Value Comparison of EV and House Batteries at End-user Level under Different Grid Tariffs

Sigurd Bjarghov, Magnus Korpås, Salman Zaferanlouei
Department of Electric Power Engineering
Norwegian University of Science and Technology
Trondheim, Norway
Email: {sigurd.bjarghov, magnus.korpas, salman.zaf}@ntnu.no

Abstract

With the introduction of real-time price signals through smart meters, the electric vehicle (EV) battery can become a powerful tool. Its relatively high charging power and capacity makes it attractive for both cost minimization and self-balancing. Focusing in particular on comparing EV and home batteries, the objective of this paper is to investigate the economic potential of utilizing PV and batteries at an end-user level. In simulations based on data from a single residence in Trondheim, Norway, a dynamic programming algorithm is used to minimize the electricity costs under four different grid tariff structures. This method guarantees to find the global optimum. Leveraging the variations in spot price and hourly grid tariff costs, the simulation results indicate reduced annual electricity cost. When utilizing an EV battery together with rooftop PV, the cost is reduced by 12.0 - 19.2 %, depending on the grid tariff structure, whereas a home battery installation together with PV reduces the cost by 8.9 - 14.4 %.

Nomenclature

η_{ch}	Charging efficiency of battery.
η_{dis}	Discharging efficiency of battery.
C_{el}	Total customer cost of electricity [€].
C_{low}	Energy price above P_{sub} during low load hours [€ct/kWh].
C_{peak}	(€ct/kWh) bought above P_{sub} kW during peak load hours [kWh].
$E_{bat,min}$, $E_{bat,max}$	Minimum and maximum energy capacity of battery [kWh].

E_{bat}	Energy capacity of battery [kWh].
E_{ddp}	Energy spent by EV for daily driving purpose [kWh].
F	Monthly fixed cost [€].
$P_{bat,max}, P_{bat,min}$	Maximum and minimum charge rate of battery [kW].
P_{bat}	Charging/discharging power of battery [kW].
P_{grid}	Power supplied by or delivered to the grid [kWh/h].
P_{load}	Residence load demand [kWh/h].
P_{PV}	Photovoltaic power production [kWh/h].
P_{sub}	Subscribed power [kW].
SOC	Battery state of charge [%].
SOC_{arr}	State of charge at EV arrival [%].
SOC_{dep}	State of charge at EV departure [%].
SOC_{max}, SOC_{min}	Maximum and minimum battery state of charge [%].
t	Time index [h].
$T, \Delta t$	Total number of discrete time intervals and time step.
$y(t)$, $z(t)$	Energy consumed above P_{sub} kW during low load hours and peak load hours [kWh].

1 Introduction

In June 2017, the climate and environment department of the Norwegian government published a climate law which states that Norwegian annual greenhouse gas emissions are to be reduced by 40 % of 1990 level by 2030 [1]. Road transport is the third largest emission sector in Norway, and is thus a focal point for the government's plan for emission reduction. The result has been a strong political will to increase EV adoption in Norway. Through tax exemption and other economical advantages, Norway has developed the largest EV share per habitant in the world, which complements the 96 % hydro power share in the electricity mix [2] [3]. This political will has resulted in more than 150 000 EVs on Norwegian roads as of May 2017, and do now represent 35 % of nationwide new car sales [4].

With the ongoing rollout of smart meters in Norway, new pricing structures for grid utility tariffs can be utilized to promote efficient use of the grid. Use of renewable energy is vital to this efficiency increase strategy, but also comes with new challenges. Meanwhile, PV and battery prices are plummeting [2], [5], which could be a driver for higher penetration of distributed energy storage. A price reduction of this magnitude raises the question once again whether rooftop PV together with battery on an end-user level can be economically profitable for the customer.

This paper investigates the interaction between PV and battery on end-user level, and compares the use of a dedicated home battery and an EV battery. The goal is to highlight to which extent the powerful EV batteries together with PV can be economically profitable. A dynamic programming optimization algorithm has been developed to calculate annual electricity costs for a residence in Trondheim. In addition, the simulations are performed with different grid tariff structures in order to determine which structures are suitable for more efficient use of the distribution grid. The economic operation of home battery with PV is studied in detail in [6–8]. This paper extends the study in [6] and compares an EV battery with a home battery, in order to show the economic potential of both installations.

Note that although the two batteries that are being compared differ greatly in size and performance, the basic idea of this paper is to see to which extent an EV battery solution can compete with a dedicated home battery solution. Thus, two batteries that exist on the market today have been chosen in this paper. Note that all prices were originally calculated in NOK, and have been converted to euro with an exchange rate of 9.5838 NOK per euro which was the exchange rate during the writing of this paper.

The paper is structured as follows. Section 2 describes the system model, whereas section 3 describes the dynamic programming optimization algorithm along with the simulated grid tariffs. Section 4 shows the input data used in the model, and results and discussions are presented in section 5. Conclusion and future work is then presented in section 6.

2 End-user system model

2.1 Residence model

The power balance is calculated as seen in Fig. 1 and Eq. 1, and is considered loss free. The system model is deterministic, meaning that the load and PV production is known at all times. Therefore, P_{grid} is a function of P_{bat}.

$$P_{grid} = P_{load} + P_{bat} - P_{PV} \tag{1}$$

The grid is stiff, meaning that it has the balancing function, supplying and receiving power as a result of the balance equation. PV is modelled as in [9] based on [10].

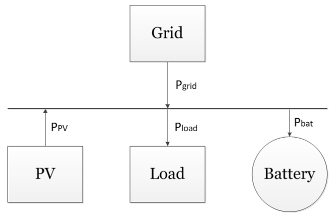

Figure 1: Model of the residence. Positive power flow direction is indicated by arrows.

3 Dynamic Programming Model

3.1 Optimal battery operation

In order to assess the economic potential of EV battery and PV utilization, an optimization algorithm is used. By utilizing dynamic programming, the algorithm calculates the price for every single charge and discharge possibility, when the spot price, grid tariff, load and PV production is known.

The algorithm is generic, and can therefore be utilized for either a house battery or an EV battery. In the house battery setup, the optimization is run for $T = 8760$ periods. For the EV battery setup, the total time interval per optimization is $T = 16$ discrete time steps where Δt is one hour, due to the resolution of the load, PV and pricing data. After every 16 hour optimization, normal load balance is assumed. For weekends, the optimization is being run from Friday at 4 pm to Monday at 8 am. EV availability is shown in Tab. 1.

Table 1: EV availability

Availability	**Weekdays**	**Weekend**
Available	4 pm - 8 am	Always
Unavailable	8 am - 4 pm	Never

The function f is a description of the optimization target. The function is given by Eq. 2. $f(P_{bat})$ is then minimized

$$f(P_{bat}) = C_{el} P_{grid} \tag{2}$$

where P_{grid} is defined in Eq. 1.

Therefrom, minimize $f(P_{bat})$ as in Eq. 3.

$$
\begin{aligned}
SOC(t+1) &\leq SOC_{max} \\
SOC(t+1) &\geq SOC_{min} \\
P_{bat}(t) &\leq P_{bat,max} \\
P_{bat}(t) &\geq -P_{bat,max} \\
E_{bat}(t+1) &= E_{bat}(t) + \eta_{bat} P_{bat}(t)\Delta t \\
SOC(t+1) &= \frac{E_{bat(t+1)}}{E_{bat,max}}
\end{aligned} \tag{3}
$$

Note that

$$\eta_{bat} = \eta_{ch}, P_{bat}(t) \geq 0$$

$$\eta_{bat} = \eta_{dis}, P_{bat}(t) < 0$$

For $P_{grid} > 0$, both grid tariffs and energy price will be paid, both of which has taxes. For $P_{grid} < 0$, only the spot price will be received. As equation 1 shows, P_{grid} consists of three variables, of which two are known; P_{load} and P_{PV}. Thus, P_{bat} is decided for every hour to minimize the cost from 1 to T. The result are grids of nodes, where different possible SOCs for every time step in T are calculated. The goal is to find the path of SOCs that result in the lowest possible price for the given input. Fig. 2 illustrates how the dynamic programming with N time steps and M levels of SOC are calculated. Note that because the battery's maximum charging power $P_{bat,max}$, not all SOCs are reachable.

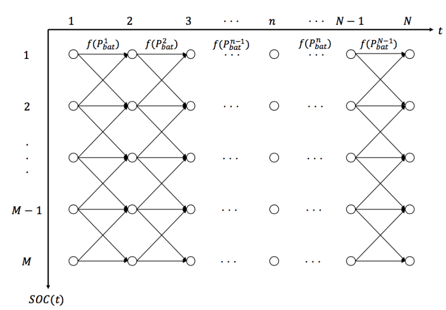

Figure 2: Illustration of dynamic programming with N time steps and M levels of SOC.

The EV battery state of charge at departure is set to $SOC_{dep} = 90$ % at 8 am on weekdays in order to assure the owner (almost) full range of the EV. On weekdays, $E_{ddp} = 7$ kWh are spent for driving [11], resulting in SOC_{arr} to be $SOC_{arr} = SOC_{dep}$ - $\frac{E_{ddp}100\%}{E_{bat,max}} = 81$ %.

3.2 Grid tariffs

3.2.1 Energy based tariff

The energy based tariff is the one broadly being used in Norway today, and is perhaps the simplest way of billing the customer. However, it creates no incentive for grid-friendly use. The grid tariff consists of an annual fixed cost and a variable cost which is based on kWh consumption.

3.2.2 Time-of-use tariff

While still being consumption based, the time-of-use tariff utilized daily load profiles to create time zones where grid use is more expensive. The tariff distinguishes between weekend and weekdays, as well as night, morning, afternoon and evening pricing. The prices are shown in Tab. 2. A mid-level price is set for normal hours, which is doubled for peak load hours and reduced to half during low load hours.

Table 2: Overview of different price zones with the time-of-use tariff

Day		**Hours**	**Price**
Weekdays	Night	23-05	1.26 €ct / kWh
	Standard	5-7, 10-18, 21-23	2.52 €ct / kWh
	Peak	7-10, 18-21	5.05 €ct / kWh
Weekend	Standard	00-24	2.52 €ct / kWh

3.2.3 Power based tariff

The power based tariff increases the price per kWh per kW used by the customer. This gives incentive for leveling the residence load as much as possible. The calculated price for the power tariff was 2.44 €ct/kWh/kW. Thus, when using less than one kW, the price per kWh is 2.44 €ct/kWh. Between 1-2 kW, it is 4.88 €ct/kWh etc.

3.2.4 Subscription based tariff

The subscription based tariff is a tariff consisting of two parts. The first part is a subscription fee, where a customer chooses a certain amount of kilowatts he wants to subscribe to, and pays a fixed monthly price for each subscribed kilowatt. The second part is an energy based cost, where all energy used at a power above the subscribed power has a certain price. This price is split into two prices, one for low and one for peak load hours. Peak load hours are 7-10 am and 6-9 pm, while the rest are low. The fixed price is as following 4:

$$F(x) = C_{Fixed} + P_{sub}C_{Power} \tag{4}$$

where P_{sub} is the subscribed power. The total annual price for this grid tariff is as described in equation 5.

$$C_{year}(P_{sub}, t) = 12F(P_{sub}) + C_{low}\sum_{t=1}^{T} y(t) + C_{peak}\sum_{t=1}^{T} z(t) \tag{5}$$

To achieve equal prices under this structure compared to the structure that exists today, the prices were calculated to be the following. $C_{Fixed} = 9.4$ €, $C_{Power} = 9.4$ €, $C_{low} = 4.72$ €ct/kWh and $C_{peak} = 9.43$ €ct/kWh.

4 Data input

4.1 Load data

The load data are taken from a large residence in Trondheim. The data resolution is hourly, and is rounded to the closest 600 watts due to privacy reasons. The load heatmap is shown in Fig. 3, and shows the average electricity consumption per hour for each weekday for all of 2015. It should be mentioned that due to high amount of space heating, electricity consumption is much higher during winter.

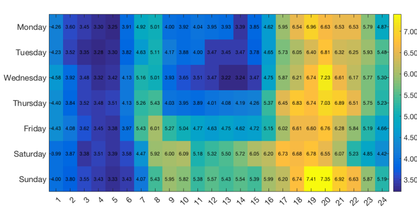

Figure 3: Heat map of the 2015 household load. The matrix shows the average kW consumption for the specific hour at the specific weekday.

4.2 Battery specifications

Two batteries are used for these simulations. The most important one is an EV battery. The second one is a house battery for the comparison between the two. Their specifications are given in Tab. 3. While most EVs in Norway as of 2017 are fairly small, bigger cars with bigger batteries are about to be released on the market. An EV battery with $E_{bat,max} = 80$ kWh is chosen. The maximum power of an EV is normally above 100 kW, but a max limit of $P_{bat,max}$ 15 kW to reduce losses and keep inverter costs down is set. For the house battery, data based on the Tesla Powerwall will be utilized [12]. Note that the minimum and maximum limits of the batteries are set to 0 and 100 %, although it could be argued that a minimum limit of 5 % should be set due to lifetime concerns. In this paper this is not taken into account as the goal of this paper is to do an economic potential analysis, and technical details are secondary issues. It could also be argued that this is already done by the manufacturer to increase the amount of equivalent cycles the battery can perform before its end of life.

Table 3: Battery specifications

	$P_{bat,max}$	E_{cap}	SOC_{max}	SOC_{min}	η_{dis}	η_{ch}
House Battery	7 kW	13.5 kWh	100 %	0 %	0.95	0.95
EV Battery	15 kW	80 kWh	100 %	0 %	0.95	0.95

4.3 PV production data

Irradiation and temperature data are taken from LMT, Landbruksmeteorologisk Tjeneste [13]. LMT is a governmental funded project operated by NIBIO (Norsk Institutt for Bioøkonomi) for measuring and publishing weather data from all over Norway. By using a PV production model based on [10], PV production data is created with MATLAB. To calculate the exact values, the PV panel Sanyo HIT-240HDE4 is used. The specification sheet [14] gives a $NOCT$ of 44 °C and an α_T of -0.3 %/°C. Nominal installed power P_{nom} is set to 7 kW. With 190 W/m^2, the installation is 36.84 m^2. The resulting produced power is shown in Fig. 4.

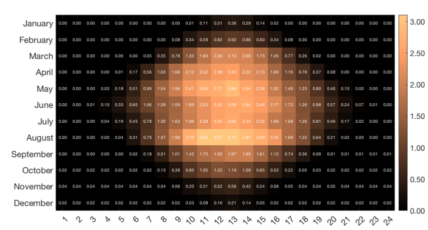

Figure 4: Heat map of the 2015 PV production using the realistic model. The matrix average kWh production per hour for the different months.

4.4 Energy prices

Complete spot price data were downloaded from Nord Pool Spot's database [15], and has a one hour resolution. Fig. 5 shows the prices downloaded from Nord Pool Spot in heatmap. Tab. 4 shows some key values from the figure.

As Fig. 5 shows, the prices are low at night, then rise in the morning due to higher demand. It has to be noted that the spot price for 2015 is historically low, and the lowest since 2005.

Table 4: Average, minimum and maximum prices in 2015. All prices are presented in €ct per kWh.

Year	Mean	Variance	Min	Max
2015	1.98	0.049	0.11	6.14

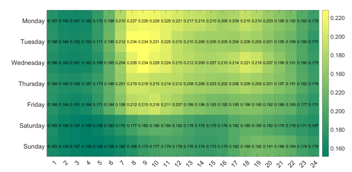

Figure 5: Heat map of the 2015 spot price. The matrix shows the spot price in NOK/kWh for the specific hour at the specific weekday. (1€= 9.58 NOK)

A general spot price contract from a local retailer is chosen, which contains a monthly cost, plus a small addition to the spot price to assure company revenues. The monthly cost is C_{fixed} = 3.92 €/month. In addition, a 0.645 €ct/kWh is added on every kWh bought from the spot market, which consists of a 0.26 €ct revenue margin and a 0.38 €ct green certificate cost. A 25 % tax (VAT) is added on all these costs.

4.5 Grid tariffs

Grid tariffs in Norway make up about one third of the electricity bill of a household customer. Today it is energy based and consists of a yearly fixed price and a fee for every kWh consumed as described in section 3. The prices are regulated by NVE (governmental regulator). The load data used are as mentioned from Trondheim, which belongs to the distribution grid under the jurisdiction of Trønderenergi Nett AS. Their grid tariffs for 2015 are shown in Tab. 5. The remaining three grid tariffs have price levels constructed to give the DSO the same income as with the energy based tariff before an optimization is run.

Table 5: Overview of total grid tariff prices including consumer tax and VAT.

Year	Fixed annual cost	Variable cost	Consumer tax	VAT
2015	139.8 €	2.29 €ct/kWh	1.29 €ct/kWh	25 %

5 Results and discussion

5.1 Total customer cost

The results shown in Tab. 6 and Fig. 6 the total annual customer costs. This includes grid tariffs, taxes, fees and energy prices. In other words, the actual costs that the customer has to pay. Fig. 6 shows the relative cost of each scenario, again compared to the basecase. Note that all scenarios with an EV battery, the cost of energy spent driving the EV was subtracted from the original sum, to avoid the results including the cost of daily transport. The values used were the average driving distance of a Norwegian car which was approximately 35 km/day. With an average efficiency of 0.2 kWh/km, this accumulates to 7.0 kWh/day. All numbers are taken from [11].

Table 6: Total costs for customer for different scenarios and tariff structures. All numbers are given in €.

Structure	Basecase	Basecase incl. PV	House battery	EV battery	House battery incl. PV	EV battery incl. PV
Photo-voltaic	-	X	-	-	X	X
EV Battery	-	-	-	X	-	X
House Battery	-	-	X	-	X	-
Energy Based	3 733	3 319	3 717	3 538	3 311	3 167
Power Based	3 704	3 295	3 623	3 478	3 213	2 099
Time-of-use	3 697	3 264	3 610	3 390	3 186	2 988
Subscr. based	3 698	3 394	3 665	3 509	3 363	3 255

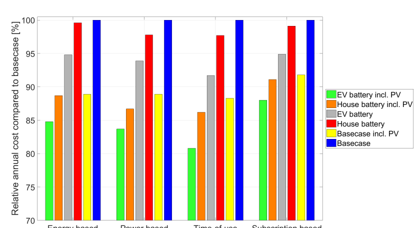

Figure 6: Relative annual cost for different scenarios, all compared to the basecase cost.

Even though there are some variations in the annual cost, there overall clear tendency shown in the results, is that the EV and PV battery solution is the highest saving solution, with savings from 3 to 7 hundred €(12.0-19.2 %) per year depending on tariff structure. The house battery and PV installations saved 8.9-14.4 %, when PV is included. The same tendency is observed when PV is not included - the EV battery is capable of saving quite a bit, whereas the house battery is only able to save a few percent.

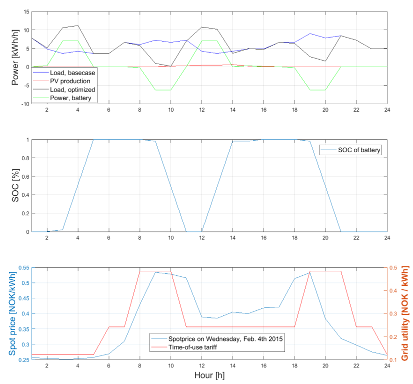

Figure 7: Overview of basecase load, PV production, optimized load, house battery charge and discharge, SOC and spot price for October 20th, 2015.

Fig. 7 illustrates how the battery operates to minimize cost. The figure is an extraction of a day with high prices in 2015, shown for the house battery, and gives an indication of how the battery is charged during low price hours and discharged again during high price hours.

5.2 Battery SOC utilization

Fig. 8 illustrates how the batteries are being used in the case of a subscription based tariff. It also shows that the amount of energy passing through the battery is higher for an EV than a house battery. Although the EV battery is not always available, the increased power and energy capacity allows it to store more energy within its operating hours, which explains why the EV battery solution has higher savings. In addition, Fig. 8 also shows that the EV battery almost never is reduced below 40 kWh (50 % SOC). This implies that a battery half the size could provide close to equal cost reductions, and that this solution is not limited to EVs with big batteries.

5.3 Break even energy price

In order to determine which energy price is required for this investment to pay for itself, the net present value method is used. It is assumed that annual production remains at the 2015 level (5 439 kWh) for the lifetime of the PV panels. Discount rates of 3, 4 and 5 percent are analyzed to determine the break even cost of energy. According to [16], the cost of installing roof mounted

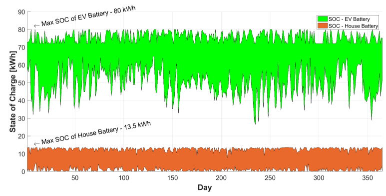

Figure 8: SOC usage in kWh for both batteries.

PV in Norway is approximately 2 100 €per kWp. For the simulated 7 kWp installation, investment costs end up at 14 700 €. Even though the lifetime is guaranteed to be 25 years by most Norwegian PV merchants [16], the general statement is a lifetime of 30-40 years. 25 years is used as lifetime in these calculations. Because the primary use of an EV battery is to provide fuel for transport, the EV battery investment is considered to be zero. Due to few available house batteries at the market, with Tesla's Powerwall costing 8 400 €, break even calculations for PV and house batteries are not included. All assumptions made for these calculations are summarized:

Installed power photovoltaic	7 kWp
Cost per installed kWp	2 100 €/kWp
Lifetime	25 years
EV battery investment cost	0 €
Annual PV producton	5 453 kWh

The resulting break even price is shown in Tab. 7. The savings for the PV and EV battery system span from 444 - 710 €depending on grid tariffs, which with 5 453 kWh saves 8.65 - 13.00 €ct/kWh. In other words, those are the numbers which have to stand in comparison.

Three different installation cost scenarios are shown. The first one is calculated with today's prices in Norway [16]. The second one is with Norwegian prices, but includes subsidies from Enova (green project funding governmental organ). With 7 kW installed, the support provided by this governmental organ adds up to 1 956 €. For scenario two, the investment cost is therefore 12 651 €. The third scenario is calculated with German installation prices ($\tilde{1}$ 252 €/kWp) taken from [17], which adds up to 8 764 €.

Table 7: Break even energy cost for different discount rates. Note that the cost is the average cost saved per kWh produced by the PV, and includes all taxes and grid tariffs.

Scenario	**Inv. cost**	**3 %**	**4 %**	**5 %**
#1	14 607 €	15.39 €ct/kWh	17.15 €ct/kWh	19.01 €ct/kWh
#2	12 651 €	13.74 €ct/kWh	15.32 €ct/kWh	16.98 €ct/kWh
#3	8 764 €	9.01 €ct/kWh	10.13 €ct/kWh	11.23 €ct/kWh

5.4 Deciding economic factors

While today's conditions do not appear to provide economic reason to invest in PV and battery installations in Norway, several things can change in the future. The economic potential of this investment is still depending on:

- Future increase in energy prices [18]
- Future reduction in PV and battery prices [5] [2].
- Future grid tariff price and structure.
- Future electricity consumption behaviour [19].
- Degradation of battery and assumed battery investment cost.

6 Conclusion

The presented results show that utilization of PV as of 2017 is on the verge of being economically profitable with Norwegian conditions due to high investment costs, low energy prices and semi-low irradiation, even with deterministic dynamic programming algorithms. However, the paper also shows that when Norwegian PV installation costs reach German levels ($\tilde{4}0$ % reduction), the investment will be profitable. Moreover, higher electricity prices e.g. due to raising CO2-prices will lead to even better profitability.

In general, the EV battery proved to provide more savings than a house battery due to capacity and power capabilities. Because an EV battery can be considered a "free" investment, net present value analysis of the system show better potential compared to a stationary battery which has very high investment costs compared to the savings provided. Still, the annual savings potential is fairly dependant on which grid tariff structure is being used, differing from 12.0 - 19.2 % for the PV and EV battery system compared to 8.9 - 14.4 % for the PV and home battery system.

For future work, it would be useful to study the economic potential under different scenarios for different EV availability profiles, load profiles and PV production profiles. Time resolution could also be increased in order to improve precision of PV and load data. In addition, the dynamic programming framework allows for including more technical details such as voltage, current, charging efficiency dependencies and battery degradation parameters. Another interesting aspect is to expand this model to a stochastic or rolling horizon dynamic programming algorithm, which could be used for simulating online operation under uncertainty.

Acknowledgment

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