 6.24, EVs with larger battery capacities can charge more efficiently during periods of lower prices. The analysis shows that the future case battery utilizes a higher charging capacity than the base case in July and October. Furthermore, Figure 6.27 indicates that the amount of discharge will increase significantly with a larger battery capacity in 2022. As such, the EV can be a more effective balancing tool and provide arbitrage opportunities for the EV owner.

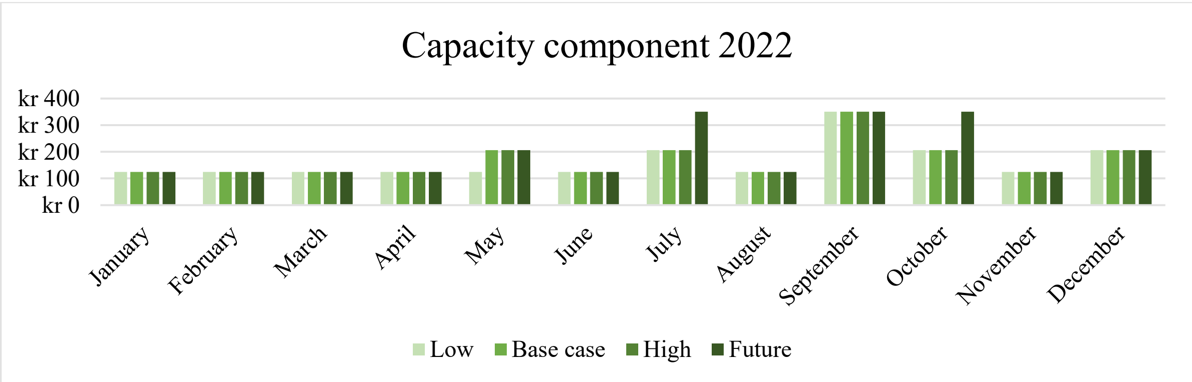


Figure 6.24 – Capacity component with different battery capacities 2022

2021

Figure 6.25 depicts the charging cost for different battery capacities in 2021. The graph reveals that investing in an EV with a larger battery capacity would not be beneficial for most of the year. However, at the end of December, there was a peak in volatility in the day-ahead prices, as shown in Figure 6.12, resulting in a cost decrease. The discrepancy in the amount discharged between the different scenarios is also negligible, as demonstrated in Figure 6.27. This indicates that the EV could not have utilized the potential offered by a larger battery capacity for arbitrage opportunities and grid balancing opportunities in 2021.

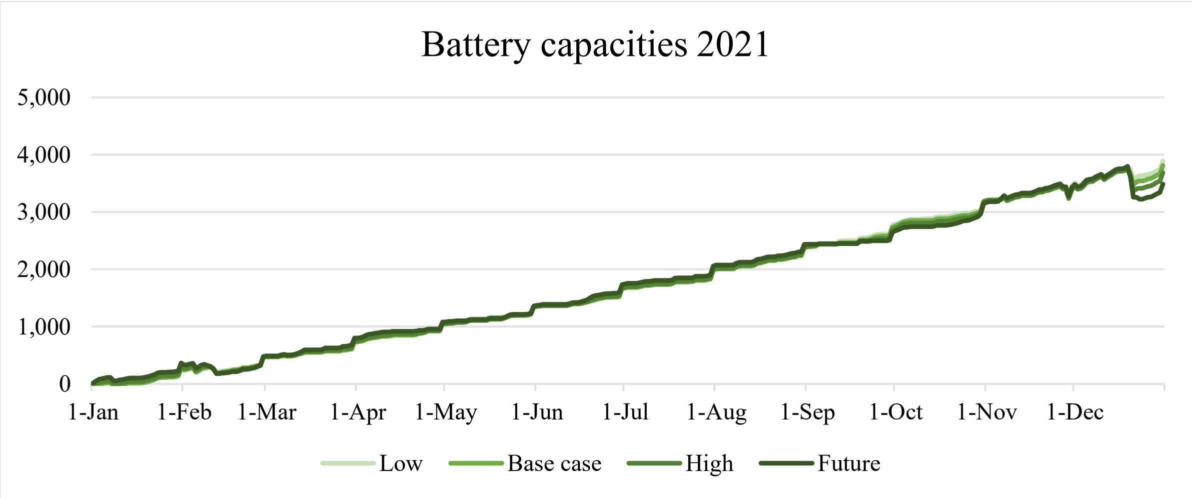


Figure 6.25 – Scenario battery capacities 2021

Furthermore, it is noteworthy that using a charging capacity higher than 2 kW would not be economically profitable throughout the year in any scenario. This results in the lowest level of the capacity component in the grid tariff each month, as shown in Figure 6.26.

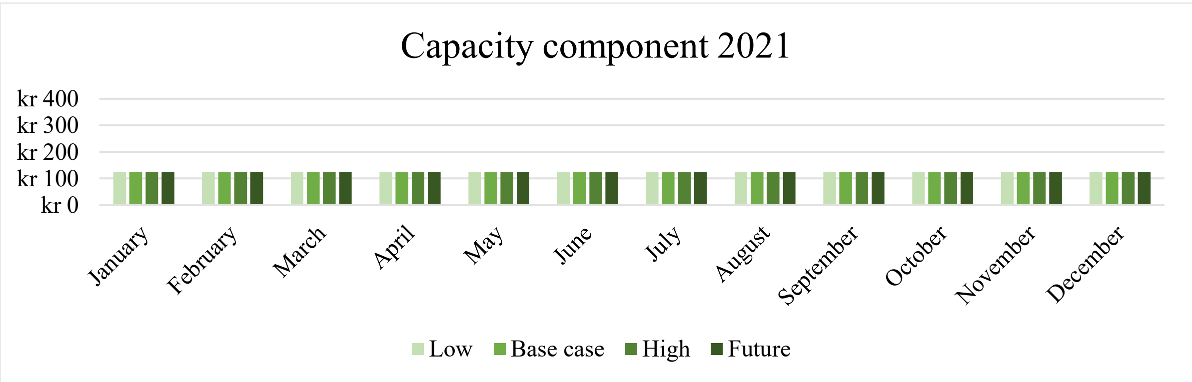


Figure 6.26 – Capacity component with different battery capacities 2021

Summary scenario battery capacities

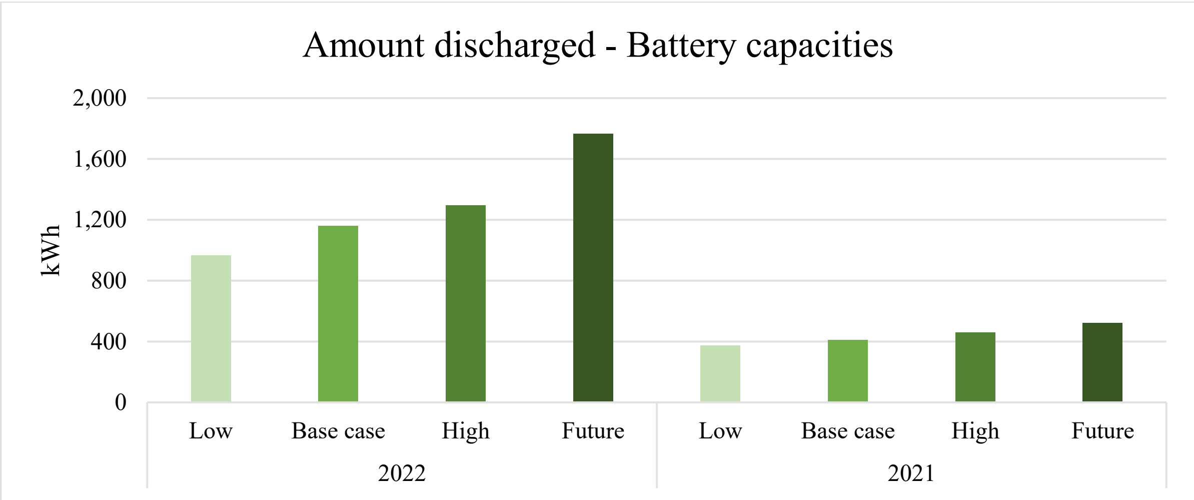


Figure 6.27 – Amount discharged with different battery capacities

	2022	*%*	*2021*	*%*	*2015 - 2020*	*%*
Low	NOK 5,698	7.37%	NOK 3,890	2.05%	NOK 3,211	0.50%
Base case	**NOK 5,307**	**0%**	**NOK 3,812**	**0%**	**NOK 3,195**	**0%**
High	NOK 4,673	-11.95%	NOK 3,686	-3,31%	NOK 3,165	-0.94%
Future	NOK 3,635	-31.51%	NOK 3,487	-8,53%	NOK 3,096	-3.10%

Table 6.4 – Total costs with different battery capacities

Table 6.4 presents the total cost of charging each year with the different battery capacity scenarios. The data reveals a larger battery capacity offers greater cost benefits within a year. Additionally, a future battery capacity can reduce the charging cost almost down to a 2021 level, even though the electricity prices were significantly higher in 2022.

6.2.2 Scenario 2 – EV consumption

This section examines how EV consumption influences bidirectional charging, all else equal. EV consumption is referred to as consumption per km driven. A lower consumption per km driven decreases the amount to be charged and increases the potential for cost savings. The values for consumption used in this scenario are displayed in Table 5.9.

In this scenario, the "high case" represents the worst-case scenario, as high consumption is less favorable than low consumption.

2022

As evident in Figure 6.28, a lower consumption per kilometer would naturally lead to lower costs. However, it is interesting to note that the cost patterns remain identical with different slopes. Figure 6.32 supports this observation, where only slight deviations in the amount discharged are visible. This suggests that electric vehicle consumption is not a crucial factor in the utilization of bidirectional charging, neither for arbitrage opportunities nor grid balancing.

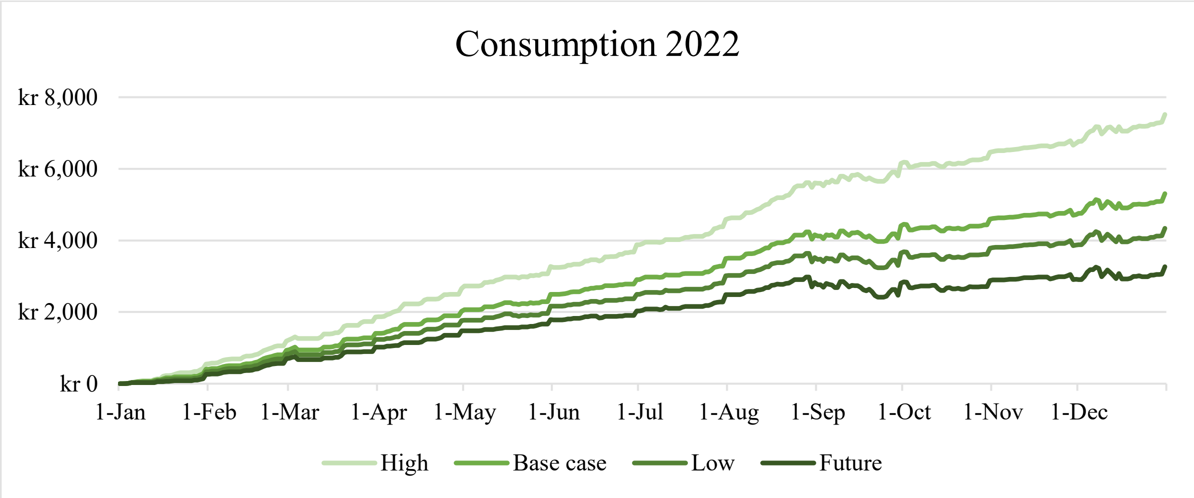


Figure 6.28 – Scenario consumption 2022

Except for using a lower charging capacity for the future case in May and a higher charging capacity in June with the high case, the capacity component is identical for all scenarios throughout the year, see Figure 6.29.

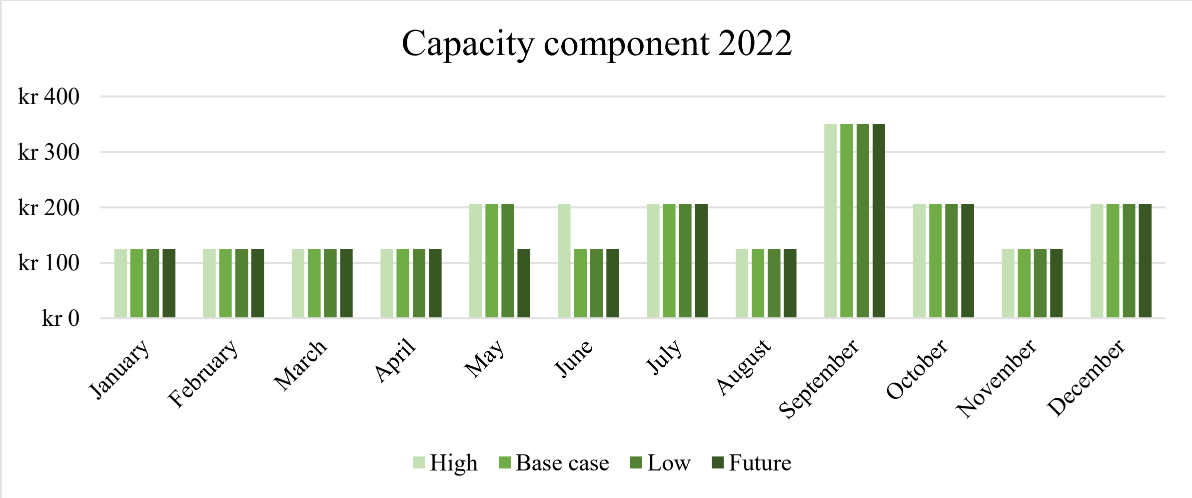


Figure 6.29 – Capacity component in scenario consumption 2022

2021

In 2021, the costs associated with different consumptions had almost identical slopes, although with slight variations, see Figure 6.30. Figure 6.32 supports this observation, revealing only minor differences in the amount discharged among the various scenarios.

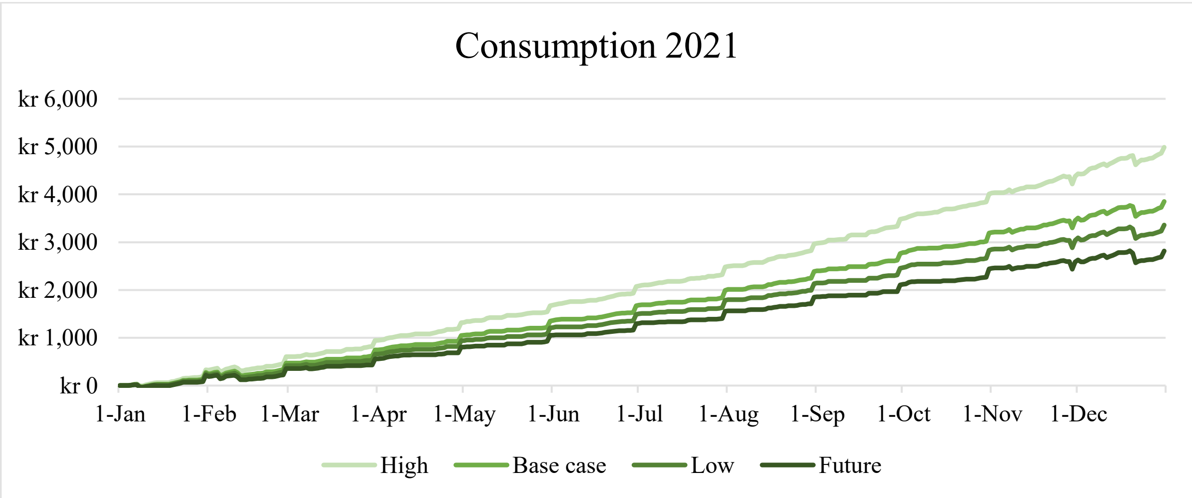


Figure 6.30 – Scenario consumption 2021

Correspondingly, a maximum charging capacity of 2 kW is used all year. This results in the lowest level of the capacity component in the grid tariff each month, as shown in Figure 6.31.

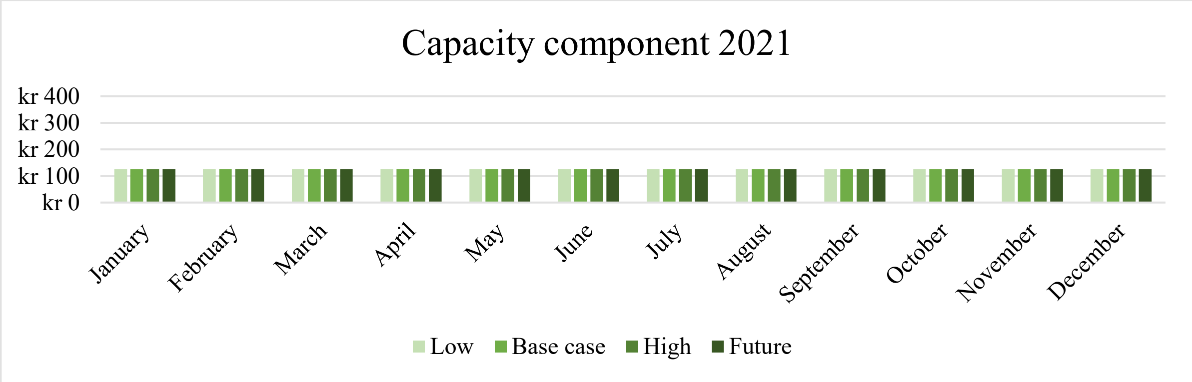


Figure 6.31 – Capacity component in scenario consumption 2021

Summary scenario consumption

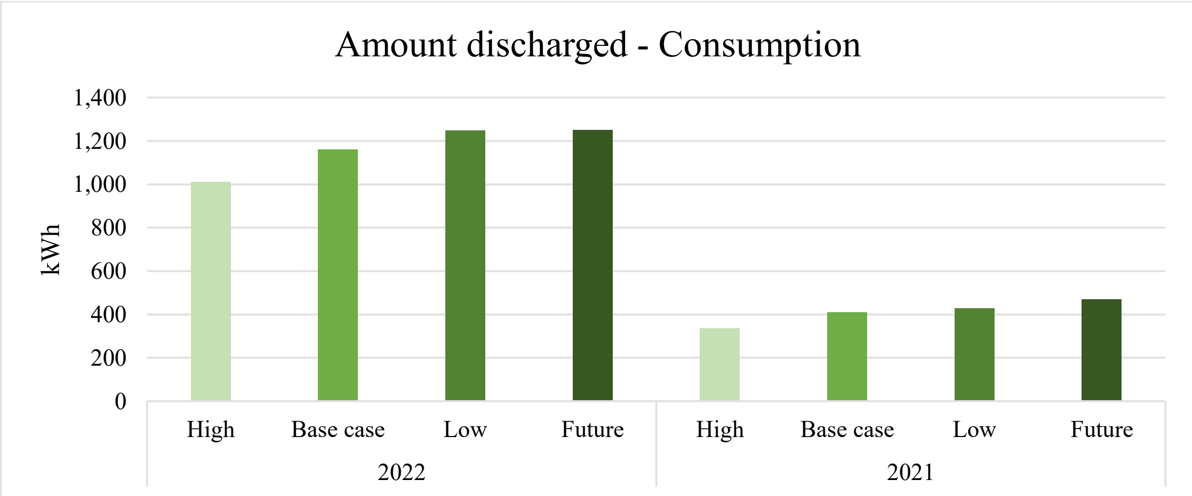


Figure 6.32 – Amount discharged with different consumption

	2022	*%*	*2021*	*%*	*2015 - 2020*	*%*
High	NOK 7,518	41,66%	NOK 4,934	29.43%	NOK 3,716	16.31%
Base case	**NOK 5,307**	**0%**	**NOK 3,812**	**0%**	**NOK 3,195**	**0%**
Low	NOK 4,339	-18,24%	NOK 3,324	-12.80%	NOK 2,822	-11.67%
Future	NOK 3,267	-38,44%	NOK 2,785	-26.94%	NOK 2,516	-21.25%

Table 6.5 – Total costs with different consumption

Table 6.5 presents the total charging cost with different consumption per driven kilometer. As mentioned earlier, a lower consumption per km driven decreases the amount to be charged and increases the potential for cost savings. This is also in line with vehicles that use diesel or petrol engines, as lower driving consumption reduces the need to refuel more frequently.

6.2.3 Scenario 3 – Charging capacities

This section examines how the charging and discharging capacity influence bidirectional charging. The higher the capacity, the faster the EV can charge or discharge. In theory, the EV should then be able to utilize the price fluctuations in the power market to a greater extent. The charging capacities used in this scenario are displayed in Table 5.6. These capacities are the maximum amount the EV can charge or discharge at a point in time.

Constraints 4.2, 4.4, and 4.6 are modified in the model to comply with the different maximum charging capacities.

2022

Figure 6.33 illustrates the cost of charging in 2022 while varying the maximum charging and discharging capacities. Minimal deviation is observed in the costs until September. Following this period, a discernible trend emerges, whereby costs decrease as the maximum capacities for charging and discharging increase.

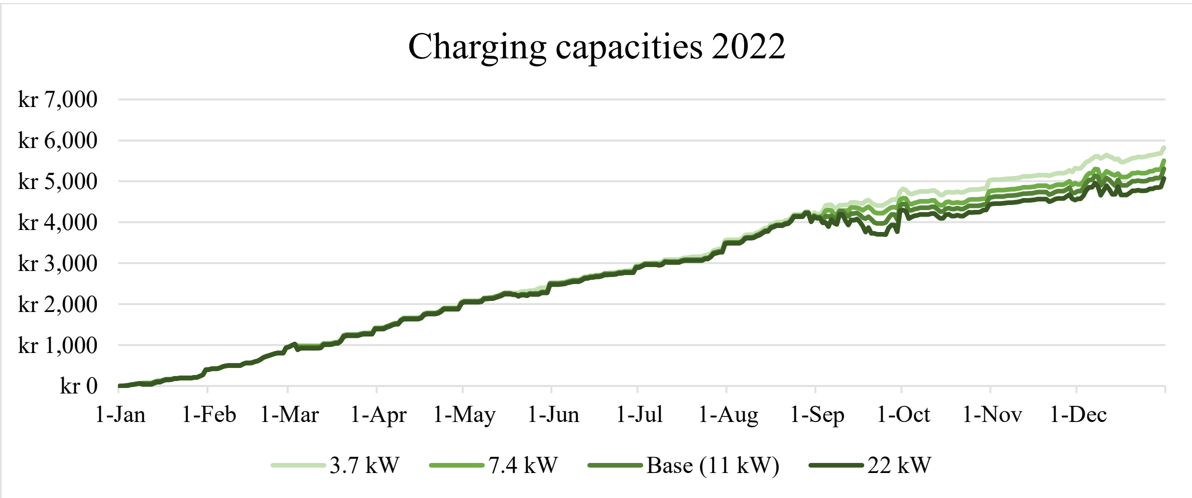


Figure 6.33 – Scenario charging capacities 2022

Figure 6.34 presents a significant finding wherein it is observed that the use of a higher charging capacity of 11 kW becomes economically viable only in September when the volatility of prices is at its peak. Consequently, it can be deduced that a charging capacity of 5 kW is adequate for most of the year since the increasing cost of the capacity component outweighs any potential arbitrage gains from utilizing a higher charging capacity. In contrast, the discharging capacity is independent of the capacity component and is utilized at higher levels whenever feasible.

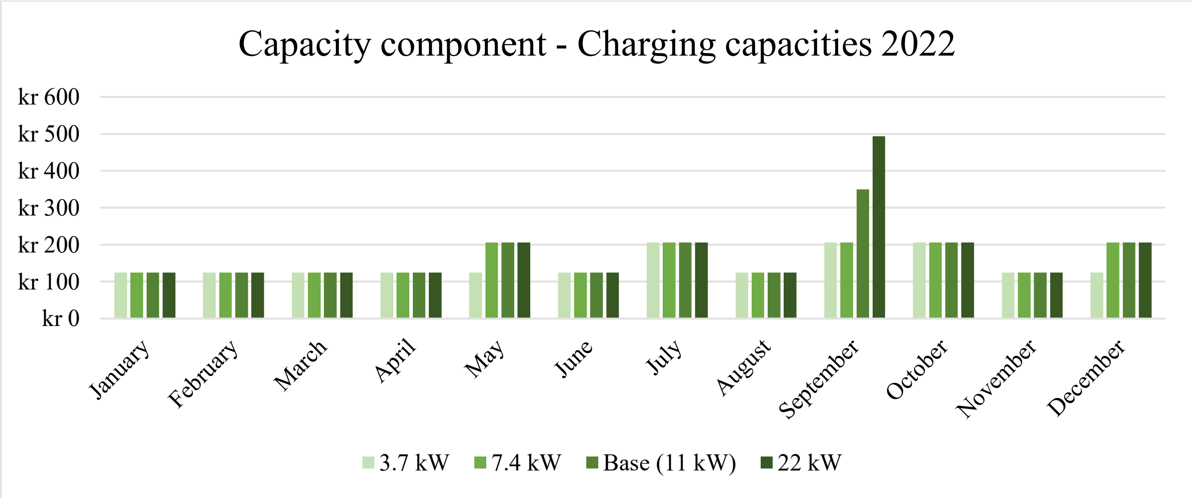


Figure 6.34 – Capacity component when changing charging capacities 2022

More electricity is returned to the grid with higher capacities, with most electricity discharged in September. The profitability of higher charging capacities relies on the extent of volatility in the day-ahead prices over time, while a higher discharging capacity is always preferable. Figure 6.37 displays the amount discharged with different maximum capacities.

2021

The cost development for varying charging capacities in 2021 is illustrated in Figure 6.35. The findings suggest that the costs associated with changes to the maximum charging capacities are marginal, with slight cost advantages becoming discernible towards the latter part of the year.

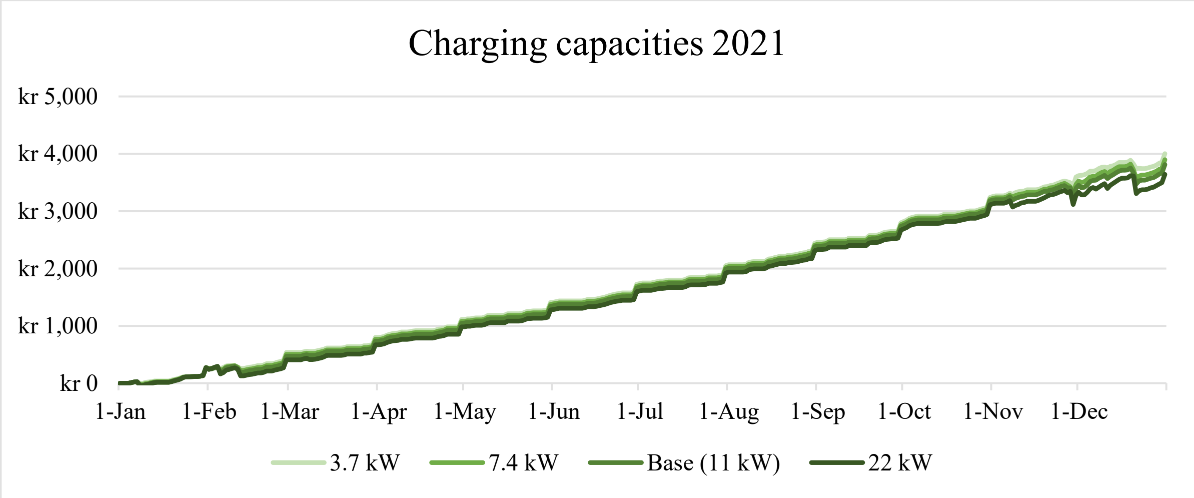


Figure 6.35 – Scenario charging capacities 2021

The capacity component is presently at its lowest level, see Figure 6.36, and it is optimal to utilize a maximum charging capacity of 2 kW throughout the year. This implies that the economic advantages of employing higher charging capacities exclusively stem from the utilization of a higher discharging capacity.

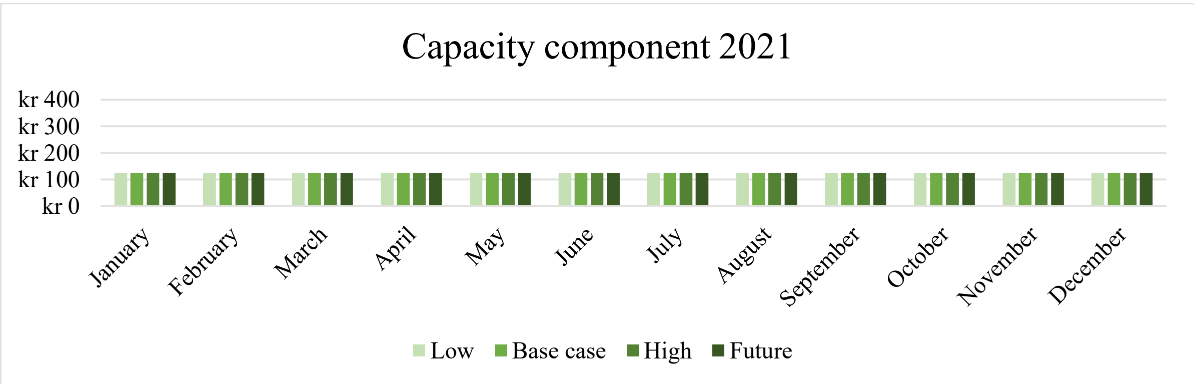


Figure 6.36 – Capacity component when changing charging capacities 2021

Figure 6.37 depicts the quantity of electricity discharged at varying charging capacities. The availability of higher capacities results in more electricity being fed back into the grid, making the EV better equipped to be a tool in the balancing markets.

Summary charging capacities

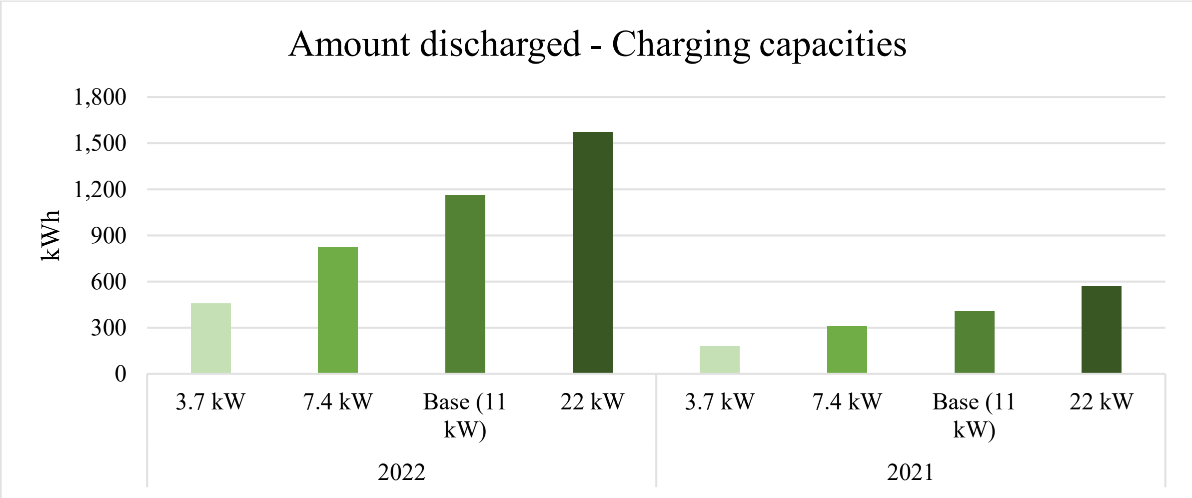


Figure 6.37 – Amount discharged with different charging capacities

	2022	*%*	*2021*	*%*	*2015 - 2020*	*%*
3.7 kW	NOK 5,822	9,70%	NOK 4,002	4.98%	NOK 3,195	0.00%
7.4 kW	NOK 5,504	3,71%	NOK 3,899	2.28%	NOK 3,195	0.00%
Base (11 kW)	**NOK 5,307**	**0,0%**	**NOK 3,812**	**0.00%**	**NOK 3,195**	**0.00%**
22 kW	NOK 5,072	-4,43%	NOK 3,642	-4.46%	NOK 3,195	0.00%

Table 6.6 – Total costs with different charging

Table 6.6 presents the total charging cost with different maximum charging and discharging capacities. A finding is that even though the amount of kWh discharged varies significantly depending on the capacities, which is favorable for the grid to use the EV's battery as a balancing tool, the total costs do not vary to the same extent for the EV owner. It can be deduced that the increasing cost of the capacity component of the grid tariff outweighs most of the arbitrage gains from utilizing higher charging capacities.

6.2.4 Scenario 4 – Grid tariffs

This section will investigate how the regulatory framework influences arbitrage trading opportunities with bidirectional charging. The current grid tariff is set up against the old and proposed grid tariff to discover the tariff's impact on bidirectional charging. The grid tariff prices can be found in section 5.1.2.

The model is modified to comply with the different tariffs. The modification is done by changing the variable price data in parameter $e_{t,d}$ and modifying the capacity component to be a fixed cost[35]. The weekly structure of parameter e for the tariffs is attached in Table A.8-A.10 in the appendix.

2022

The proposed grid tariff offers a distinct advantage over the other tariffs, resulting in lower costs, particularly beyond September 2022, see Figure 6.38. This translates into tangible benefits for EV owners, stemming from increased electricity trading that opens up profitable arbitrage opportunities. As shown in Figure 6.40, the proposed tariff enables greater amounts of electricity to be discharged, thereby increasing the EV's viability as a resource in the market's balancing mechanisms. These effects apply to the old tariff as well. While it does not yield clear cost benefits compared to the current grid tariff, it facilitates a more favorable environment for bidirectional charging to serve as a valuable tool in the balancing markets by enabling more electricity to be discharged.

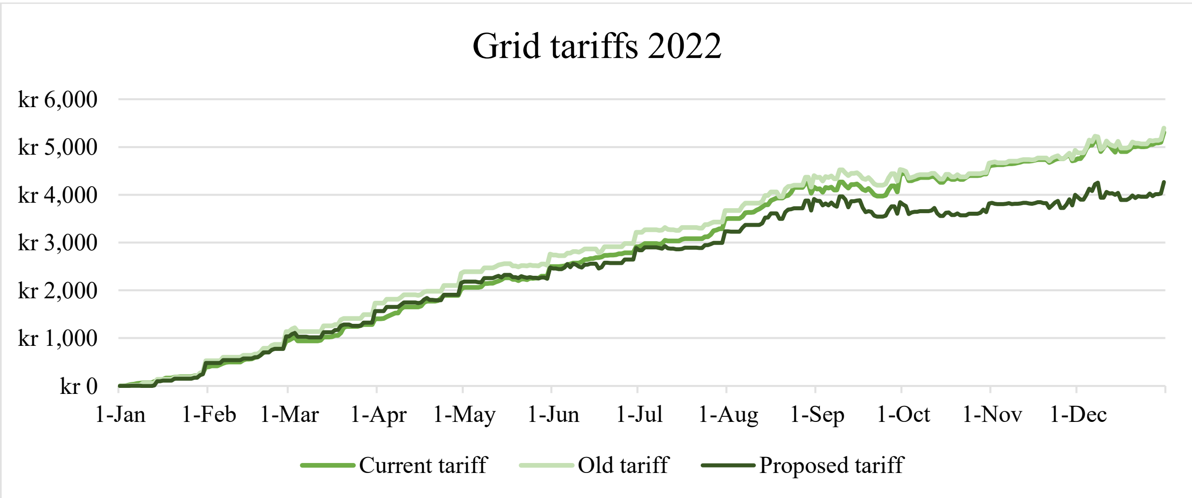


Figure 6.38 – Scenario grid tariffs 2022

[35] With the previous and proposed grid tariff the maximum charging capacity is no longer limited by the capacity component, but by the home charging unit set to 11kW.

2021

When contrasting the grid tariffs for 2021 in Figure 6.39, it is evident that the old tariff presents unfavorable costs. Conversely, the current and proposed grid tariffs yield nearly equivalent annual charging costs, with the latter's capacity component price remaining fixed every month, resulting in a more gradual progression. The fundamental objective of bidirectional charging entails generating cost savings for EV owners while simultaneously functioning as a balancing mechanism for the power market. As demonstrated in Figure 6.40, employing the proposed grid tariff enhances the EV's efficacy as a balancing tool.

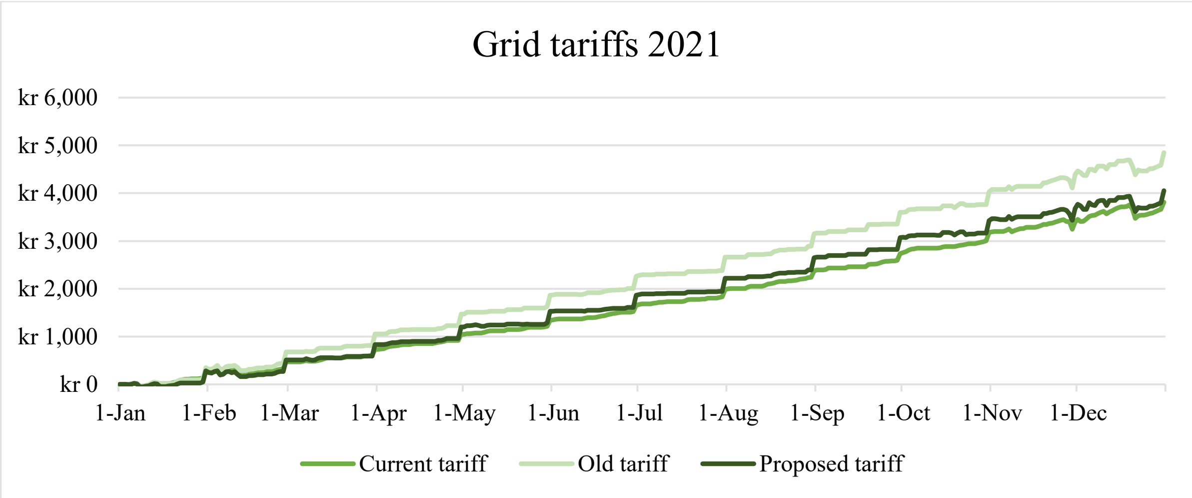


Figure 6.39 – Scenario grid tariffs 2021

Summary grid tariffs

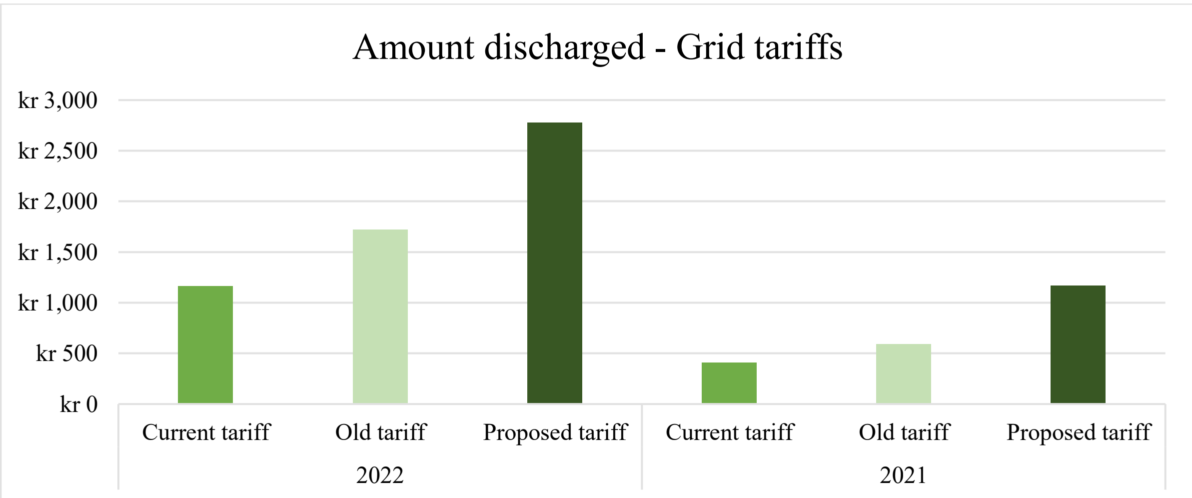


Figure 6.40 – Amount discharged with different grid tariffs

	2022	*%*	*2021*	*%*	*2015 - 2020*	*%*
Current tariff	**NOK 5,307**	**0.00%**	**NOK 3,812**	**0.00%**	**NOK 3,195**	**0.00%**
Old tariff	NOK 5,394	1,64%	NOK 4,849	27,20%	NOK 4,611	44.32%
Proposed tariff	NOK 4,265	-19,63%	NOK 4,052	6,30%	NOK 4,042	26.51%

Table 6.7 – Total costs with different grid tariffs

Table 6.7 presents the total cost of charging with different grid tariffs. A significant finding is that the current grid tariff is more economically beneficial than the old grid tariff, but the old tariff facilitates a more favorable environment for bidirectional charging to serve as a tool in the balancing markets. With the old and proposed tariffs, consumption is not punished when grid capacity is high. It enables consumers to take advantage of periods of high grid capacity, such as at night, to utilize a higher charging capacity and charge their EVs more quickly when electricity prices are lower.

6.2.5 Scenario 5 – Electricity support package

In this scenario, the electricity subsidy is considered in the day-ahead prices to investigate whether the subsidy affects the bidirectional charging behavior. More precisely, it is interesting to see how much the incentives of being flexible weaken when electricity subsidies are calculated on hourly electricity prices. The base case model is used, and prices for 2022 are examined.

The price data for 2022 is modified to reflect the proposed updated support package, as mentioned in section 5.1.3. The price data is adjusted by defining:

$$\bar{P}_{t,d} = P_{t,d} - (\max[0,\ P_{t,d} - 0.70] \cdot 90\%)$$

Figure 6.41 presents consumers' day-ahead prices, with and without implementing the power support package. Notably, the depicted data reveals a diminishing price disparity, thereby eliminating the prospect of purchasing electricity at lower rates and selling it at higher rates.

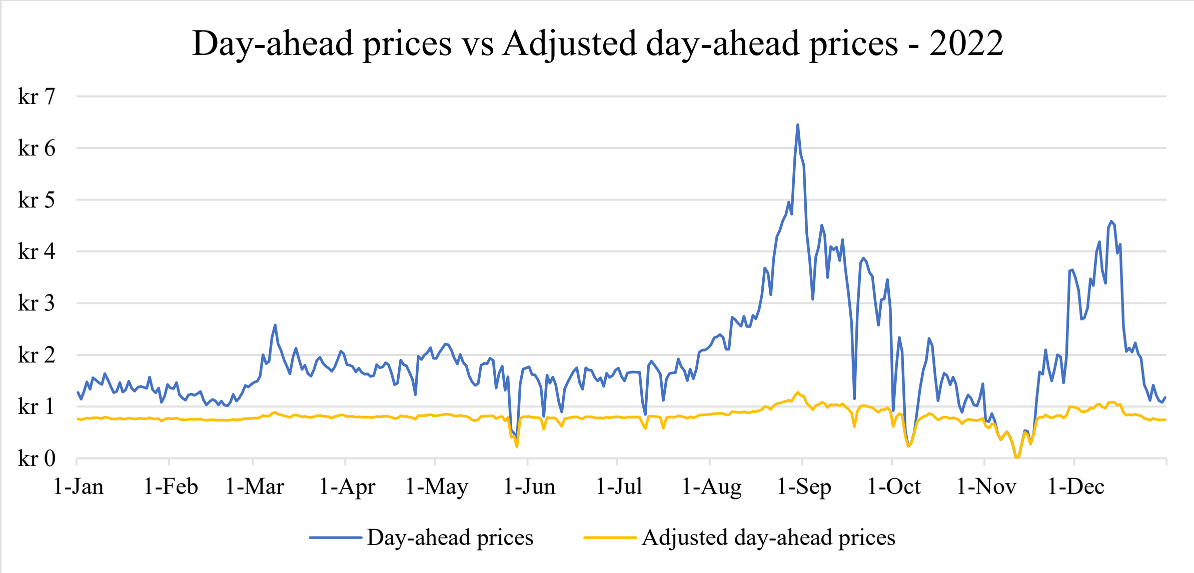


Figure 6.41 – Day-ahead prices vs. Adjusted day-ahead prices – 2022

Intriguingly, upon interpreting the adjusted prices in the model, it is observed that no kWh is discharged, making bidirectional charging redundant. Consequently, the costs associated with both technologies become identical, as displayed in Figure 6.42.

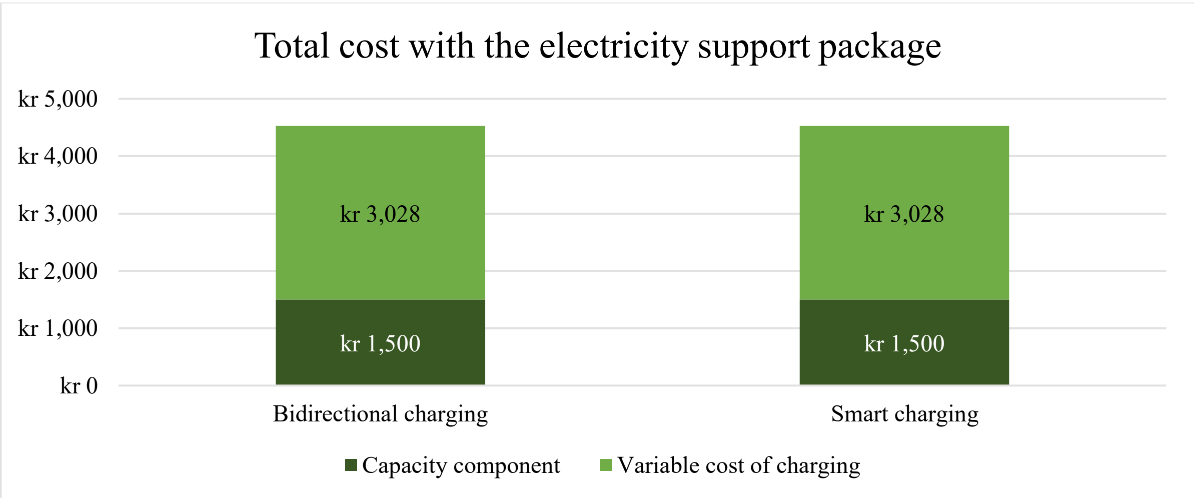


Figure 6.42 – Total costs with the electricity support package

Throughout the year, a maximum charging capacity of 2 kW is consistently employed with both technologies, resulting in a monthly capacity component of the grid tariff amounting to NOK 125.

Previous scenarios have provided evidence indicating that bidirectional charging becomes financially viable primarily in situations characterized by substantial volatility in day-ahead prices. It was also observed that the profitability of bidirectional charging is correlated with the magnitude of these prices. Figure 6.43 compares the volatility in day-ahead prices, clearly demonstrating a diminishing level of volatility. Table 6.8 shows that the modified day-ahead prices for 2022 were significantly less volatile than in 2022.

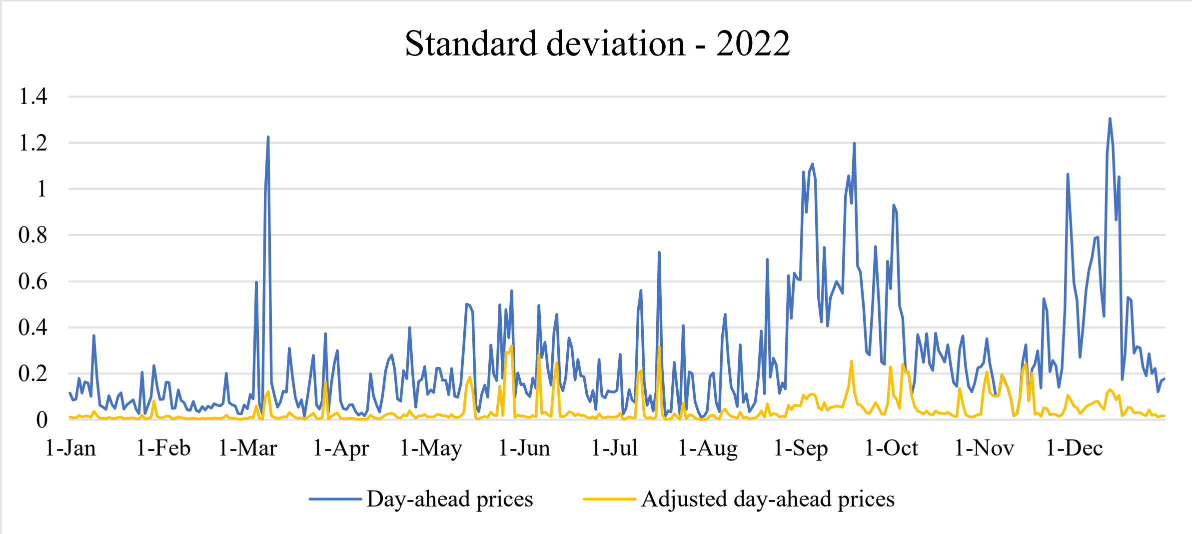


Figure 6.43 – Standard deviation – 2022

Year	Lowest price	25% quantile	75% quantile	Highest price	St. Dev
2022	0	1.329	2.138	7.820	1.092
Modified	0	0.763	0.844	1.412	0.168

Table 6.8 – Summary statistics of day-ahead prices

Considering the findings indicating that bidirectional charging provides limited advantages compared to smart charging in conjunction with the proposed support package, one may question the profitability of adopting emerging technologies such as smart charging and bidirectional charging. Consequently, the model was adjusted to restrict EV owners to charging exclusively on Tuesday and Thursday evenings, specifically between 5 pm and 10 pm, as this timeframe typically exhibits the highest day-ahead prices[36].

The outcomes of this modification reveal an increase in costs, as depicted in Figure 6.44. However, this increase is primarily attributed to the shorter charging window, necessitating the utilization of a higher charging capacity. A maximum charging capacity of 5 kW was

[36] See Figure 5.1 and Figure 5.2.

employed consistently throughout 2022 to address this limitation. Consequently, the monthly cost of the capacity component of the grid tariff amounts to NOK 206. Comparing the forced evening pattern with and without the implementation of the electricity support package, the cost saving for 2022 equals NOK 3,322[37].

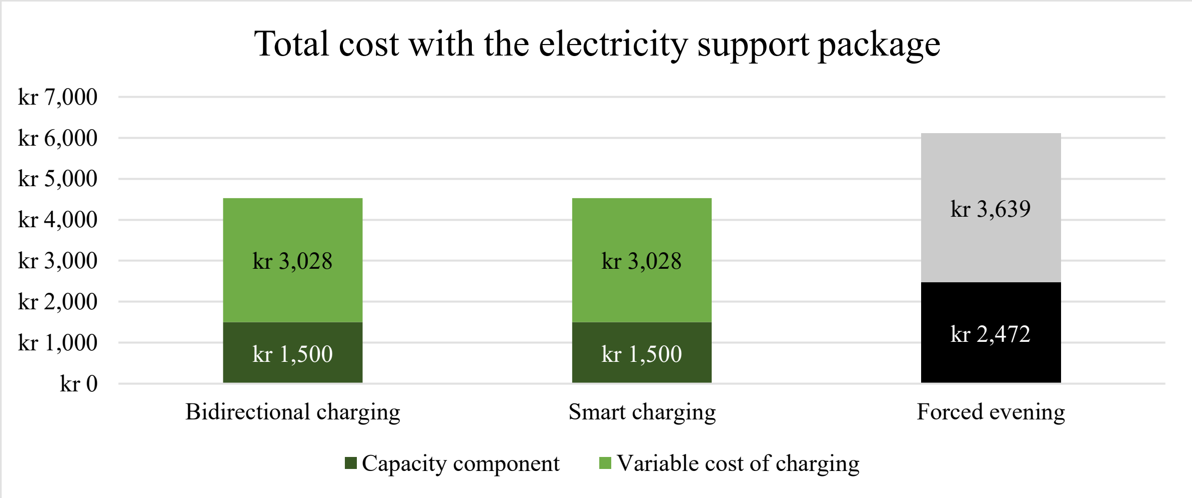


Figure 6.44 – Total costs with the electricity support package

Without the motivation to adopt smart charging practices, EV owners may charge their vehicles during peak hours, exacerbating demand during strained periods. This surge in electricity consumption can strain the grid infrastructure, potentially leading to increased energy costs, grid instability, and unsustainable reliance on conventional power sources.

Given the global push towards electric mobility to reduce greenhouse gas emissions and combat climate change, supportive policies and incentives must align with the promotion of smart charging technologies. By encouraging and rewarding intelligent charging behaviors, we can maximize the environmental and economic advantages associated with electric vehicles while ensuring our energy systems' long-term stability and sustainability.

[37] $NOK\,9{,}433 - \text{NOK } 6{,}111 = \text{NOK } 3{,}322$

6.2.6 Summary scenario analyses

Bidirectional charging is affected by various factors, including battery capacity, EV consumption, charging capacity, and the grid tariff. Larger battery capacity can provide greater cost benefits during periods of high volatility in day-ahead prices, while EV consumption has little impact on bidirectional charging. A charging capacity of 5 kW is generally sufficient for most of the year, as the capacity cost outweighs the benefits of higher charging capacity. Higher discharging capacity is always preferable, increasing the possibility of selling electricity fast when prices are relatively high.

The proposed grid tariff is the most advantageous option for EV owners, as it offers clear balancing benefits and increased arbitrage opportunities, mainly when price volatility is high. The proposed grid tariff gives consumers more incentives to charge smart and penalizes those that do not, creating a viable environment for bidirectional charging.

In summary, bidirectional charging offers evident advantages. The level of profitability is influenced by various components within the process, each with varying degrees of impact. However, the electricity support package introduced by the Norwegian government compromises the full potential of bidirectional charging. This subsidy eliminates the essential price volatility necessary for bidirectional charging, thus eradicating incentives for intelligent technologies like bidirectional charging.

7. Discussion

This chapter will discuss the model's limitations and the validity of the results obtained. Additionally, potential future topics that build upon the research in this thesis will be proposed.

7.1 Financial investment decision

In Chapter 6, we presented that bidirectional charging offers advantages over smart charging in terms of accumulated cost savings, where the EVs availability and different parameters affected the profitability. To fully understand the potential arbitrage opportunities of bidirectional charging offers, it is also essential to discuss the financial decision of investing. This discussion will solely consider the base case behavior pattern.

First, many EV owners will be restricted by their local distribution system. As mentioned in section 2.1.2, the 230V IT system is the standard distribution system for electricity in Norway. Consequently, it limits most households' charging and discharging capacity to a maximum capacity of 11 kW, depending on the installed fuse. However, section 6.2.3 presents a significant finding wherein it is observed that a higher charging capacity of 11 kW becomes economically viable only in September 2022 when the volatility of prices is at its peak, and a charging capacity of 5 kW is adequate for most of the year. For 2021, utilizing a maximum charging capacity of 2 kW would have been optimal throughout the year. The low charging capacity shows that the increasing cost of the capacity component in the grid tariff outweighs the potential arbitrage gains from utilizing higher charging capacities. The volatility in day-ahead prices is a prerequisite for the economic benefits of bidirectional charging to be perceptible.

In contrast, the discharging capacity is independent of the capacity component[38] and is utilized at higher levels whenever feasible. To conclude, this means that many households in Norway could have significant arbitrage opportunities even though the distribution system limits many households to a charging and discharging capacity of 11 kW. Extra investments in the distribution system are, therefore, a factor that may be less emphasized.

[38] If the assumption of the prosumer scheme holds.

Second, an EV that has incorporated the technology is necessary to utilize the bidirectional charging technology. As mentioned in section 2.1.1, only a limited number of EVs offer bidirectional charging, but so far, there is no indication that manufacturers are increasing the price of the EVs due to this technology or are offering the technology in an upgrade package for the EVs. For this reason, the financial investment decision of purchasing an EV with the technology is not relevant to the same extent in this study. If EV manufacturers in the future offer upgrade packages that contain bidirectional technology, and the EV owner has to pay extra for this, the cost of incorporating the technology in the EV should be considered.

Furthermore, the EV owner must consider the cost of purchasing a charging unit that offers bidirectional charging. As mentioned in section 2.1.3, the current V2G charger on the Norwegian market is priced higher than a standard charging unit that can charge smart. With the conducted research, the payback period of investing in a bidirectional charger with 2022 prices is 11.6 years[39], and with 2021 prices, 26.5 years[40]. The high payback period shows that the cost savings of utilizing bidirectional charging must be significantly higher since there is a high price difference between a bidirectional charging unit and a smart charging unit. Finally, a potential subscription fee must be considered. If the EV owner had to pay a subscription fee to benefit from bidirectional charging, the monthly fee could not have exceeded NOK 63.92[41] and NOK 27.92[42] for 2022 and 2021, respectively.

7.2 Limitations

The findings presented in Chapter 6 are limited by the assumptions made when constructing the model and choosing the input data. These assumptions may impact the validity of the results. The following section elaborates on the assumptions regarding the model construction, followed by a discussion of the assumptions on key parameters.

The model is an ex-post optimization, which means the optimization is done when perfect information about the relevant price data and driving behaviors exists for an entire year. The

[39] Comparing the two Zaptec charges: $\text{NOK } 15{,}875 - \text{NOK } 7{,}000 = \text{NOK } 8{,}875$; $\frac{\text{NOK } 8{,}875}{\text{NOK } 767} = 11.6$ years

[40] Comparing the two Zaptec charges: $\text{NOK } 15{,}875 - \text{NOK } 7{,}000 = \text{NOK } 8{,}875$; $\frac{\text{NOK } 8{,}875}{\text{NOK } 335} = 26.5$ years

[41] $\frac{\text{NOK } 767}{12} = \text{NOK } 63.92$

[42] $\frac{\text{NOK } 335}{12} = \text{NOK } 27.92$

findings present the best possible solution given the relevant parameters. If the optimizations were conducted in a prospective matter, the model would include uncertainty in electricity prices and driving behavior in a stochastic optimization. This type of optimization would make the model more realistic; however, as this study tends to investigate the full arbitrage opportunity with bidirectional charging, it is relevant to optimize with perfect information.

The different behavior patterns investigated are assumed to be simplifications of natural driving behaviors in Norway and are considered to reflect an average week of driving. Section 3.2 states that the patterns do not consider more extended periods where the EV is available or unavailable for bidirectional charging. In reality, the behavior will differ. For instance, the model assumes that the EV is always connected to the home charging unit when at home. EV owners might not have this behavior in real life and let the EV stay unconnected. In addition, the model does not consider the opportunity to charge the EV in places other than at home. An EV owner occasionally charges the EV at public stations throughout the year or even at work if the employer offers charging opportunities.

The price components used as data input are subject to limitations. The day-ahead prices are specific for the NO5 bidding zone in Norway and do not reflect prices in other zones. In addition, the random fluctuations or noise in the data are filtered out using the average hourly price data for the period 2015 – 2020. The average prices, therefore, result in a more stable and predictable trend which may reflect the results of no amount discharged in the period. Additionally, research by Bruckner & Hanemann (2018) indicates that bidirectional charging has a smoothing effect on electricity prices. Large implantation of V2G would lead to lower price fluctuations, decreasing arbitrage opportunities.

Further, the costs for the grid tariff are set by the local network provider BKK. The grid tariff will vary depending on the network provider in the bidding zone. The proposed grid tariff is also: a proposal. There is currently no DSO in Norway that has implemented this tariff. Therefore, the results only represent the chosen bidding zone and network provider and will not accurately reflect charging costs in other areas.

As mentioned in section 3.1, the model assumes that a bidirectional chargeable EV is classified as a vehicle and the EV owner is a prosumer with its power supplier, hence the regulatory uncertainty. Therefore, the results depend highly on this simplification and will be subject to potential adjustment if the parameters differ. Additionally, the model does not consider the capital cost of the EV nor the capital costs regarding a home charging unit with implemented bidirectional charging technology. These costs are assumed to be sunk and considered irrelevant when investigating arbitrage opportunities with bidirectional charging.

Parameters regarding the EV-specific components highly influence the obtained results. First, the base case parameters reflect the current most sold EV in Norway, Tesla Model Y. As mentioned in section 5.3, this model does currently not contain V2G technology. However, since investigating arbitrage opportunities, it is used as a benchmark in the optimization model to show how much EV owners in Norway could benefit from bidirectional charging. The parameters in the base case model are, therefore, only applicable to the specific EV. For this reason, the study examines how the charging cost deviates from the benchmark to changes in parameter values.

Further, driving consumption is also a parameter significantly impacting the charging cost. The EVs consumption refers to the amount of electricity consumed per km driven and is simplified in two ways: an assumed fixed consumption per km and a fixed amount consumed every driven hour. First, it is difficult to determine a definite energy consumption value for the optimization model because it can vary greatly depending on factors such as speed, weight, driving style, climate, and route conditions. Therefore, using an average consumption rate based on data is done since these factors make it unfeasible to find a perfect consumption rate for the model. Second, the fixed amount consumed every driven hour is a significant simplification. The amount consumed is based on the average driving distance in 2021 for EVs in Norway. This year was subject to Covid-19 restrictions; however, the average daily distance only increased from 34.61 km in 2019 to 34.99 km in 2021, while in 2020, the distance was 33.41 km (SSB, 2021). Despite potential limitations, the increase in average daily distance aligns with the current trend[43] and is considered a valid representation of normal behavior.

The model is also simplified by not considering battery degradation. As section 2.1.1 states, bidirectional charging degrades the battery faster due to the extra charging cycles used to deliver electricity back to the grid. As analyzed in section 6.2.1, the battery capacity impacts the charging costs. If implemented, the EV capacity would decrease throughout the year.

[43] See appendix Table A.11.

The essential part of bidirectional charging is purchasing and selling electricity, which is done by charging and discharging the EV. First, the model does not consider that the charging capacity decreases when the SOC is between 80%-100%. Most EVs are programmed to reduce the charging capacity in this area to prevent the battery from overheating (Tchir, 2022). Overheating would stress the cells in the battery and degrade its capacity. This parameter is fixed in every behavior pattern and the scenario analysis in the thesis. Second, there is an underlying assumption that discharging capacity can reach 22 kW in the scenario analysis. As mentioned in section 2.1.2, the current home charging units with bidirectional technology can only charge up to 11 kW, and the current technology in EVs only allows discharging up to 9.6 kW. As this thesis investigates the arbitrage trading potential, it is relevant to assume that there exists an EV and a charging unit that can deliver higher capacities.

7.3 Further work

The completion of this thesis marks the culmination of extensive research. Even so, there are many avenues for further work. This section presents potential directions for further research that can expand upon the knowledge gained from this study.

In this study, a major assumption regarding the regulatory framework of bidirectional charging was conducted. As there currently is no implemented framework in the EU or Norway, the optimization model assumes that the EV owner is a prosumer with their power supplier. It would therefore be of high interest to investigate the effects of specific legislation on the potential for arbitrage trading, as more EV manufacturers are adopting bidirectional charging technology, and the EU has banned the sale of new petrol and diesel cars from 2035.

Second, the current study incorporates day-ahead prices as a parameter to examine the potential for arbitrage trading opportunities. The optimal optimization would be if the model only knew the day-ahead prices 24 hours into the future. Day-ahead prices in Norway are only published one day ahead at 1 pm, not for an entire year. If this is implemented, the EV must make decisions with less information and base charging behavior on this information.

Third, investigating V2G in interaction with a DER system would be highly interesting. DERs produce electricity to supply the home or business with power. If any excess energy is not being used or if it is not profitable to sell at the current time, it can be sent back to the EV to be stored. In this way, an EV owner will reduce their electricity costs by using their own produced electricity in combination with electricity purchased from a power supplier.

Further, a study that explores the potential benefits of bidirectional charging for EV owners considering charging scenarios beyond home charging would be interesting. Uncovering the advantages and implications associated with bidirectional charging at workplaces (V2G), malls, housing cooperatives (Borettslag), and other public locations could contribute to the growing knowledge of EV charging, charging infrastructure, and sustainable transportation.

At last, exploring momentum strategies for bidirectional charging could also present an intriguing avenue for research. These strategies can inform investment decisions and strategic actions within the bidirectional charging domain by harnessing historical performance and momentum indicators. This research becomes especially relevant given the constraint of day-ahead price availability, which limits the foresight to only 24 hours ahead. Consequently, implementing momentum strategies could serve as a valuable guide for EV owners, empowering them to optimize their benefits from bidirectional charging.

8. Conclusion

By maximizing economic benefits from an EV owner’s perspective, this thesis investigates if bidirectional charging can offer potential arbitrage opportunities to an EV owner. An optimization model considering an EVs bidirectional charging behavior in the NO5 Norwegian power market was constructed, where electricity price fluctuations are exploited by utilizing the storage opportunities in an EV battery. In addition, a scenario analysis was conducted to examine how sensitive the profitability of bidirectional charging is to changes in parameter values.

The results show that bidirectional charging offers advantages over smart and unmanaged charging in terms of accumulated cost savings and the capacity to send electricity back to the grid. Compared to smart charging, the annual cost savings when utilizing bidirectional charging range from NOK 415 – NOK 1,275 in 2022 and NOK 176 – NOK 625 in 2021. The arbitrage opportunities are significantly higher when the EV is connected to the charging unit for a more extended period, giving the EV more time to engage in electricity trading. Additionally, it is imperative to note that substantial volatility in day-ahead prices is a prerequisite for the economic benefits of bidirectional charging to be perceptible. This is seen both when investigating the total cost and amount discharged between the years in the behavior patterns. Furthermore, the magnitude of the economic benefits increases with higher day-ahead prices during periods of high volatility.

The results from the scenario analysis reveal that various components influence the level of profitability. A larger battery capacity can provide greater cost benefits during periods of high volatility in day-ahead prices, as it enables EVs to charge more electricity when the price is low and sell more electricity when the price is high. However, a higher charging capacity does not show cost benefits to the same extent, as the increasing cost of the capacity component of the grid tariff outweighs any potential arbitrage gains from utilizing higher charging capacities. A charging capacity of 5 kW in 2022 was generally sufficient for most of the year, while in 2021, a maximum charging capacity of 2 kW was sufficient. In contrast, higher discharging capacity is always preferable as it increases the possibility of selling electricity fast when prices are relatively high. Further, EV consumption is not crucial to gain arbitrage opportunities with bidirectional charging. A lower consumption per km driven would naturally decrease the amount to be charged and increases the potential for cost savings, but it has little impact on bidirectional charging as the cost patterns remain almost identical.

In addition, the current grid tariff does not facilitate an environment for bidirectional charging to serve as a tool in the balancing markets. The current grid tariff model does not sufficiently incentivize individuals to modify their consumption patterns due to the minimal deviation in pricing, as the current grid tariff discourages high consumption regardless of the capacity on the grid due to the capacity-based fixed price model. Even though the grid capacity is high, the model still limits the charging capacity (kW) to avoid reaching the next level of the capacity component. The proposed grid tariff is the most advantageous option for EV owners, as it offers clear balancing benefits and increased arbitrage opportunities, mainly when price volatility is high. The proposed grid tariff gives consumers more incentives to charge smart and penalizes those that do not, creating a viable environment for bidirectional charging. The proposed grid tariff also enables more electricity to be discharged, thereby increasing the EV's viability as a resource in the market's balancing mechanisms.

At last, the full potential of bidirectional charging is compromised by the electricity support package introduced by the Norwegian government. This subsidy eliminates the essential price volatility necessary for bidirectional charging, thus eradicating incentives for intelligent technologies like bidirectional charging. Supportive policies and incentives must align with the promotion of smart charging technologies. Encouraging and rewarding intelligent charging behaviors can enhance EVs' environmental and economic advantages while ensuring our energy systems' long-term stability and sustainability.

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A. Appendix

	01.01.22	02.01.22	03.01.22	04.01.20	05.01.22	06.01.22	07.01.22
0	1.328	1.135	1.249	1.318	1.333	1.257	1.346
1	1.292	1.116	1.234	1.320	1.235	1.249	1.301
2	1.320	1.065	1.227	1.287	1.118	1.249	1.231
3	1.113	1.045	1.215	1.156	1.035	1.298	1.227
4	1.122	1.040	1.222	1.135	1.060	1.399	1.227
5	1.138	1.058	1.235	1.332	1.218	1.468	1.278
6	1.221	1.119	1.206	1.435	1.385	1.518	1.409
7	1.185	1.052	1.210	1.550	1.389	1.535	1.534
8	1.184	1.115	1.265	1.680	1.390	1.659	1.571
9	1.177	1.158	1.325	1.668	1.393	1.667	1.579
10	1.199	1.219	1.229	1.674	1.393	1.678	1.578
11	1.170	1.213	1.231	1.647	1.382	1.688	1.617
12	1.171	1.124	1.239	1.601	1.371	1.687	1.625
13	1.200	1.113	1.266	1.558	1.370	1.681	1.619
14	1.244	1.114	1.337	1.553	1.368	1.682	1.634
15	1.248	1.181	1.377	1.586	1.372	1.669	1.675
16	1.355	1.223	1.374	1.615	1.419	1.677	1.681
17	1.498	1.297	1.437	1.679	1.483	1.672	1.664
18	1.506	1.359	1.451	1.646	1.439	1.660	1.646
19	1.437	1.283	1.428	1.540	1.403	1.665	1.667
20	1.402	1.163	1.422	1.469	1.378	1.684	1.613
21	1.397	1.102	1.395	1.417	1.392	1.724	1.587
22	1.350	1.048	1.307	1.373	1.371	1.558	1.547
23	1.233	1.101	1.136	1.143	1.357	1.397	1.455

Table A.1 – Extract of the day-ahead price structure

A.1 Parameter structures

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
0	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1
7	0	0	0	0	1	1	1
8	0	0	0	0	1	1	1
9	0	0	0	0	1	1	1
10	0	0	0	0	1	1	1
11	0	0	0	0	1	1	1
12	0	0	0	0	1	1	1
13	0	0	0	0	1	1	1
14	0	0	0	0	1	1	1
15	0	0	0	0	1	1	1
16	0	0	0	0	1	1	1
17	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1

19	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1
22	1	1	1	1	1	1	1
23	1	1	1	1	1	1	1

Table A.2 – EV availability, $g_{t,d}$ – base case

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
7	5.2	5.2	5.2	5.2	0	0	0
8	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0
16	5.2	5.2	5.2	5.2	0	0	0
17	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0

Table A.3 – EV consumption, $f_{t,d}$ – base case

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
0	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1
11	1	1	1	1	1	0	1
12	1	1	1	1	1	0	1
13	1	1	1	1	1	0	1
14	1	1	1	1	1	0	1

15	1	1	1	1	1	0	1
16	1	1	1	1	1	0	1
17	1	1	1	1	1	1	1
18	1	0	1	0	1	1	1
19	1	0	1	0	1	1	1
20	1	0	1	0	1	1	1
21	1	0	1	0	1	1	1
22	1	1	1	1	1	1	1
23	1	1	1	1	1	1	1

Table A.4 – EV availability, $g_{t,d}$ – High availability

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
11	0	0	0	0	0	5.2	0
12	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0
16	0	0	0	0	0	5.2	0
17	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0
20	0	5.2	0	5.2	0	0	0
21	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0

Table A.5 – EV consumption, $f_{t,d}$ – High availability

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
0	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1
7	0	0	0	0	0	1	1
8	0	0	0	0	0	1	1
9	0	0	0	0	0	1	1
10	0	0	0	0	0	1	1
11	0	0	0	0	0	0	1

12	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0
16	0	0	0	0	0	0	1
17	1	1	1	1	1	1	1
18	1	0	1	0	1	1	1
19	1	0	1	0	1	1	1
20	1	0	1	0	1	1	1
21	1	0	1	0	1	1	1
22	1	1	1	1	1	1	1
23	1	1	1	1	1	1	1

Table A.6 – EV availability, $g_{t,d}$ – Low availability

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
7	5.2	5.2	5.2	5.2	5.2	0	0
8	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
11	0	0	0	0	0	5.2	0
12	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0
14	0	0	0	0	0	0	5.2
15	0	0	0	0	0	0	0
16	5.2	5.2	5.2	5.2	5.2	5.2	0
17	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0
20	0	5.2	0	5.2	0	0	0
21	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0

Table A.7 – EV consumption, $f_{t,d}$ – Low availability

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
0	0.399	0.399	0.399	0.399	0.399	0.399	0.399
1	0.399	0.399	0.399	0.399	0.399	0.399	0.399
2	0.399	0.399	0.399	0.399	0.399	0.399	0.399
3	0.399	0.399	0.399	0.399	0.399	0.399	0.399
4	0.399	0.399	0.399	0.399	0.399	0.399	0.399
5	0.399	0.399	0.399	0.399	0.399	0.399	0.399
6	0.499	0.499	0.499	0.499	0.499	0.399	0.399
7	0.499	0.499	0.499	0.499	0.499	0.399	0.399

8	0.499	0.499	0.499	0.499	0.499	0.399	0.399
9	0.499	0.499	0.499	0.499	0.499	0.399	0.399
10	0.499	0.499	0.499	0.499	0.499	0.399	0.399
11	0.499	0.499	0.499	0.499	0.499	0.399	0.399
12	0.499	0.499	0.499	0.499	0.499	0.399	0.399
13	0.499	0.499	0.499	0.499	0.499	0.399	0.399
14	0.499	0.499	0.499	0.499	0.499	0.399	0.399
15	0.499	0.499	0.499	0.499	0.499	0.399	0.399
16	0.499	0.499	0.499	0.499	0.499	0.399	0.399
17	0.499	0.499	0.499	0.499	0.499	0.399	0.399
18	0.499	0.499	0.499	0.499	0.499	0.399	0.399
19	0.499	0.499	0.499	0.499	0.499	0.399	0.399
20	0.499	0.499	0.499	0.499	0.499	0.399	0.399
21	0.499	0.499	0.499	0.499	0.499	0.399	0.399
22	0.399	0.399	0.399	0.399	0.399	0.399	0.399
23	0.399	0.399	0.399	0.399	0.399	0.399	0.399

Table A.8 – Variable cost of the grid tariff, $e_{t,d}$ – Current grid tariff

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
0	0.430	0.430	0.430	0.430	0.430	0.430	0.430
1	0.430	0.430	0.430	0.430	0.430	0.430	0.430
2	0.430	0.430	0.430	0.430	0.430	0.430	0.430
3	0.430	0.430	0.430	0.430	0.430	0.430	0.430
4	0.430	0.430	0.430	0.430	0.430	0.430	0.430
5	0.430	0.430	0.430	0.430	0.430	0.430	0.430
6	0.430	0.430	0.430	0.430	0.430	0.430	0.430
7	0.430	0.430	0.430	0.430	0.430	0.430	0.430
8	0.430	0.430	0.430	0.430	0.430	0.430	0.430
9	0.430	0.430	0.430	0.430	0.430	0.430	0.430
10	0.430	0.430	0.430	0.430	0.430	0.430	0.430
11	0.430	0.430	0.430	0.430	0.430	0.430	0.430
12	0.430	0.430	0.430	0.430	0.430	0.430	0.430
13	0.430	0.430	0.430	0.430	0.430	0.430	0.430
14	0.430	0.430	0.430	0.430	0.430	0.430	0.430
15	0.430	0.430	0.430	0.430	0.430	0.430	0.430
16	0.430	0.430	0.430	0.430	0.430	0.430	0.430
17	0.430	0.430	0.430	0.430	0.430	0.430	0.430
18	0.430	0.430	0.430	0.430	0.430	0.430	0.430
19	0.430	0.430	0.430	0.430	0.430	0.430	0.430
20	0.430	0.430	0.430	0.430	0.430	0.430	0.430
21	0.430	0.430	0.430	0.430	0.430	0.430	0.430
22	0.430	0.430	0.430	0.430	0.430	0.430	0.430
23	0.430	0.430	0.430	0.430	0.430	0.430	0.430

Table A.9 – Variable cost of the grid tariff, $e_{t,d}$ – Old grid tariff

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
0	0.200	0.200	0.200	0.200	0.200	0.200	0.200
1	0.200	0.200	0.200	0.200	0.200	0.200	0.200
2	0.200	0.200	0.200	0.200	0.200	0.200	0.200
3	0.200	0.200	0.200	0.200	0.200	0.200	0.200
4	0.200	0.200	0.200	0.200	0.200	0.200	0.200

5	0.200	0.200	0.200	0.200	0.200	0.200	0.200
6	0.800	0.800	0.800	0.800	0.800	0.200	0.200
7	0.800	0.800	0.800	0.800	0.800	0.200	0.200
8	0.800	0.800	0.800	0.800	0.800	0.200	0.200
9	0.800	0.800	0.800	0.800	0.800	0.200	0.200
10	0.300	0.300	0.300	0.300	0.300	0.200	0.200
11	0.300	0.300	0.300	0.300	0.300	0.200	0.200
12	0.300	0.300	0.300	0.300	0.300	0.200	0.200
13	0.300	0.300	0.300	0.300	0.300	0.200	0.200
14	0.300	0.300	0.300	0.300	0.300	0.200	0.200
15	0.800	0.800	0.800	0.800	0.800	0.200	0.200
16	0.800	0.800	0.800	0.800	0.800	0.200	0.200
17	0.800	0.800	0.800	0.800	0.800	0.200	0.200
18	0.800	0.800	0.800	0.800	0.800	0.200	0.200
19	0.800	0.800	0.800	0.800	0.800	0.200	0.200
20	0.800	0.800	0.800	0.800	0.800	0.200	0.200
21	0.200	0.200	0.200	0.200	0.200	0.200	0.200
22	0.200	0.200	0.200	0.200	0.200	0.200	0.200
23	0.200	0.200	0.200	0.200	0.200	0.200	0.200

Table A.10 – Variable cost of the grid tariff, $e_{t,d}$ – Proposed grid tariff

Year	Average yearly driving distance (km)	Average daily driving distance (km)
2015	11 380	31.18
2016	11 788	32.30
2017	11 818	32.38
2018	12 171	33.35
2019	12 631	34.61
2020	12 193	33.41
2021	12 772	34.99

Table A.11 – Variable cost of the grid tariff, $e_{t,d}$ – Proposed grid tariff

A.2 Results 2015 – 2020

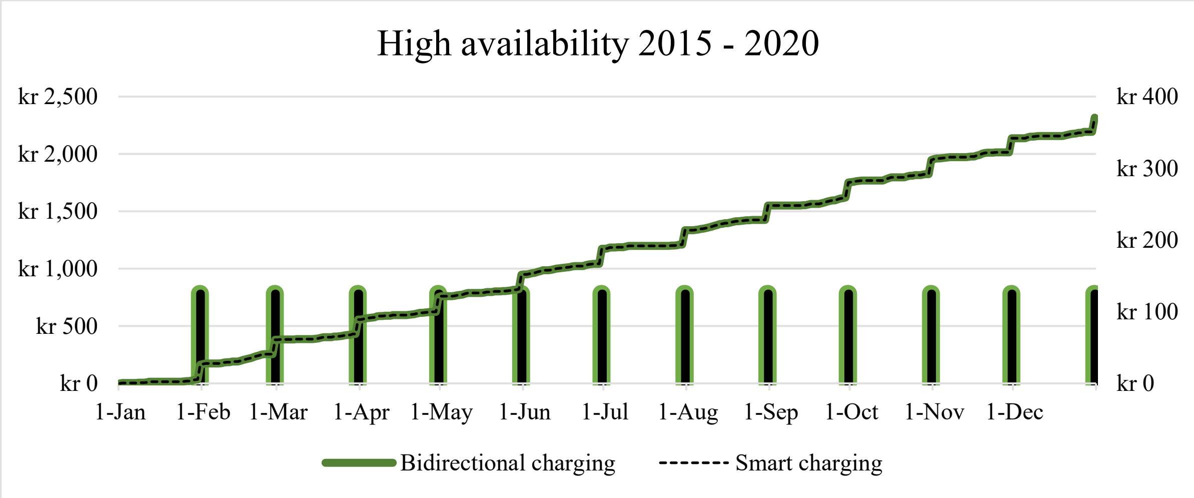

Figure A.1 – High availability 2015 – 2020

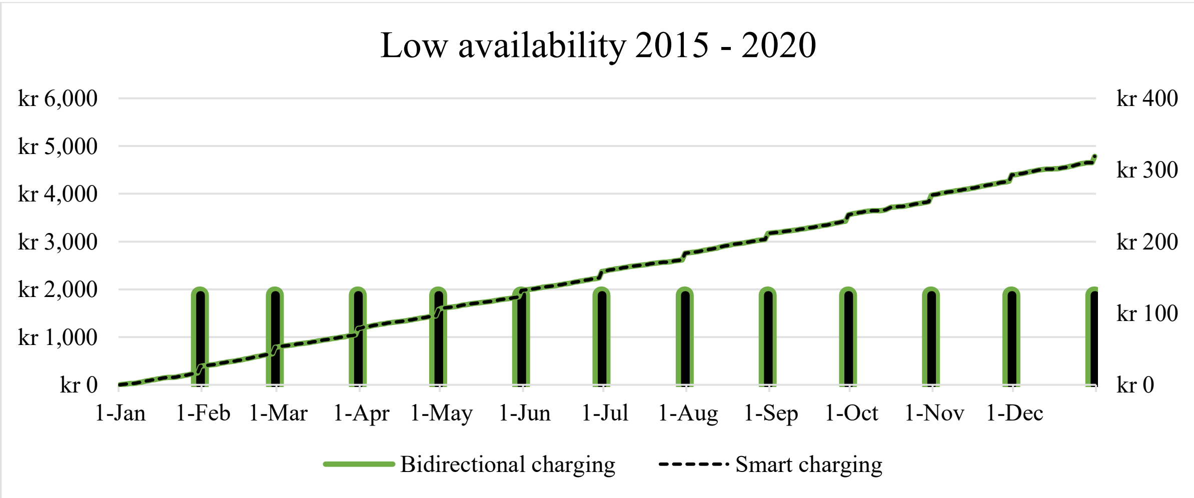

Figure A.2 – Low availability 2015 – 2020

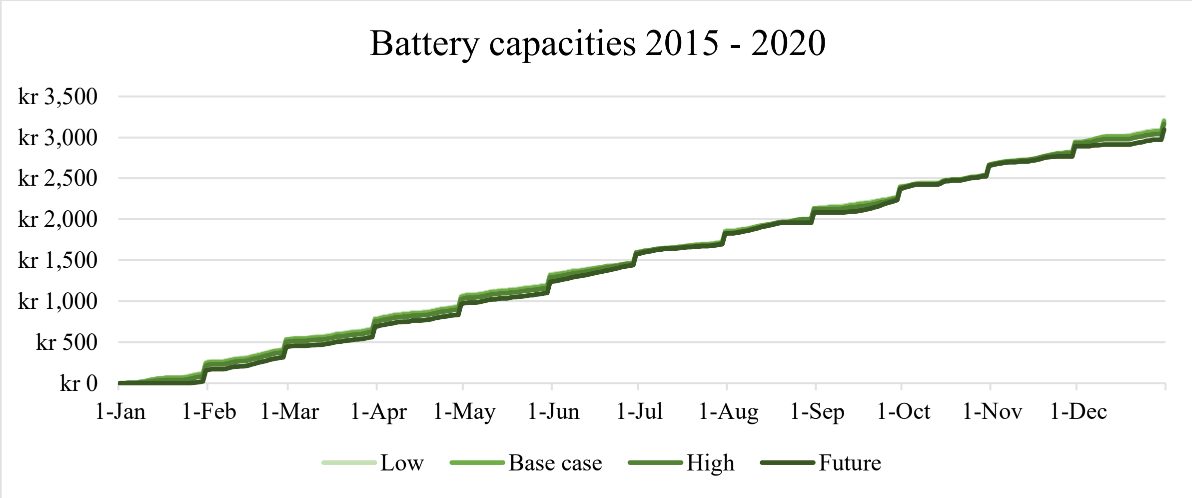

Figure A.3 – Battery capacities 2015 – 2020

Throughout the period of 2015 – 2020, no electricity was discharged in any of the battery capacity scenarios.

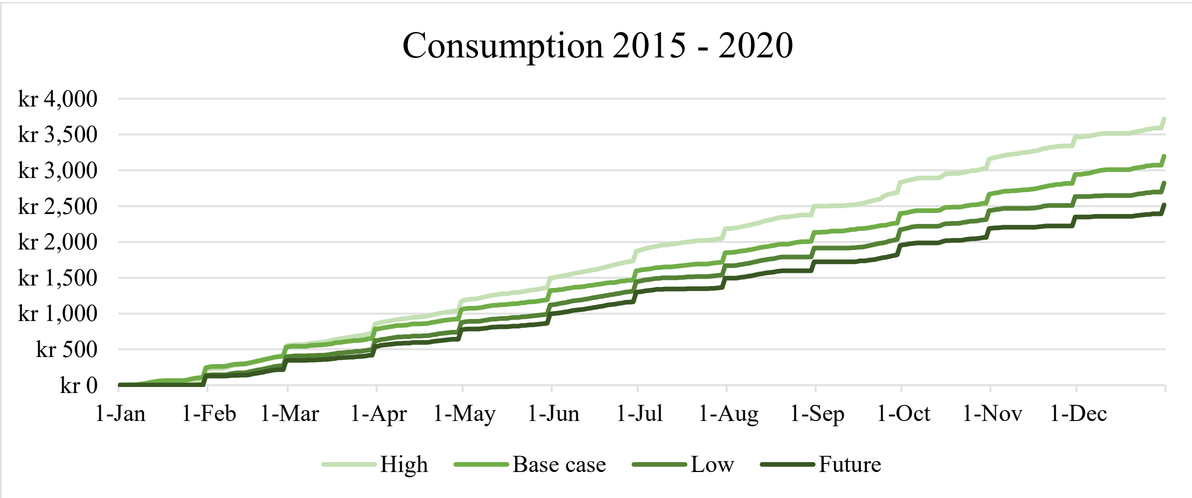

Figure A.4 – Consumption 2015 – 2020

Throughout the period of 2015 – 2020, no electricity was discharged in any of the consumption scenarios. The decreased costs observed in these scenarios were only because less electricity was needed when consumption was lower.

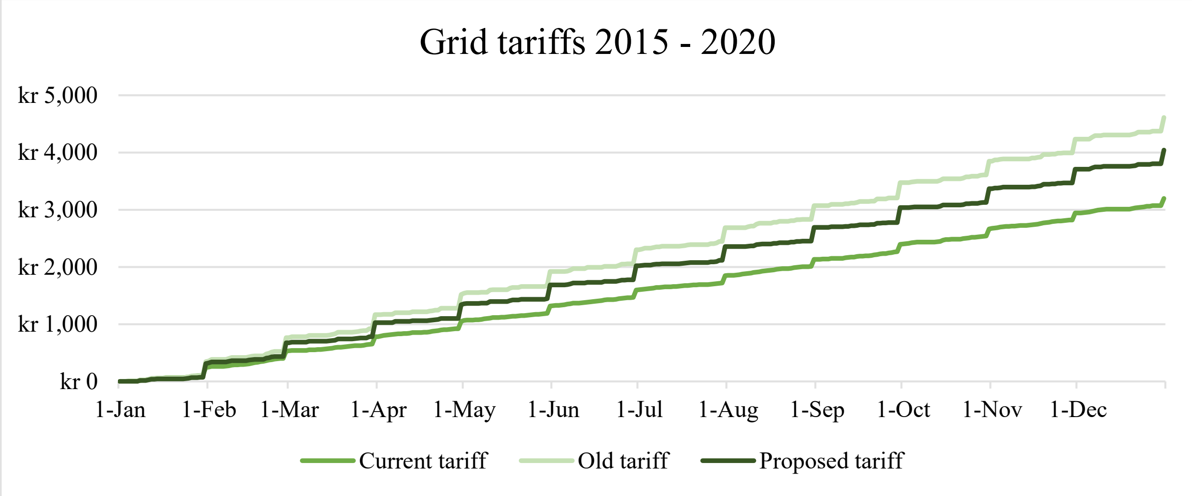

Figure A.5 – Grid tariffs 2015 – 2020

During the 2015 – 2020 period characterized by low prices, the current grid tariff exhibited superior cost efficiency. This can be attributed to the tariff's variable capacity component in contrast to the fixed rates of other tariffs. However, despite the cost-efficiency of the grid tariffs, discharging was not observed, indicating that bidirectional charging did not function as a tool for balancing the power market.

Charging capacities 2015 – 2020

During the period of 2015 – 2020, there was no variation in costs when comparing the base case to alternative charging and discharging capacity options. This can be attributed to the lack of economic benefits associated with utilizing a charging capacity greater than 2 kW and the fact that no electricity was discharged.