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Utilizing batteries in the Norwegian distribution grid

How will batteries be important for the energy transition in Norway, and which legislation should be done by the government to incentive battery implementation?

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EOM-*3901 Master's thesis in energy, climate and environment 30 SP, June 2023*

Abstract

Recent research indicates that photovoltaic (PV) induced overvoltage can occur in high PV-penetration low voltage distribution networks, due to reverse power flow from power injected to the grid. Since January 2020, the number of PV installations in Norway has seen a 2.7-fold increase in a rising trend. Simultaneously there have been several reports of grid-overvoltage and PV curtailment in the relation of grid-connected PV systems. This study aims to investigate the effects of batteries on peak injected power to the grid in Norwegian conditions. Further, an economic evaluation is done for different battery usage scenarios, including PV power self-consumption, peak shaving for reduced grid fee cost and arbitrage trading. Finally, the study investigates what regulation measures that must be in place, to make PV battery energy storage systems more profitable than PV-only systems. The study confirms that batteries can be used to reduce overvoltage, also in Norwegian conditions. Additionally, the findings indicates that for all scenarios investigated, batteries can only be considered profitable using electricity prices from 2022 averaging at 3.88 NOK/kWh, including taxes, in the NO1 price area. Conclusively, battery subsidies of 2666 NOK/kWh capped at 47500 NOK in combination with a fixed feed-in tariff of 30% is suggested, and the findings shows that for most scenarios, such a change in legislation would make batteries a more favourable investment than PV, if a PV-system already is installed.

Acknowledgements

I would like to express my gratitude to Professor Matteo Chiesa for his wonderful supervision throughout the completion of this thesis. His expertise in the field of renewable energy has been of great importance, offering insightful suggestions and ideas throughout the research.

To Mette Fjelltveit Rye-Larsen of Otovo, I would like to convey my gratitude for introducing me to an important topic in the solar energy industry.

Many thanks to my fellow students for providing me with excellent companionship during the previous five years of our study.

Last but not least, I want to thank my family for all of their continuous support during the course of my studies.

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Abbreviations

AC	Alternating Current
BESS	Battery Energy Storage Systems
DC	Direct Current
DoD	Dept of Discharge
EMS	Energy Management Strategy
MUF	Maximum Utilisation Factor
NVE	Norwegian Water Resources and Energy Directorate
O.P	Output Power
FIT	Feed-In Tariff
NV	Nominal Voltage
LV	Low-Voltage
PCC	Point of Common Coupling
PP	Pay-back Period
PV	Photovoltaic
RME	Norwegian Energy Regulatory Authority
SoC	State of Charge

1 Introduction

The world's reliance on fossil fuels including coal, oil, and natural gas has led to an increase in CO_2 emissions, and thus strongly affected global climate change. As a result, Norway and other European nations have actively encouraged the use of renewable energy sources like wind and solar, to diversify their energy mix and reach the ambitious greenhouse gas reduction targets of the Europe Green Deal. As a result, the EU has been able to raise its overall renewable electricity generation sources from 16% in 2004 to 39% in 2022 thanks to the sector's pace. Although hydropower has long been the dominant source of energy in Norway, while wind and solar power also have grown significantly over the last years. To fulfil the rising demand for electricity, the switch to renewable energy sources and the electrification of transportation and industry call for a major growth of renewable installation capacity. However, this transformation has its own set of difficulties, primarily the variations in the production of renewable energy caused by natural fluctuations in the energy production. Additionally, recent reports in Norway suggest that the increase of PV installations can cause PV curtailment and grid overvoltage due to reverse power flow in the distribution from excess PV power injected to the grid(Bjørheim, 2023; Lillebo et al., 2020), which is backed by recent international research (Sharma et al., 2023). However, the problem of overvoltage in low voltage distribution networks in Norway is still in its initial phase, as the total PV power generation in Norway, only consisted of 0.041% of total power generation for the year 2022. Thus, the issues with overvoltage is currently not too prevalent. However, with a recent rise in electricity prices as well as PV panels become more affordable, the PV-investment case is looking better for every year. The PV-investment case combined with the global trajectory of more installed renewable energy, the number of PV installations in both the residential and commercial sector is anticipated to continue growing in Norway as well, and therefore grid-overvoltage is an issue that is likely to become more frequent in the coming years.

1.1 Former research

1.1.1 PV induced overvoltage

Several studies indicate that PV induced overvoltage can occur in high PV-penetration low voltage distribution networks. The studies suggest that excess PV power produced fed into the grid, will create reverse power flow. The studies concludes that this can lead to PV curtailment and grid overvoltage. (Hashemi & Østergaard, 2017; Safayet et al., 2015; Sharma et al., 2023).

1.1.2 Battery storage utilization to reduce PV induced overvoltage

To the best of the authors' knowledge, little study has been done on this subject and none has been done in Norwegian contexts. Still, a 2023 study looked at how smart inverters and battery storage affected how much financial loss Australian PV systems experienced due to overvoltage-related PV curtailment. Three different approaches were investigated, including the use of smart inverters, the use of batteries and a combination of both. In the initial case, smart inverters reduced overvoltage by 90% but increased PV curtailment by 3%. In the second case, when batteries were implemented, results suggested a reduction in overvoltage by 63% and PV curtailment by 56%. The final scenario paired intelligent inverters with battery storage, which resulted in a 90% decrease in overvoltage and a 47% reduction in PV curtailment. The study found that using batteries and smart meters together was the most effective approach, with batteries alone coming in second. It did, however, also draw attention to the fact that most of the PV batteries currently available on the market are unable to supply reactive power, indicating that the combined solution might be more useful in the future..

1.2 Objective

The objective of this study is to evaluate the technical and financial feasibility of batteries in the combination with photovoltaics, based on the question: Can batteries help reduce PV induced overvoltage in the Norwegian low-voltage grid, and what change in legislation should be implemented by the authorities to encourage prosumer battery investments?

This study aims to answer this question by utilizing a PV-BESS simulation model that simulates the behaviour of a PV-BESS system over a year, charging and discharging the battery depending on PV production data, household consumption and battery capacity and the battery energy output and input power. Further, an economic evaluation is done for different battery usage cases, that includes PV-battery storage self-consumption, peak shaving for lower grid fees, and utilizing electricity arbitrage for trading purposes.

1.3 Structure of the study

In chapter 2, theory on power regulations, the effect on PV systems on distribution grid, and BESS applications is presented. Chapter 3 presents the data and methods, which include investigating batteries effect on PV peak injected power to grid and economic viability for battery investments for Norwegian prosumers. The result of the study is presented and described in chapter 4, which encompasses the PV-BESS simulation and the economic feasibility of batteries when implemented for PV energy self-consumption, peak shaving, and arbitrage trading. Chapter 5 discusses the results of the study, errors, and limitations. In chapter 6 the study is summarized, including suggestions for future work, and concluding remarks.

The work in the study is based on the author's project paper from autumn 2022 and is an extension of the stated.

2 Theory

2.1 Power regulation and the power market

Globally, countries have historically relied largely on traditional primary energy sources including coal, oil, and natural gas (Fouquet & Hippe, 2022), as presented in figure 1. These fossil fuels have been a major source of energy for the commercial, transportation, and household sectors. However, the reliance on these sources have strongly impacted global warming and has further led to environmental damage (Covert et al., 2016; Johnsson et al., 2019). In the recent years, countries in Europe have promoted the use of renewable energy sources, such as wind, solar, and hydropower. This gives the advantage of a more diversified energy mix, but more importantly it has been done to meet the Europe Green Deal's target of lowering net greenhouse gas emissions by at least 55% compared to 1990 levels, within 2030 (European Comission, 2021).

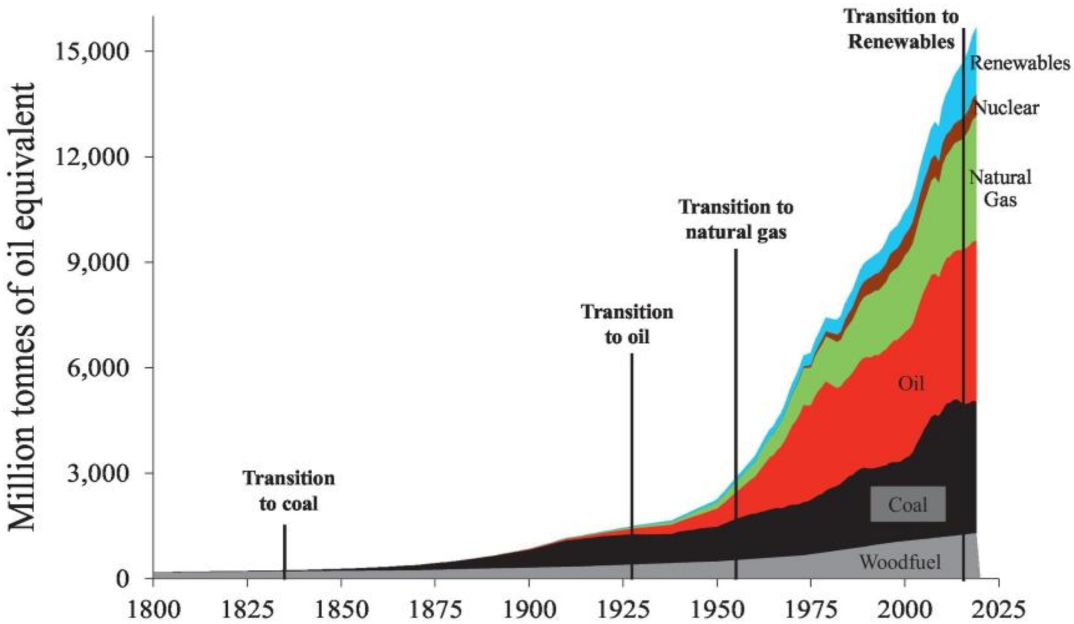

Figure 1 Historical primary energy consumption, worldwide (Fouquet & Hippe, 2022).

Currently, the transition to cleaner and more sustainable energy systems has advanced considerably in Europe. With governments investing in wind farms, solar energy, and hydropower plants, renewable energy has gained momentum, resulting in the EU increasing its total renewable energy electricity generation sources from 16% in 2004 to 39% in 2022 (European Concil, 2023). Norway, which is renowned for having a wealth of hydroelectric resources, has for many years had success using hydropower electricity generation. Still, in the most recent years, wind and solar energy has seen a distinct increase in Norway as well, with wind power production increased by 5.3 fold since 2016 (SSB, 2023), and PV power production increased by 2.7 fold since 2020, compared to the year 2022 (Elhub, 2023). This increase has in 2022 lead to wind being the second leading renewable energy source after hydro power with 10% of total energy production, while solar energy staying at only at 0,04 % of total energy production, as illustrated in figure 2.

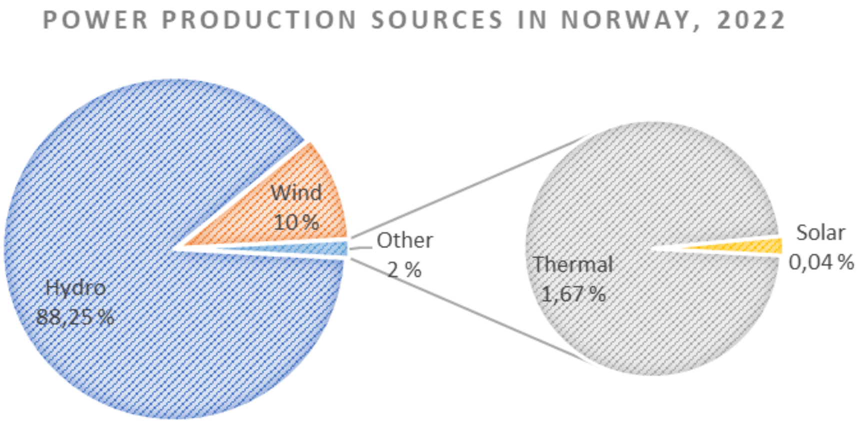

Figure 2 Power production statistics for the year 2022 in Norway

Looking ahead, the energy transition will demand a phase out of oil, gas, and coal industries, while the electrification of industries and the transport sector will substantially increase the demand for electricity for the whole European sector. The renewable energy transition paired with higher electricity demand, will lead to a considerable expansion of renewable energy installations and production through whole of Europe. According to the current trend, leading energy production sources will be wind and solar (IEA, 2022).

As the number of wind and solar energy installations increases, some challenges appear for the power industry. The natural fluctuations in these energy sources, opens a challenge for keeping a stable ratio between electricity generation and consumption (Eikeland et al., 2023). There are several ways of addressing this issue, including flexible power demand side management such as electricity rates and fees that fluctuates based on the supply/demand ratio, and flexible power supply (Eikeland et al., 2020). Flexible power supply includes energy sources such as natural gas and hydro power, but also other non-flexible renewable energy sources paired with energy storage. There are many types of energy storage available at the market today, including pumped hydro, thermal heat storage and battery energy storage systems (BESS). Further in chapter 2.3, we will look at the integration of batteries in the Norwegian energy system, its economics and how batteries could affect grid power reliability.

2.1.1 The power market

The European power market in the Nordic, Baltic and UK regions, is a deregulated market that promotes free competition without government intervention, where Nord Pool is the leading actor (Nord Pool, 2020). Nord Pool offers the ability to transport power from areas with surplus supply to areas with high demand, which results in an energy secure market and increased efficiency (Milligan et al., 2017). As the amount of renewable energy is increasing in this market, meteorological conditions and seasonal variations will have a significant impact on supply and demand, which in turn determines energy prices and may result in more price fluctuations. The Nordic areas in the Nord Pool market, each consist of their own distinctive price regions. Figure 3 illustrates the price regions in the Scandinavian sector, and as shown in the illustration, Norway consists of five different price regions, while Sweden and Denmark each on their own consist of four and two regions, respectively.

Figure 3 Nord Pool price regions in Scandinavia, with cross-border trade to neighbouring countries in Northern Europe (Bjørnebye et al., 2017)

In the most recent years, electricity prices in Norway and Europe have seen a substantial increase. As depicted in figure 4, the Norwegian electricity prices, has since the autumn 2021 gone from a daily average of below 1 NOK/kWh, to highly volatile prices above 1 NOK/kWh, in periods reaching prices as high as above 4 NOK/kWh. This is mainly due to higher energy prices for important energy resources in European countries such as coal and gas, which has increased in relation to the recent war in Ukraine. However other factors such as higher prices for CO2 quotas, periods of low water inflow to Norwegian reservoirs, general weather conditions and the return towards pre-pandemic levels for the economy has been important (European Central Bank, 2022; Løvås, 2022).

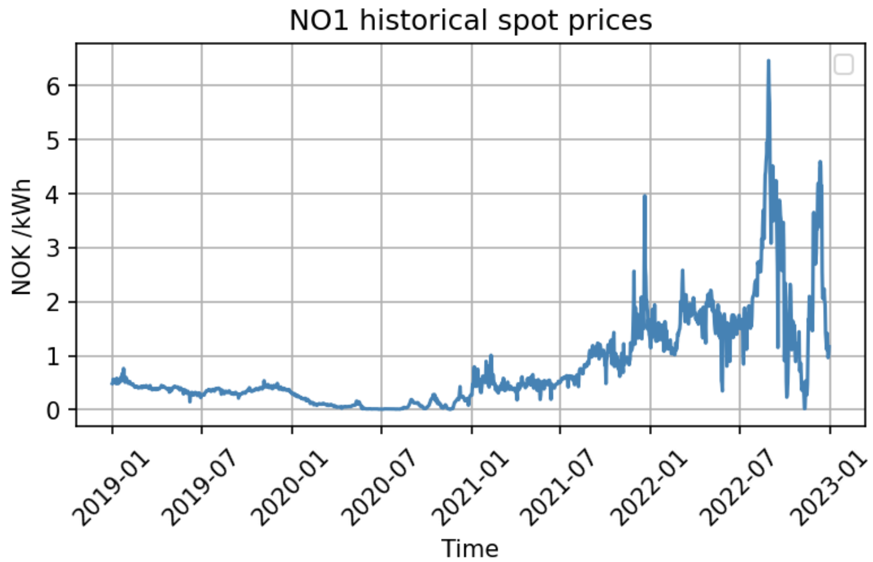

Figure 4 Daily average historical electricity spot prices in NO1 for the years 2019 to 2022, taxes not included.

2.1.1.1 Electricity cost

The various grid operators in Norway are free to determine the price structure for the different grid tariff components, within the maximum and minimum price ranges set by the Norwegian Energy Regulatory Authority (RME) (NVE, 2015). The components of the monthly electricity bill can be divided into the following:

$$Electricity\ bill\ =\ grid\ fee\ +\ electricity\ cost\ +\ taxes \quad (1)$$

The grid fee is divided into a capacity tariff and an energy tariff. The monthly capacity tariff is determined by the average of the three days per month with the highest hourly consumption peak, as shown in Table 1. Meanwhile, the price of the energy tariff is based on kWh consumption and varies depending on the time of day, as shown in table 2 (Norgesnett, 2023).

Table 1 Capacity tariff is based on the average of the three days per month with the highest hourly consumption peaks. The table illustrates the cost for private household customers at Norgesnett (Norgesnett, 2023).

kW	NOK / month
0-1,99	103,95
2-4,99	173,25
5-9,99	284,90
10-14,99	506,66
15-19,99	672,98
20-24,99	834,68
25-49,99	1 293,60
50-74,99	2 025,10
75-99,99	2 756,60
>100	4 467,54

Table 2 Energy tariff for private household customers at Norgesnett (Norgesnett, 2023).

Hour	NOK / kWh
06-22	0,4338
22-06	0,3568

Thus, the monthly grid fee can be represented as:

$$Grid\ fee = CT + \sum_{T}^{0}\left(\left(\sum_{6}^{0} EC + \sum_{24}^{22} EC\right) \cdot 0{,}3568 + \sum_{22}^{6} EC \cdot 0{,}4338\right) \qquad (2)$$

In equation (2), CT is the capacity tariff in NOK determined by monthly peak average, T is number of days in the given month, EC is electricity consumption in kWh and the sum of EC is depended on the specific hour of the day as shown in the equation for the hours zero to 24.

2.1.1.2 Feed-in tariff

In Norway, the feed-in tariff (FIT) for PV generated electricity, for residential electricity contracts at the largest power companies, is equal to the spot price without taxes, according to various power companies (Lyse, 2023), (Fjordkraft, 2023), (Tibber, 2023). This implies that the functioning FIT for PV generated electricity is at 80% of the spot price, when including 25% taxes. In Germany, however, in the last 20 years, the FIT has been at a fluctuating fixed price, giving the government the ability to modify the FIT and thus directly influence prosumers investments incentives in PV-systems and PV-BESS, if needed. As seen in figure 5, the FIT in Germany has from 2012 until 2020 gone from roughly half of gross domestic electricity price to less than 1/3 of gross domestic electricity price (Wirth, 2021). As of the new Renewable Energy Sources Act package in Germany, applicable from 30th of July 2022, the FIT in Germany is 8,6 Euro Cent for PV-systems below 10 kWp and 7,5 Euro Cent for PV-systems between 10 kWp and 40 kWp (Frahm, 2023). Moreover, the average electricity price in Germany for 2022 and for January – April 2023 has been averaging at 235,45 Euro Cents/kWh and 112,35 Euro Cents/kWh , respectively (Nord Pool, 2023). Therefore, due to such a high arbitrage between FIT and gross domestic electricity price, prosumers are encouraged to consider solutions for higher self-consumption of PV-generated power.

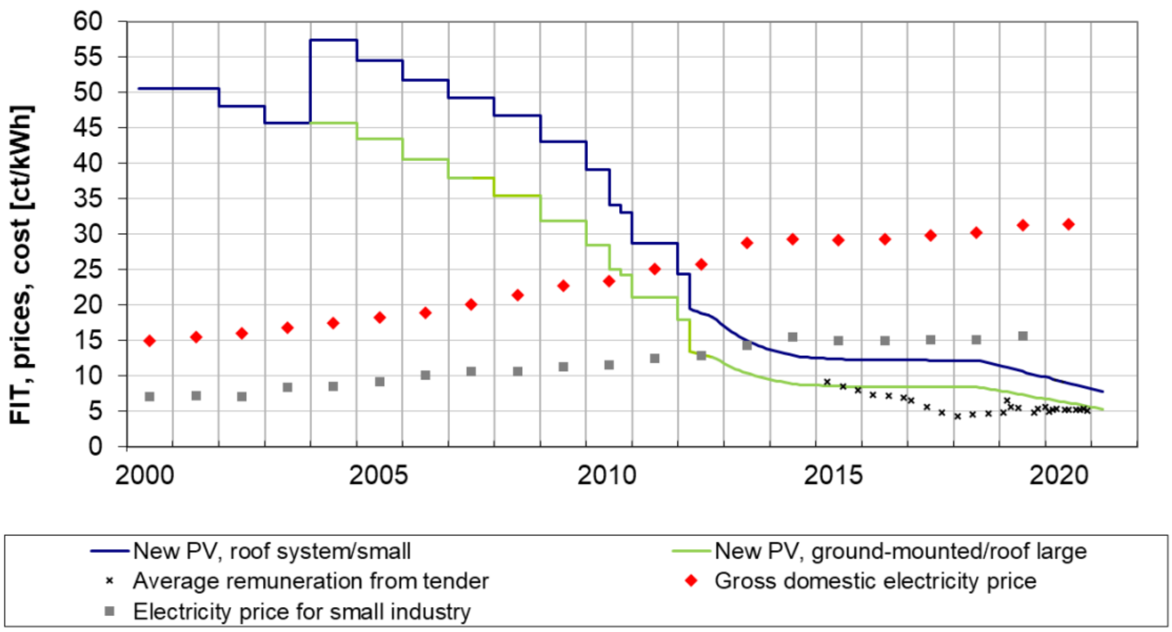

Figure 5 Feed-in tariff for PV power in Germany measured in Euro Cents as a function of commissioning date, average remuneration of the bidding rounds of the Federal Network Agency, electricity prices and average compensation for PV power (Wirth, 2021).

2.2 PV installations effect on distribution grid

Utilizing the most recent technology can be advantageous if you want to become a prosumer in the residential market. In that context, there has been an extensive advancement in solar technology and the harnessing of solar irradiance in the recent years. Solar energy has gained sizable attention due to its potential to reduce greenhouse gas emissions and thus combat climate change (IEA, 2022; Shahsavari & Akbari, 2018). Solar power production generates electricity from sunlight in either a direct or indirect way, by using a wide variety of technologies. During the last decades, there have been carried out extensive research in various technologies for both methods, to obtain the best efficiency possible in a cost-efficient way (Apostoleris et al., 2021; Apostoleris et al., 2015; Stefancich et al., 2012). Nevertheless, recently silicon-based PV, a direct electricity generating technology that converts sunlight into electricity for residential and industrial sectors, has dominated the industry. Therefore, silicon-based PV is the technology that will be applied for analysis in this research, which also has become the most affordable form of electricity production available at present time (Apostoleris et al., 2018, 2019). However, since the price estimates are dependent on large-scale production, it is somewhat difficult to utilize the same price predictions for small scale application, but they do show the price trend that can be considered and optimized for small-scale domestic installations.

The number of PV installations has substantially increased the recent years in Norway, due to factors such as higher electricity prices, government subsidies and reduced PV investment costs (Øvrebø, 2022). While the number of PV installations increases, so does the amount of solar energy injected into the grid, as depicted in figure 6. The energy injected into the grid, is the excess produced solar energy not consumed by the prosumer. Such PV installations is mainly installed in the low-voltage distribution network, as opposite of different types of energy sources like wind and hydro (Lillebo et al., 2020).

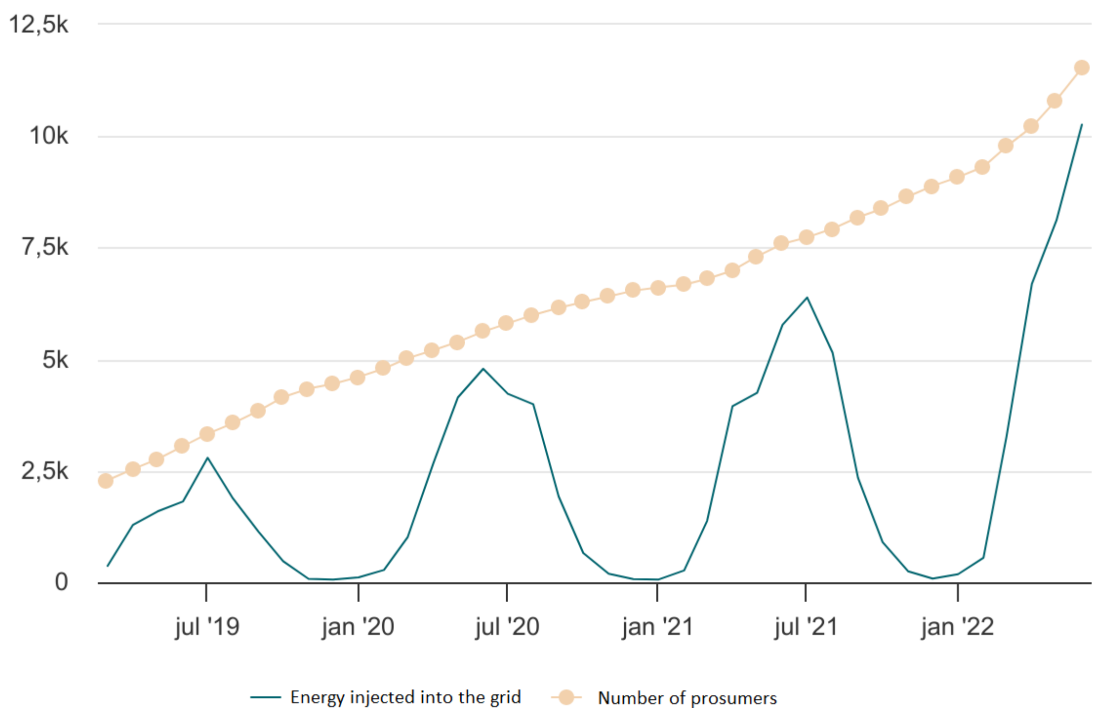

Figure 6 MWh of Solar energy injected into Norway's electrical grid from January 2019 to June 2022, and the total number of prosumers for the same time period (Øvrebø, 2022).

The grid system in Norway, is built such a way that the power from production, is transferred to high-voltage transmission grid before it gradually is transformed into lower voltage in the distribution-grid. At lower voltage, the cross section in cables and the capacity of components is reduced. Thus, the grid in Norway is dimensioned for the electricity to flow in only one direction (Birkeland et al., 2020). Further, reverse power flow in the distribution grid can create several operational difficulties in countries with substantial PV integration. Power injected into the grid from PV production will raise voltage, just as greater consumption causes a drop in voltage, at the connection point. The change in voltage is affected by quantity of power delivered into the grid and the grid's ability to withstand short circuits. The voltage problems experienced in countries with high PV penetration include protection device malfunctions, PV curtailment and overvoltage in LV distribution grids. Whereas one of the more prevalent types of problems in these countries is overvoltage (Sharma et al., 2023).

2.2.1 Maximum utilisation factor

In Norway, power companies apply a maximum utilisation factor (MUF) as a starting point during the planning process when developing LV distribution networks. The MUF is represented by the simultaneous sum of loads that is less than the total of all individual load peaks, as shown in figure 7, and can be represented by the following equation:

$$S_i = \frac{P_i(t = t_{s,max})}{P_{i,max}} \tag{3}$$

Where the MUF is represented by S_i, P_i is the individual load in kW, and $t_{s,max}$ is the point in time when the maximum load of the system is induced (Lindberg et al., 2022). Power companies size the low-voltage grid's network infrastructure with the insight that not every customer will use the entire installed capacity at once. This is partly due to Norway having a generally a stable energy consumption, as the majority of electricity use is due to electrical heating, thus historically, voltage limits is only violated in a few hours through the year when outdoor temperatures is especially low (Berg et al., 2023). Therefore, in Norway, the MUF typically ranges from 40% to 60%. This effectively means that power companies plan for a grid capacity of between 40% to 60% percent of the total size of all individual load's main fuses. However, for a PV energy prosumer the likelyhood of power injected to the grid beeing more than 60% of the main fuse at peak production is relatively high, depending on installed capacity, and thus the MUF for a prosumer would be close to 100% at peak production periods (RME, 2023). As the number of prosumers is drastically inrceasing in Norway, as illustrated in figure 6, it is fair to assume that voltage problems could be more prevalent in the future.

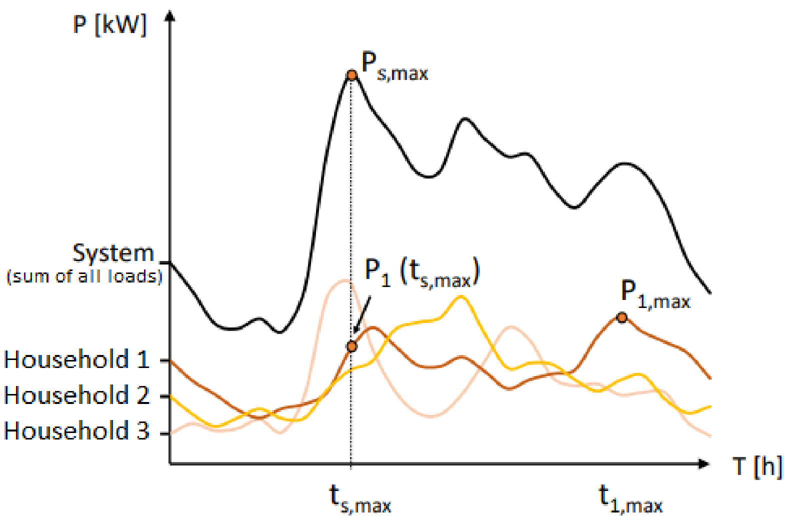

Figure 7 Illustration of maximum utilisation factor (MUF) Lindberg et al., 2022)

2.2.2 Research on voltage issues due to PV installations

One of the smaller grid opreators in Norway, Norgesnett, holds roughly 3% of the eletriciy customer market in Norway (NVE, 2022). Recently, Norgesnett has experienced overvoltage and PV curltailment issues from 5 PV installations, for their region, and they do expect PV-voltage issuges to occure more frequent in the future (Bjørheim, 2023).

Furthermore, RME has raised awareness that feeding power from PV systems into LV distribution networks, could result in excessive voltage on the grid that is beyond the voltage boundaries of what is required by law, which also has been supported by international research (Hashemi & Østergaard, 2017; Safayet et al., 2015). In 2020 a technical analysis was done on behalf of RME to determine how solar power installations affects low-voltage networks in Norway, and to examine what circumstances this required grid operators to reinvest in grid upgrades (Lillebo et al., 2020).

According to the analysis's findings, weak transmission grids in rural areas, were where overvoltage issues were most prevalent, a finding that's in line with recent research (Eikeland et al., 2021). For this scenario, the voltage variations were due to a high amount of energy injected into the grid. For the rural areas, two different representative grid network areas were tested, an area with relative low grid impedance and an area with high grid impedance where capacity was already fully utilized. The results showed that for rural areas with low impedance, a production limit of 70% of injected power to the grid, would solve the voltage variations. However, for areas with high impedance, when having a goal of not creating any grid overvoltage, the amount of power available for prosumers to inject into the grid was equivalent to zero (Lillebo et al., 2020).

The results also showed that issues also could occur in urban conditions, when a high number of prosumers injected power into the grid for a single network. However, the voltage variations in urban conditions were related to thermal network limits in cables and transformers. In the suburban areas, results indicated that PV installations of up to 10 kWp was possible, before overload happened in the transformers, and for even higher kWp installations, overload would also be experienced in transmission cables. For the townhouse areas 8 or 9 kWp installations was the limit, before voltage issues occurred, depending on roof azimuth, but this limit is typically close to the maximum installation capacity of townhouse roofs (Lillebo et al., 2020).

All things considered, there were few indications that PV installations in urban conditions was a pressing issue that needed to be resolved, partly due to voltage issues mostly being prevalent in aging, underperforming networks (RME, 2023).

2.2.3 The possible solutions to PV grid voltage issue suggested by RME

The cost of upgrading reasonably robust networks for consumers who want to install solar power plants behind their meters, has raised some concerns among grid companies. They do contend that it is not socially acceptable that a customer's solar energy investment, results in a need for network upgrades at the cost of all other customers. Still, in a letter to the Norwegian Oil and Energy Department dated 13th March 2023, RME states that grid companies are the responsible actor for paying the cost of necessary grid upgrades. Therefore, at current legislation, costly grid upgrades due to PV installations, would be an expense shared by all grid customers (RME, 2023).

In the same letter, RME suggest two different solutions to solve the issues regarding PV curtailment and overvoltage in Norway:

1. Continue at current legislation, with different operating measures:

    1a. Costly investments in grid network upgrades.

    1b. Introduce an injected power bottleneck for periods with high production, where the customer gets compensated for missed income.

2. Set a percentage limit of injected power relative to the main fuse for each prosumer. The suggested limit is a MUF of 50-60%.

2.3 Batteries in the distribution grid

2.3.1 Battery technology

Because of their high energy density, efficiency, and extended lifespan, lithium-ion batteries (Li-ion batteries) are leading the way in battery technology development. The cost of Li-ion batteries has dropped dramatically over the past ten years, from $1183 per kWh in 2010 to $156 per kWh in 2019, which corresponds to an 87% drop, mainly due to the increased demand for batteries in electrical vehicles (Birkeland et al., 2020). While the electrical vehicle battery industry was valued at USD 50.12 billion in 2021, the global BESS market was worth USD 4.04 billion for the same year (Polaris Market Research, 2022a, 2022b). Further, Li-ion batteries also rule the world of battery storage systems, accounting for 90% of all newly installed stationary storage capacity in 2017 (Birkeland et al., 2020). The remaining percent was made up of lead and sodium-sulphur batteries, which have the potential to be inexpensive and may one day be used in large-scale storage systems. There are numerous different Li-ion batteries in the market today, however lithium iron phosphate (LiFePEO4) is utilized for this study.

2.3.1.1 State of Charge

The State of Charge (SoC) indicates the level of charge of a battery compared to its capacity. State of charge is important to calculate the rate of charge, as at high SoC the battery will have a lower rate of charge, and at low SoC the battery will have a lower rate of discharge. The SOC can be calculated using the following equation:

$$\mathrm{SoC} = SOC_0 - \frac{1}{C_{25}[-\alpha \cdot (25 - T)]} \int_{t0}^{t1} \eta I dt \tag{4}$$

In equation (4), SOC_0 is the original SoC, C_{25} is the available capacity under 25 ℃, α is temperature coefficient, T is current temperature and η is the Coulomb efficiency (Zheng, 2011). For a LiFePO4 battery the rate of charge is severely lower at the nominal voltage of 3.2V, as shown in figure 8. This is when the battery is charged to about $\frac{3.2V}{3.65V} = 87\%$ of its maximum capacity. The rate of charge does level out and the charging efficiency does decline after the SoC reaches 87% of maximum capacity, as illustrated in figure 8.

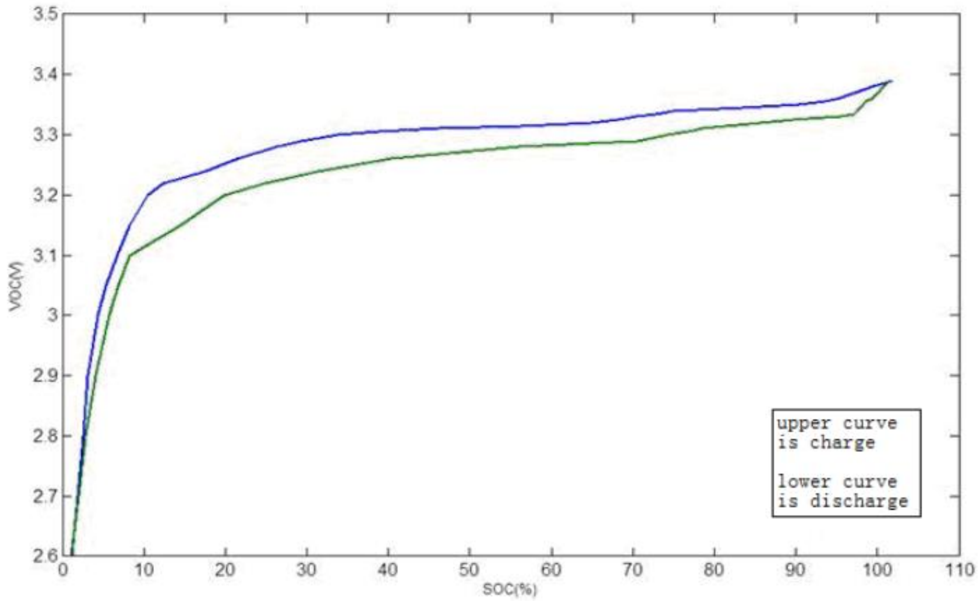

Figure 8 Relation between SoC and open circuit voltage (VOC) for a LiFePO4 battery, NV of 3.2V and final charge voltage of 3.65V. The relation effectively shows the rate of charge (Zheng, 2011)

2.3.2 Applications

Batteries have diverse applications and can be categorized into two groups: grid services and market objectives. Load balancing, energy supply security, and maintaining high-quality services like voltage control, phase compensation and frequency adjustments are essential components of the grid services (Birkeland et al., 2020). Energy supply security in Norway involves a continuous flow of electricity, encompassing energy security, power reliability, and operational reliability (Olje- og Energidepartementet, 2019). On the market side, BESS can provide a variety of services, and a few examples are capitalizing from electricity price arbitrage through trading, reducing grid fee through peak shaving, and storing electricity from PV generation for higher self-consumption. But at times, a grid service and a market objective might coexist for the same application. Peak shaving, for instance, could theoretically be a grid service with a market goal if it made financial sense. These uses demonstrate the adaptability and promise of batteries for grid control as well as market optimization.

2.3.2.1 Services for supplied quality

End consumers located in areas with weak power networks can experience voltage fluctuations, which may result in flickering and even damage to electrical components (Odin F. Eikeland et al., 2022). By using a battery, voltage control can be implemented by the input of active or reactive effect into the power grid. In the case of active effect, the battery provides active effect when the grid voltage is lower than desired and can charge the battery when voltage is higher than desired (Birkeland et al., 2020).

With a frequency requirement of 50 Hz, and with a maximum deviation of +/- 0.1 Hz, the power grid must constantly be kept in balance, adjusting the frequency when needed (Olje- og Energidepartementet, 2019). A battery can pull active power to restore balance if the grid's frequency rises. If the frequency is too low, on the other hand, the battery can provide the grid with active power. Because of the quick response time, a battery could be a good choice for frequency regulation (Odin Foldvik Eikeland et al., 2022). Additionally, batteries can assist in phase compensation, addressing voltage asymmetry issues caused by solar installations and electric vehicle chargers. By supplying current from the battery system to the phases experiencing the highest load, the capacity utilization of the network can be improved (Birkeland et al., 2020).

In grid regions with large power electronics, harmonic oscillations are a problem that can be resolved in part by batteries. Batteries aid in the improvement of voltage quality in these locations by helping to remove harmonic vibrations. Finally, batteries can improve a grid's short-circuit performance. Batteries can supply electricity to the grid during grid failures, allowing fuses to trip thus preventing component damage and limiting the scope of the network failure.

2.3.2.2 Marked objectives

For prosumers, BESS can be integrated with a PV-systems to increase self-consumption and by that potentially reduce electricity cost. PV-BESS can also serve as a grid service, by reducing power injected to grid, and at the same time reduce the power ejected from grid. Therefore, the effect of the total load reduction is twice of the utilized battery capacity, by integrating BESS with PV-systems. However, since peak injected power and peak ejected power occur at different times, the peak load reduction will not see the same effect as the sum of peak injected power and peak ejected power. Another potential market objective is the adoption of local flexibility markets, where end users can contribute with frequency support.

The use of batteries to reduce electricity cost, can be done by ejecting power form the grid to the battery in periods with lower electricity rates. The end user can also sell any extra energy back to the grid. However, it is advantageous for there to be a sizable difference between peak and bottom electricity rates, for price arbitrage utilization to be profitable. Lastly, batteries can be used for peak shaving for a reduced grid fee, in countries where the grid fee is based on peak consumption, as it is in Norway. This is done by initiating battery use in times when electricity consumption reaches a predefined level. Peak shaving and exploiting electricity price arbitrage with BESS can be utilized without an already pre-installed PV-system, however, this requires an additional installation of battery inverter which increases the investment cost.

2.3.3 Energy management strategy (EMS)

Energy management strategies for batteries in the combination of PV systems can be divided into two distinct operation modes. EMS_0 charges the battery when there is excess PV production and discharges when PV production is lower than energy load. Meanwhile, EMS_1 is a time-dependent energy management strategy, where the battery is not charged until the expected overvoltage period starts. A reduction in voltage levels of roughly 12% can be expected using the EMS_1 strategy, as illustrated in figure 9 (Sharma et al., 2023). However, the EMS_1 strategy may reduce the total utilized battery capacity, depending on factors such as battery size and PV production. If utilizing a EMS_1 strategy, it could be advantageous to use a EMS_0 strategy in winter months, when PV production is lower, and overvoltage is less likely to occur.

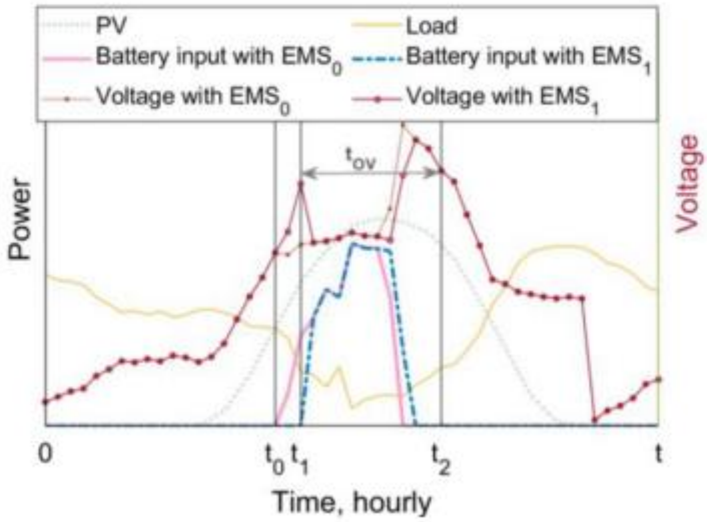

Figure 9 Comparison of EMS_0 and EMS_1 battery strategies and the corresponding voltage. (Sharma et al., 2023)

2.3.4 Related research regarding solutions to PV voltage issues using batteries

There does not appear to be much research on the subject. However, in an article published in 2023, research is done for Australian PV systems, looking into how smart inverters and battery storage could reduce financial loss from PV-curtailment due to overvoltage by power regulation (Sharma et al., 2023).

The study investigated three different scenarios, using smart inverters, batteries, and smart inverters and batteries combined, to reduce PV curtailment and overvoltage. In scenario 1, applicable for a PV system with a smart inverter and no battery, a smart inverter with Volt-Watt (V-P) and Volt-VAr (V-Q) modes is tested in a simulation. The V-P and V-Q modes on smart PV inverters allow for active and reactive power regulation depending on the voltage at the point of common coupling (PCC). When the voltage reaches the threshold, the V-P mode limits active power generation, which causes PV curtailment. When operating in the V-Q mode however, the inverter absorbs reactive power to lower high voltages, and supplies reactive power to increase low voltages, at the PCC.

In scenario 2 battery storage was simulated using a EMS_1 strategy. Finally in scenario 3, battery storage was likewise simulated using EMS_1 strategy, however at times when battery charging was restricted due to EMS_1 limitations, V-P and V-Q modes were activated on the smart-inverter.

The results in the study indicated that PV systems with smart inverts could reduce overvoltage by 90%, at the expense of PV curtailment increasing with 3%, in scenario 1. Further using a battery with EMS_1 strategy in scenario 2, resulted in a reduction of PV curtailment by 56% and overvoltage by 63%. Lastly, in scenario 3 when combining a smart inverter and battery storage, a 47% reduction in PV curtailment and 90% reduction in overvoltage instances was observed. Conclusively, the research showed that batteries and smart inverts could substantially reduce PV curtailment and overvoltage. The results indicated that batteries paired with smart meters was the most efficient solution, and moreover the battery only scenario was the second most efficient solution. Further it should be mentioned that the article emphasize the important fact that PV-batteries on the market today, mostly are not able to provide reactive power, indicating that PV and smart inverters together is a solution not applicable to the current battery market, but may become more relevant in the near future (Sharma et al., 2023).

3 Data and Methods

3.1 Data

3.1.1 Consumption data

The grid operator Norgesnett has submitted anonymized hourly consumption statistics from a small number of different households and businesses in the NO1 price area, for the year 2022. The data chosen for the research is from three different consumers, with a total yearly consumption of 23 000 kWh, 68 000 kWh and 79 000 kWh. The 23 000 kWh consumer is from a household, whereas the 68 000 kWh and 79 000 kWh consumer is from an unspecified sector. All three different consumers are used in the peak shaving approach. However, for the PV-BESS simulation and arbitrage trading approach, only one consumer at 23 000 kWh is used. This consumer is chosen due to a yearly consumption close to the average for a Norwegian household, which were at 20 230 kWh in 2012 (SSB, 2014).

3.1.2 PV production data

PV production data is from households in NO1 price region and is provided by the solar installation company Otovo. The projects chosen for the research are 9 roof installations with a roof angle between 26° and 41° from the horizontal, with installation size ranging from 6,48 kWp to 13,32 kWp. The chosen roof installations have an azimuth angle of 180° +/- 10°.

3.1.3 Electricity prices

Electricity prices is supplied by Nord Pool database and is hourly electricity prices from the NO1 market area in Norway. The data applied in the different models is from the year range 2019 to 2022.

3.1.4 Investment cost

The estimated costs for the PV hardware and installation are broken down into ranges of varying prices for every 4 kWh installed and are based on projects that have already been sold by Otovo in Norway in autumn 2022.

The battery hardware and investment cost are based on sold projects for Otovo in Germany in Q2 and Q3 in 2022, and are split into different cost for 5 kWh, 10 kWh and 15 kWh batteries. The battery hardware cost is split into cost for batteries and cost for smart meters, while the battery installation cost is split into installation cost for batteries and for smart meters. The cost for batteries above 15 kWh is based on estimates, as shown in table 3. The battery-ready inverter is assumed to have same costs as a similar PV-inverter without battery adaption.

Table 3 Battery prices (Otovo, personal communication, 01/10/2022)

kWp	NOK / kWp	Source
5	14 950	Otovo
10	9 734	Otovo
15	7 322	Otovo
15-18	6 750	Estimates
18-25	6 500	Estimates
25+	6 500	Estimates

3.1.3.4 Subsidies

There are currently no battery subsidies in Norway. For calculations in the thesis, using battery subsidies, a price model similar to the current subsidies for PV installations has been implemented. The subsidy model can be presented by the following equation:

$$S = 7500 + 2667 * k \tag{5}$$

In equation 5, the constant k represents battery capacity in kWh and S is the total subsidies that get subtracted from total investment cost of the BESS. In the model, the subsidy is capped at 47 500 NOK.

3.2 Battery specifications

3.2.1 Battery modules

LUNA2000-5/10/15-S0 batteries is used for data and computations in the analysis. The batteries are made of lithium iron phosphate (LiFePO4). The capacity of the battery ranges from 5 kWh to 15 kWh, depending on the number of battery modules. For a 5 kWh battery, the maximum output power is 2,5 kW, and for 10 kWh to 15 kWh batteries the maximum output power is 5 kW, as stated in table 5.

Table 4 Battery sizing and specifications (Huawei, 2022a)

	LUNA-5-S0	LUNA-10-S0	LUNA-15-S0
Capacity	5 kWh	10 kWh	15 kWh
Max input/output power	2,5 kW	5 kW	5 kW
NV (3-phase)	600 V	600 V	600 V

3.2.2 Inverter

For LUNA 2000 batteries, a compatible inverter is the SUN2000-3/4/5/6/8/10KTL-M1. For a 10 kWp inverter, the efficiency is of maximum 98,6% depending on the input voltage, as shown in figure 10. The inverter approaches the maximum efficiency of 98,6%, after the load exceeds 20% of the maximum load. This indicates that the production of energy from PV is further reduced at lower stages of power generation, such as in the morning, the evening, or on overcast days, due to loss of inverter efficiency.

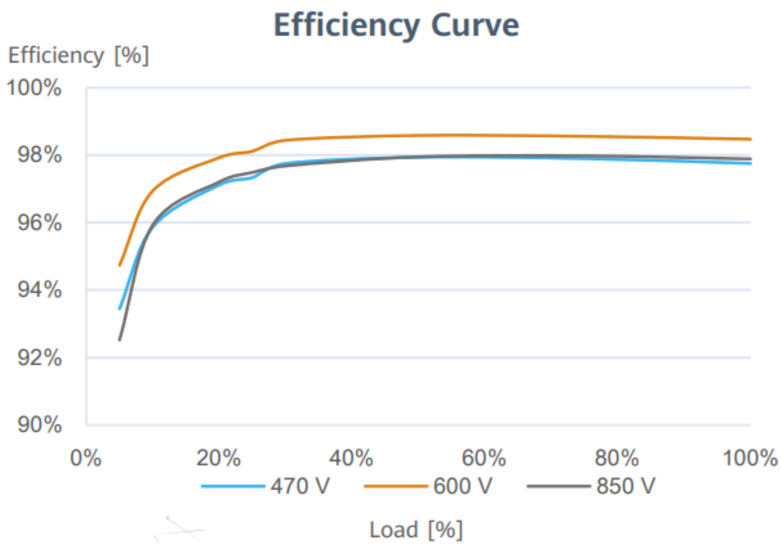

Figure 10 Efficiency Curve for SUN2000 10KTL-M1 Inverter (Smart Energy Controller, 2022).

In Norway, the most common grid type is three phase 230V systems, and a LiFePO4 battery has a nominal voltage of 600V for three phase systems as stated in table 5. Therefore, the orange curve in figure 10 is applicable efficiency curve, for the PV-BESS investigated.

3.2.3 PV-BESS

In the scenarios investigated in the paper, PV panels and battery is connected in a parallel connection, which means that the energy charged into the battery, is DC coming directly from the PV panels. Instead, if the battery were connected after the inverter, this would require another inverter to convert the power from AC to DC again, before entering the battery. As shown in figure 11, inside the inverter, battery and panels are connected in parallel (panels represented by PV1 and PV2, while battery is represented by BAT), before the electricity is converted into DC, and sent to consumption or to the grid. The PV connections can be cut off by the inverter, allowing the battery to receive grid-supplied power as well. If the PV were to be connected directly in parallel with the battery, without an inverter, charging the battery from the grid would be challenging, as the current would also go through the panels. In the calculations 100% dept of discharge (DoD), and constant rate of charge is assumed. Further a battery efficiency of 100% is assumed.

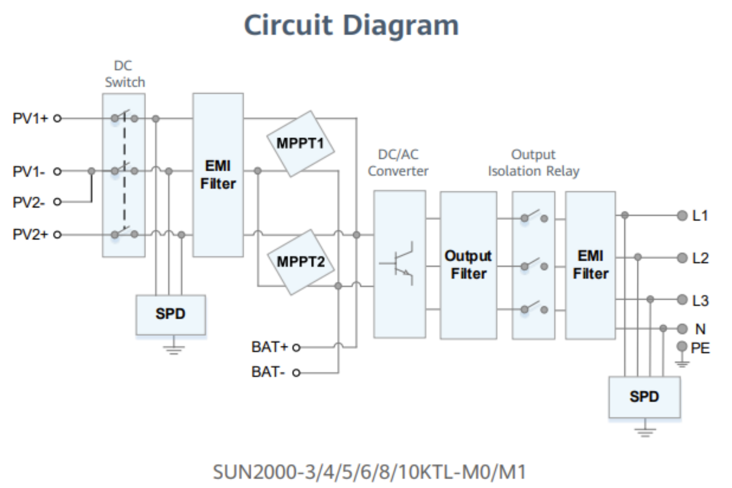

Figure 11 Circuit diagram for SUN2000 10KTL-M1 Inverter (Smart Energy Controller, 2022).

3.2.4 Lifetime

The Luna 2000 series of LiFePO4 batteries, has a life time of estimated 15 years reported by the manufacturer (Huawei, 2022b). Considering on daily recharge cycle, this corresponds to 5500 recharge cycles. In Norway however, the PV energy production is considerably lower in the winter due to low insolation. Therefore, you could expect most of the PV energy production, if not all, to be consumed by the household in the winter months. In such a scenario, if the BESS was solely utilized for self PV-power self-consumption, the battery may hypothetically last longer than the 15 years stated by the manufacturer. Additionally, the lifetime of PV panels are above 25 years, reaching 87% efficiency at year 25 according to the manufacturer.

3.3 Implemented models

3.3.1 The PV-BESS model

The PV-BESS model's inputs are consumption data and PV production data. The consumption data is from a consumer in the NO1 price region with a total yearly consumption of 23 000 kWh, while the PV production data is from four PV systems in the range of 6-10 kWp and for five PV systems in the range of 10-14 kWp from the NO1 price region. The model simulates a battery using a EMS_0 strategy. The model is based on hourly input data for one year, where simulated output data is energy injected to the grid and energy injected into the prosumer's household. The simulated battery is charged when PV energy production is higher than the households total energy consumption, until the battery is fully charged, if relevant. The amount that the battery is maximum charged per hour, depends on the maximum output power of the battery, as stated in table 5. If the battery is fully charged or if excess production is higher than maximum input power, the surplus PV energy production is injected to grid. As soon as hourly energy consumption is higher than hourly PV energy production, often towards the end of the day, the battery is discharged by the difference in kWh capped at the maximum output power. Ultimately, this implies that if peak energy production occurs after the battery is fully loaded, the total excess produced power at peak production is injected to the grid.

3.3.1.1 PV-BESS payback period

The PV-BESS model described above in chapter 3.3.1, is further utilized to calculate the payback period of a PV-BESS investment, where the final goal is to compare the payback period of several PV-BESS investments with two PV-system investments with distinct installed capacities, using electricity prices from various years. The implemented variables are PV production, battery capacity and hourly electricity prices.

3.3.2 Analysis of grid fee

To analyse the economic potential for a BESS utilizing the Norwegian grid fee model, a peak shaving model is applied. As outlined in chapter 2.1.2, the monthly grid fee is based on the three highest hourly consumption peaks for separate days each month. Considering this, a monthly grid fee with BESS. The input variables for the peak shaving model are battery capacity and hourly power consumption. The model utilizes the given battery capacity and divides the total battery capacity onto different hours through the day with highest consumption, so that the highest peaks are minimized to a flattened level, according to the battery capacity, for a single charge per day.

Additionally, the energy tariff, which has varying electricity rates throughout the day and night, is not considered in the computation of the analysis of grid fee.

3.3.3 Analysis of BESS power arbitrage

The power arbitrage models' variables are hourly power prices, battery capacity and the battery's corresponding input and output power. In the model, the simulated battery has one full cycle each day. Depending on the battery capacity and input power ratio, the battery is charged every 24 hours during the two or three cheapest electricity hours. The battery is then discharged at the two or three most expensive electricity hours, depending on the battery capacity and input power ratio, every 24 hours. Further, depending on the hourly electricity rate, the daily earnings is calculated. Finally, the payback period is calculated from the investment cost and the yearly earnings.

3.3.4 Payback period

Pay-back Period (PP) is used as the main economic formula to indicate profitability in the paper. PP measures how long it takes to recoup an investment's cost. Shorter pay-back periods indicate a more profitable investment. The formula is used to determine PP is:

$$Payback\ Period = \frac{Cost\ of\ Investment}{Average\ Annual\ Cash\ Flow} \tag{5}$$

Pay-back periods of less than six years can be considered a good investment, when comparing to the S&P 500. The S&P 500 has had a yearly average return of 11,88% since inception in 1957 (Investopedia, 2022), which corresponds to a PP of 6,1 years.

PP is a relatively simple economic formula, which is advantageous for making quick calculations. However, this does come with a few disadvantages. PP disregards the concept of the time value of money, inflation, and is unable to make accurate calculations for investments that have high variance in yearly cash flows. More suitable economic models for such calculations could be Net Present Value (NPV) and Levelized Cost of Electricity (LCOE).

4 Results

4.1 PV-BESS simulation plots

4.1.1 Simulation with 15 kWh battery

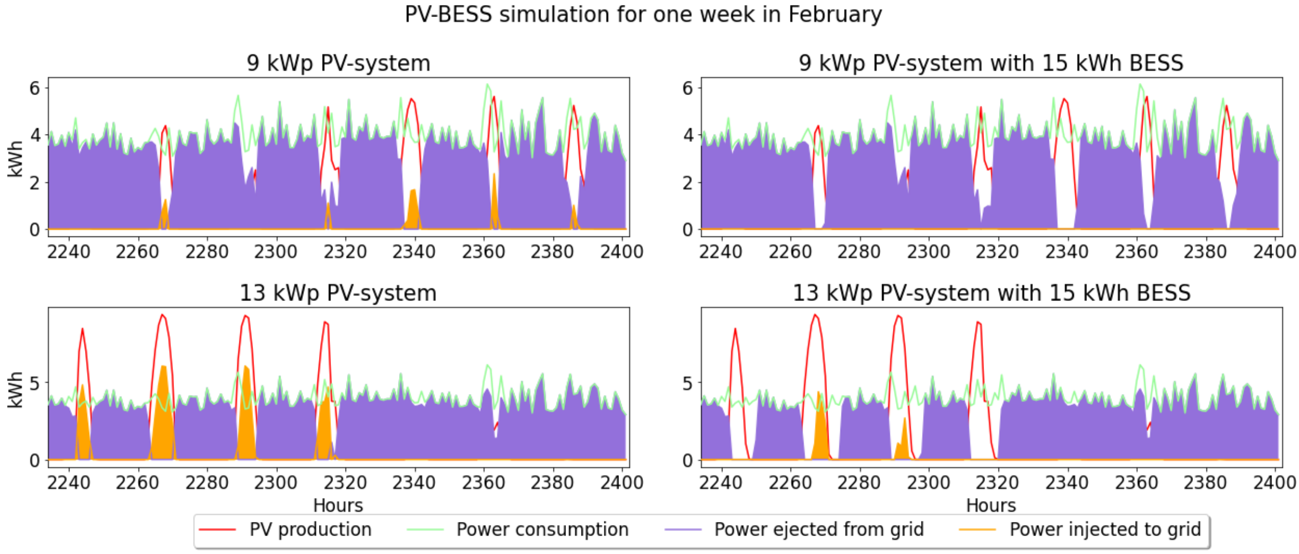

Figure 12 PV-BESS simulation plots for 9 kWp and 13 kWp PV-system, and 15 kWh BESS, for one week in February 2021. PV production is data from prosumers, and power consumption is data from consumers in the NO1 price region. Power ejected from grid and power injected to grid are simulated data.

Figure 12 compares a 9 kWp and a 13 kWp PV system with and without a 15 kWh BESS, based on data from the NO1 price region on consumer consumption and prosumer PV-production from February 2021. As seen in the plots, by integrating a battery to the PV-system, the power injected to grid is partly reduced, while the power ejected from grid is reduced with the same amount.

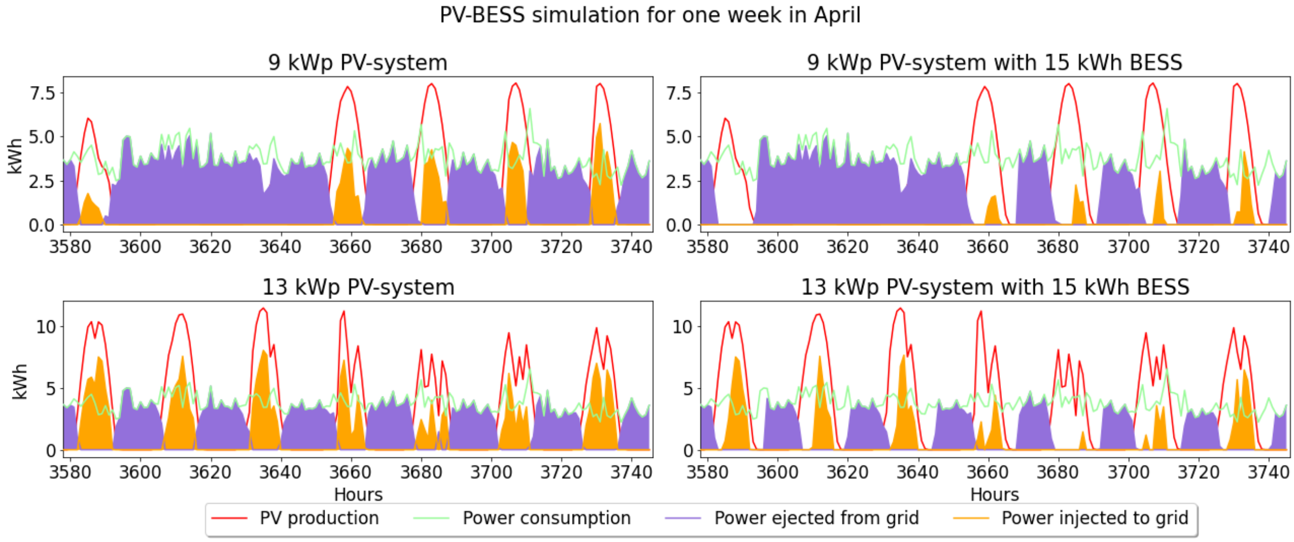

Figure 13 PV-BESS simulation plots for 9 kWp and 13 kWp PV-system, and 15 kWh BESS, for one week in April 2021. PV production is data from prosumers, and power consumption is data from consumers from the NO1 price region. Power ejected from grid and power injected to grid are simulated data.

A 9 kWp and a 13 kWp PV system with and without a 15 kWh BESS are compared in Figure 13. The input data is based on PV-production statistics from prosumers and consumer usage data from the NO1 price region. The findings illustrated in the plots indicates that for the 9 kWp PV systems, a sizable peak reduction is seen in the power ejected to grid using data from April 2021 for a 15 kWh battery. However, under the same circumstances for a 13 kWp PV system, the results suggests that the peak ejected power to grid sees a reduction, only on the days with reduced PV production, due to reasons as i.e., cloudy weather, for the most part.

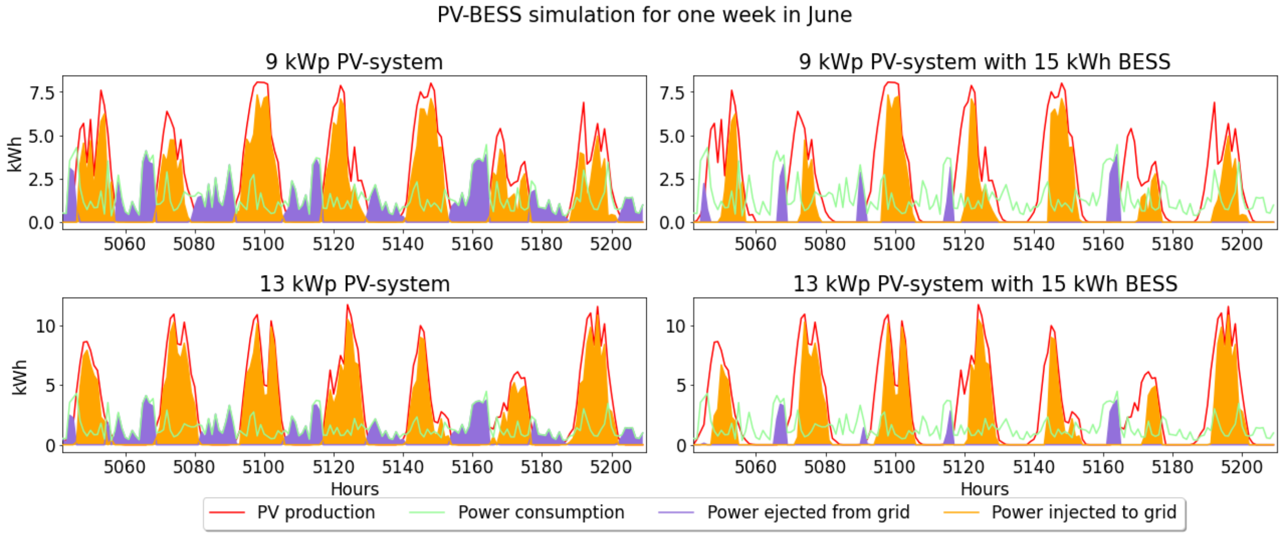

Figure 14 PV-BESS simulation plots for 9 kWp and 13 kWp PV-system, and 15 kWh BESS, for one week in June 2021. PV production is data from prosumers, and power consumption is data from consumers from the NO1 price region. Power ejected from grid and power injected to grid are simulated data.

Figure 14 compares 9 kWp and 13 kWp PV system with and without a 15 kWh BESS, using PV-production data and consumption data from prosumers and consumer in the NO1 price region. The chart shows that for the selected period in June 2021, PV production is substantially higher than the other periods tested in February and April. Further, the discoveries presented in the chart indicates that for the two different installed PV capacities that were tested, a 15 kWh battery would reduce peak injected power to the grid only for the days with noteworthy, reduced PV production.

4.2 PV-BESS payback period

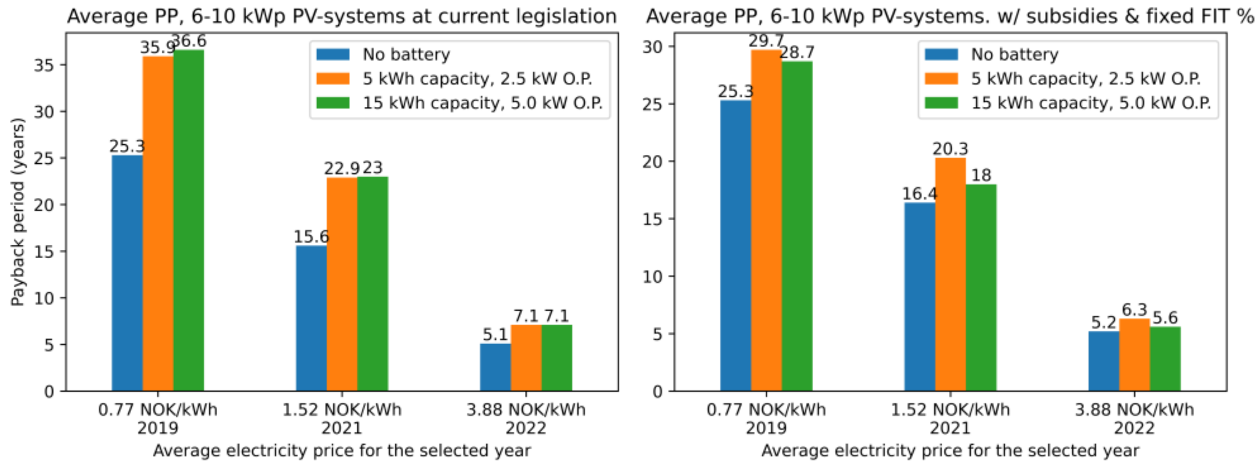

Figure 15 Average PP for four PV-systems between 6-10 kWp at current legislation to the left, in comparison with simulation of a scenario with battery subsidies and a fixed feed-in tariff at 30% of spot electricity rate.

Figure 15 illustrates the average payback period of 4 PV-systems from 6-10 kWp, with and without the integration of BESS, simulated with electricity rates from years 2019, 2021 and 2022, where the electricity rates is including taxes. A fixed FIT at 30% of spot power rates is implemented in the simulation to reduce the cost of sold energy to the grid, to investigate if this would reduce the payback period for PV-BESS. The results show that an introduction of a fixed FIT legislation, combined with battery subsidies of NOK 2667 per installed kWh with a maximum total subsidy of 47500 NOK and an initially investment subsidy of 7500 NOK, would lower the payback period for PV-BESS. However, an investment in PV-systems without BESS would still be the most beneficial for the prosumer from an economical perspective.

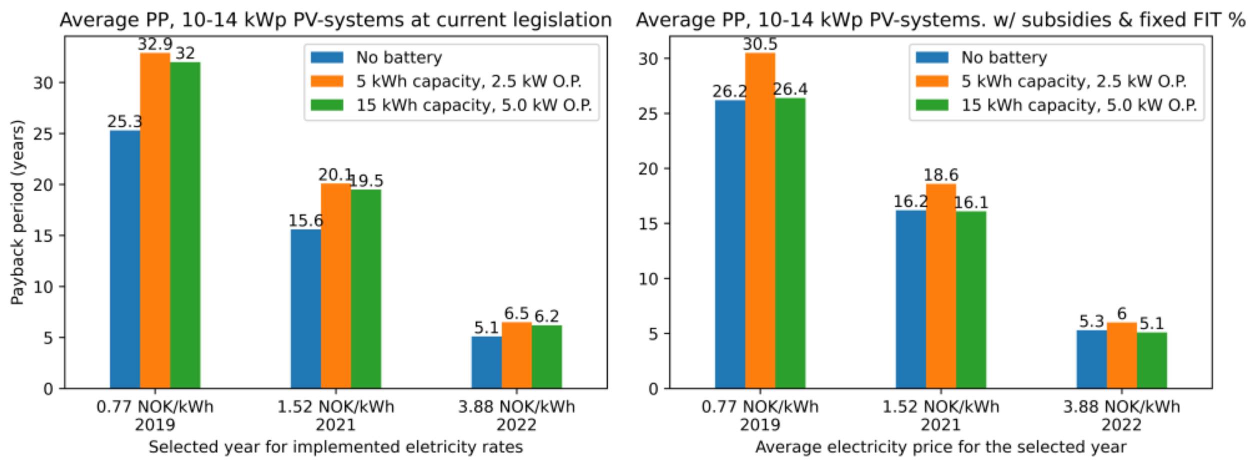

Figure 16 Average PP for four PV-systems between 10-14 kWp at current legislation to the left, in comparison with simulation of a scenario with battery subsidies and a fixed feed-in tariff at 30% of spot electricity rate.

Figure 16 displays the average payback period of 5 PV-systems from 10-14 kWp, with and without the integration of BESS, simulated with electricity rates, including taxes, from the selected years shown in the graph. According to the results, battery subsidies of up to 47 500 NOK in addition to a fixed FIT at 30% of spot power rates would shorten the payback period for PV-BESS investments, making them more profitable than PV-only systems, for the years of 2021 and 2022 using a 15 kWh battery. For a 5 kWh battery the payback period was also reduced, with a change in legislation, but PV-BESS was not financially favourable over a PV-system with no BESS. For the lower electricity rates tested in 2019, namely at 0.77 NOK/kWh on yearly average, none of the PV-BESS would be financially favourable over PV-systems with no BESS, but the results suggest a significant reduction in the payback period for a 15 kWh BESS, when implementing battery subsidies and a fixed FIT.

4.3 Utilizing BESS for peak shaving and reduced grid fee

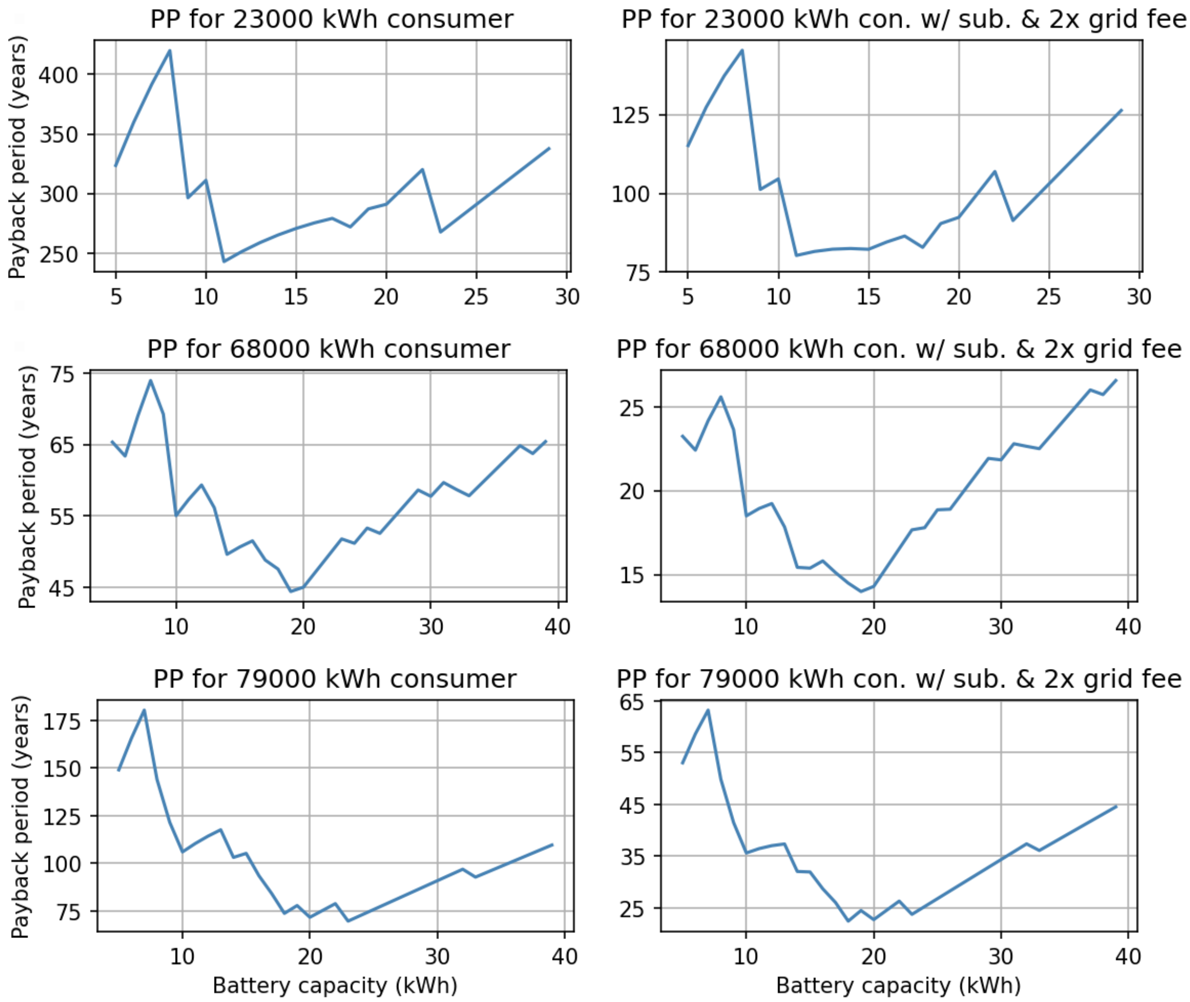

Figure 17 Payback period for a peak shaving model utilizing the grid fee capacity tariff. The plot shows the payback period for different battery capacities. The left column shows payback period at current legislation, while the column on the right side shows payback period with BESS subsidies and a double grid fee.

The payback period for a battery charging/discharging approach that aims to lower the monthly grid fee, is shown in Figure 17. The model is tested for three different consumers with a yearly consumption of 23000 kWh, 68000 kWh and 79000 kWh. The left column depicts the payback period at current legislation, and the right column depicts the payback period with BESS subsidies at 2667 NOK per installed kWh with a maximum total subsidy of 47500 NOK and an initially investment subsidy of 7500 NOK. The findings show it is possible to reduce the grid fee capacity tariff using a specific charging/discharging battery model. Further, the results shows that such utilization of battery is not financially advisable at current legislation. However, the results indicates that for larger power consumers, the payback period is substantially lower than for smaller power consumers. The findings further show that for the larger power consumers, battery subsidies and a double grid fee will give a 3-fold reduction in the payback period, resulting in a payback period of 14 years and 24 years for the 68 000 kWh and 79 000 kWh consumer, respectively.

4.4 Utilizing BESS for price arbitrage

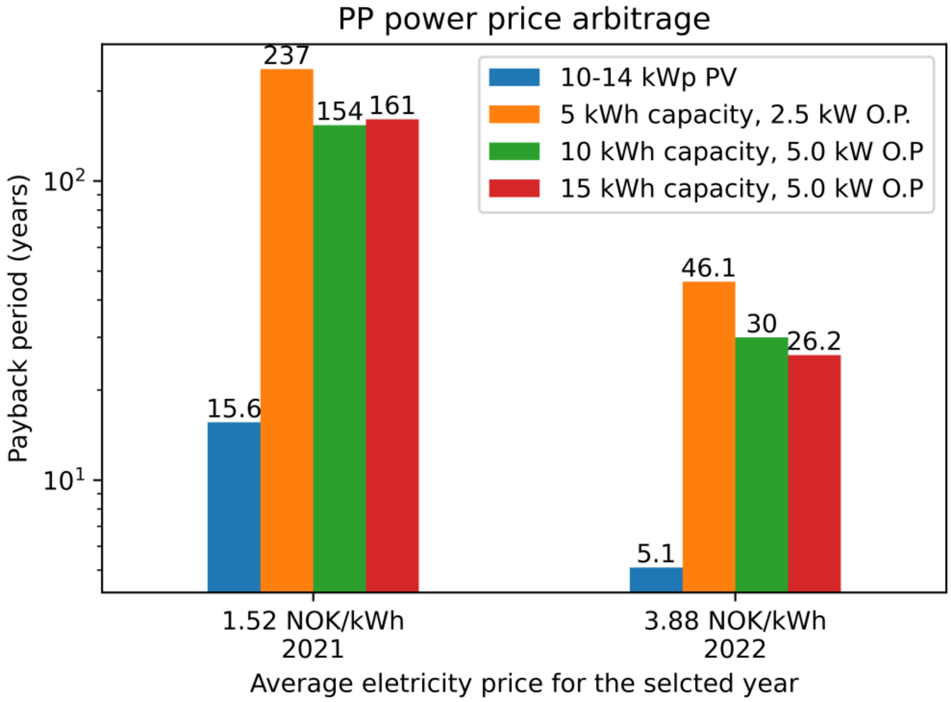

Figure 18 Payback period for BESS when utilizing power price arbitrage. For a 5 kWh installed battery capacity, the maximum output power is 2.5 kW while for a 10 kWh and 15 kWh installed battery capacity, the maximum output power is 5.0 kW. The average payback period for 10-14 kWp PV-systems is plotted for comparison, marked in blue.

Figure 18 depicts the payback period for a battery charge/discharge model, that efforts to utilizing the electricity price arbitrage. As the chart indicates, even at high electricity rates averaging at 3.88 NOK/kWh from 2022, arbitrage electricity price trading is not financially advisable, at current battery prices.

5 Discussion

5.1 PV-BESS simulation

As stated in theory, batteries could be a viable solution to reduce the voltage load issues that occurs in grids when a high number of PV installations is integrated into a LV distribution network. The graph for PV-BESS plots demonstrates that~~, in fact,~~ the integration of BESS decreased the peak ejected power to grid for both tested PV systems, and thereby a reduction in MUF was induced. However, there were considerable differences depending on seasonal variations. For February plots, the peak injected power to grid was reduced for the entire week, for both PV-installations. For April plots, the peak injected power to grid was reduced for the entire week for the 9 kWp system. However, for the 13 kWp system, only the days with reduced PV production had a reduction in peak injected power to grid. For June plots, only ~~those~~ days with reduced PV production, a BESS with 15 kWh capacity would reduce the peak power injected to grid for both PV installations that were tested.

The findings indicates that it would be beneficial to integrate BESS with PV-systems, supported by national and international research as outlined in chapter 2 (Berg et al., 2023; Sharma et al., 2023). However, the findings suggest that a BESS will not reduce peak injected power to grid in periods with high solar insolation, resulting in the battery being fully charged before peak PV production. A possible solution to this, could be a battery charging in EMS_1 mode. This charging strategy could potentially be less financially justified, but this is beyond the scope of the study and has therefore not been examined further.

5.2 Economic analysis

As presented in chapter 4.2-4.4; batteries investments in the residential Norwegian sector with current legislation, is hard to justify financially. The results demonstrates that only at high electricity prices, such as prices from 2022 (3.88 NOK/kWh), the battery investment case improves a level that can be justified financially. This is demonstrated with payback periods of 6.2 to 7.1 years for batteries at 5 kWh and 15 kWh capacity for this time period (fig. 15 and 16) for the PV-BESS simulation. Further, for all other years in the PV-BESS simulation, and for all years in both the peak shaving and arbitrage trading model, results indicated payback periods beyond 15 years. However, when introducing battery subsides of 2666 NOK/kWh capped at 47 500 NOK with an initial investment subsidy of 7500 NOK and a fixed FIT of

30% in the PV-BESS model, the results show a significant reduction in the average PV-BESS payback period. However only for the largest PV installations (10-14 kWp) the PV-BESS investment is more favourable than PV-only investments. Still, with these legislation changes, the reduction in payback period for both 6-10 kWp and 10-14 kWp PV installations, is sufficient to encourage investments in batteries from a financial perspective.

5.3 Is there a need for change in BESS legislation in Norway, and what legislation changes can be done?

With the currently PV penetration at only 0,041% of produced electricity in Norway in 2022, the occurrence of voltage problems from PV installations is at low levels, and thus reasonably maintainable. However, the number of PV prosumers in Norway has recently seen a four-fold increase in a period of three years, from 2019 to 2022, as shown in figure 6. Looking ahead, PV penetration is likely to continue its increase as PV will become cheaper, while electricity prices may continue to stay at high levels as the electricity consumption increases due to the electrification of fossil fuel consuming sectors. Further, there has recently been reports of an increase in PV curtailment and overvoltage in relation to PV systems in Norwegian conditions (Bjørheim, 2023), which claims is supported by a recent letter from RME (RME, 2023) and international research (Hashemi & Østergaard, 2017; Safayet et al., 2015).

According to the findings presented in chapter 4.1, batteries can reduce PV overvoltage in LV-distribution networks with high PV penetration in Norway, which is consistent with recent research conducted in Australian conditions (Sharma et al., 2023). This suggest that authorities in Norway stand between a few different options in the coming years, as the number of PV overvoltage occurrences is expected to increase further. Two of them, which RME proposed in March 2023, involve setting a limit of the allowable amount of excess PV power injected to grid by 50-60% of prosumers main fuse, or upgrading the distribution grid in areas with the highest PV penetration rates. Meanwhile, the third option, as suggested in this study, is a change in legislation to encourage battery investments. A capped limit of PV the amount of energy injected to grid, as suggested by RME, will lead to substantial amount of power losses, which is unfavourable given the wasted electricity and therefore could potentially have a detrimental effect on both the economy and the environment. Ultimately, Norwegian authorities stand between the choice of upgrading the grid or incentivising battery investment.

As the study suggest, the use of batteries is a viable option from a technical point of view, and a comparative evaluation against the alternative of grid reinforcement could be valuable. Which of these solutions that would be most advantageous to accommodate the anticipated rise in PV prosumers requires a political and socioeconomic analysis, which is beyond the scope of this study.

The impact of reinforcing the grid is mostly limited to periods of peak PV production, in the middle of the day during the months with highest solar insolation. Therefore, the cost of upgrading the grid may not be justified from a socioeconomic point of view. It's also important to note that the current grid infrastructure has not been created with prosumers in mind, which means that optimal integration may require extensive, and thus costly upgrades. Batteries on the other hand, additionally to the potential of reducing PV induced overvoltage, serves several other applications, as presented in chapter 2.3.2, that could improve their socioeconomic value further. This includes voltage control by supplying active and reactive power, energy supply and frequency adjustments. However, battery implementation would require legislation changes, which includes a fixed FIT and the cost of battery subsidies, as suggested in this study. Further incentivising battery investments in the combination of a national focus on battery manufacture, could create an industry with a local market, creating potential positive ripple impacts, which could further justify battery subsidies.

Moreover, as battery prices is projected to drop further in the coming years, and as PV production currently is as low as 0.041% of total yearly energy production, battery subsidies may not be necessary if the prevalence of PV induced overvoltage does not substantially increase until several more years has passed, simultaneously as battery prices continue to drop further. Still, as reports state that the occurrence of PV induced overvoltage is increasing (Bjørheim, 2023; RME, 2023), where prosumers reportedly experience PV curtailment as a result of overvoltage, the choice of strategy may need to be decided already within a short timeframe. Finally, a hybrid approach might be the most feasible solution, which includes both grid upgrades and a change in battery investment legislations. As parts of the low-voltage distribution grid is already due for upgrades, such a solution would combine the advantages presented for battery implementation and a more secure distribution grid, strongly reducing the chances of PV induced overvoltage.

5.4 Uncertainty and limitations

Payback periods is highly influenced by battery investment cost. Battery investment cost above 15 kWh capacity is bases on estimates, and lower battery capacities is based on 6-10 months old projects installed in Germany. Factors such as prices differences in Germany and Norway, hardware and installation price development and individual variations in investment cost based on the specific project creates a strong uncertainty in BESS investment cost, which has not been considered. Additionally, battery degradation and PV degradation has not been considered in the study, which would come into disfavour from a financial point of view.

Additionally, the study is focusing on south mounted panels, with an azimuth between 170°-190°. For east, west and east-west mounted panels, there could be different results, for both the technical and financial analysis. Further, the PV installations utilized in the study have an installation size between 6-14 kWp, and larger PV installations could produce different results.

Further, the life cycle of a battery is not being considered in this study. Factors such as climate gas emissions, the use of rare materials and resources, and the labour safety for workers in the production country for the batteries have not been taken into account. Before deciding whether batteries should be implemented as a solution to reduce PV induced overvoltage or not, the total cost of batteries should be evaluated, including the factors mentioned above.

Further limitations to the study include the assumptions of a 100% DoD range, a constant rate of charge and 100% battery efficiency.

6 Conclusion

6.1 Summary

In this study, I have attempted to provide an answer to the question of if batteries can provide the necessary assistance needed to reduce PV induced overvoltage in Norwegian low-voltage grids, and what legislation changes that should be made by the authorities to endorse such battery investments. The study is a response to the recent reported increase in PV induced overvoltage in Norwegian low voltage distribution grids, due to reverse power flow from excess PV generated power. By applying a PV-battery energy storage system simulation model, the results indicated that batteries could reduce the peak injected power to the grid from PV power production, for Norwegian conditions. Three different battery application models are applied to examine the financial viability of battery investments. This includes PV-battery storage for self-consumption, peak shaving for reduced grid fee and electricity price arbitrage trading. Further results indicated that at current legislation, battery storage is not financially advisable in the Norwegian sector, except for when considering relatively high electricity prices from the year 2022 at 3.88 NOK/kWh. Thus, a change in legislation is proposed, which includes battery subsidies at 2666 NOK/kWh, with a max limit of 47500 NOK, and a fixed feed-in tariff of 30%. According to the findings, if a PV system is already installed, PV systems with batteries could become a more advantageous investment than PV-only systems considering the suggested change in legislations.

6.2 Future work

Expanding the study to include an investigation of energy management strategies could be an important next step. The results given after deciding which energy management strategy would give the best results for a reduction of PV power injected to grid, could be utilized to estimate the total potential for PV induced overvoltage reduction and PV curtailment reduction. Further, an investigation that compares the total potential of cost savings from battery implementations for Norwegian prosumers including the likely needed cost of battery subsidies, with the total cost of upgrading the grid, would give valuable information for the sector.

Additionally, a battery optimization model who integrates arbitrage trading, capacity tariff peak shaving and PV self-consumption would give valuable results. Especially considering the winter months in Norway when batteries are not fully utilized due to low PV power production, other battery applications could further lower the payback period for battery investments.

6.3 Concluding remarks

This study showed that battery storage could help solve the overvoltage issues that recently has become more prevalent in Norway, in response to the recent increase in PV installations. The findings further show that battery investments in this sector cannot be financially justified with the current Norwegian legislations. Thus, a change in legislation including battery subsidies at a fixed reduction in the feed-in tariff for PV installations is suggested. The results suggest that this change in legislation would make PV-battery energy storage systems a favourable investment, over PV investments without battery, in most of the scenarios that were investigated.

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