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Impact of Power Tariff on Electric Vehicle Smart Charging

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Executive Summary

This paper investigates the optimal smart charging behavior of a battery electric vehicle, when a peak power tariff is introduced into the price model imposed by the electricity distribution system operator (DSO). An optimal control problem is formulated with the objective to minimize the combined cost of hourly electricity prices, transfer fees, taxes and the power tariff fee, while considering the reduced efficiency of the on-board charger (OBC) at low power. The cost optimal smart charging strategy is then calculated for the Swedish market during year 2023, using historical electricity prices and an actual DSO price model. The results indicate that the introduction of a power tariff has a significant impact on the optimal smart charging strategy. To compensate for the power tariff the optimal peak charging power decreases from 11 kW to about 2 kW, leading to a slight decrease in average charging efficiency. The results also indicate that it can be very costly to neglect the existence of a power tariff. For the investigated scenario overall charging costs are 27.5% lower if the power tariff is considered, as compared to the case when the power tariff is ignored.

1 Introduction

Aggregate demand for electricity is usually low from late evening until early morning, and high during early morning and late afternoon. Hourly electricity spot prices on a regional level will typically mirror the demand side, with higher prices during high demand hours and lower prices during low demand hours. It can therefore be attractive for electric vehicle owners to sign up for hourly priced electricity contracts and shift vehicle charging to off-peak hours, a concept known as Smart Charging[1, 2].
However, the steadily increasing share of battery electric vehicles (BEVs) poses new challenges for the local electrical power distribution grid. A limiting factor on the local level is often power capacity. The local transformer in most residential areas is generally not dimensioned for simultaneous charging of multiple BEVs at peak OBC power, even if it occurs during night hours when the overall demand is low on the regional grid level. A more spread out load in residential areas can lead to reduced need to reinforce the local grid and maximize utilization of the already existing infrastructure [3], [4]. One way for the DSO to incentivize households to spread out their electricity consumption is to add a fee that penalizes high peak power, a so-called power tariff [5]. The Swedish Energy Markets Inspectorate (Energimarknadsinspektionen) [6] mandates all Swedish DSOs to impose power tariffs in their price model from January 1^{st} 2027. As of February 2025 about 50 out of 170 Swedish DSOs have introduced power tariffs [7]. The typical implementation is based on a monthly fee that is proportional to the average of the top three peak consumption hour(s) of the month.
The main purpose of the paper is to investigate the optimal BEV smart charging strategy for a customer with a contract that features time varying electricity prices, i.e. spot prices, as well as a peak power tariff. More specifically, the focus is on how the optimal charging power is affected by the introduction of a power tariff and what the associated charging cost is when the power tariff is either considered or

neglected, when the optimal BEV smart charging strategy is calculated. A delimitation in the paper is that only vehicle charging loads are considered and optimized, meaning that residential home loads are ignored.

2 System Model

The paper considers an electric vehicle that is charged overnight, on a daily basis, via a three-phase AC-wallbox at a residential location in Sweden.

2.1 Vehicle Charging Model

The vehicle battery is modelled as an equivalent circuit with an open-circuit voltage, U_b, that is a non-linear and monotonically increasing function of the state of energy, SoE. The internal resistance R_b is dependent on battery temperature, T_b. The battery temperature is not modelled explicitly, it is assumed to match the ambient temperature in Gothenburg during the investigated time period. The OBC losses P_{obc}^{loss} are defined by a lookup table with respect to battery charge power, P_b, where the corresponding efficiency is reduced at low power. The temperature of the OBC is not considered and the wallbox is assumed to be ideal, i.e. without losses and dynamics, meaning that the wallbox power, P_{wb}, is identical to the OBC power. The BEV is assumed to be unidirectional with a min/max charging power of 0/11 kW. The vehicle is assumed to be plugged-in every day, from 18:00 until 06:00, and the daily charging need is assumed to be 16.5 kWh for all days of the year. The equations for the charging model can be summarized by

$$R_b = f_1(T_b), \tag{1}$$

$$U_b = f_2(SoE), \tag{2}$$

$$P_{obc}^{loss} = f_3(P_b), \tag{3}$$

$$I_b = \frac{P_b}{U_b}, \tag{4}$$

$$P_b^{loss} = R_b I_b^2, \tag{5}$$

$$\frac{d}{dt} SoE = -\frac{P_b}{E_b^{max}}, \tag{6}$$

$$P_b = -P_{wb} + P_{obc}^{loss} + R_b \frac{P_b^2}{U_b^2}, \tag{7}$$

where I_b represents battery current, P_b battery power and P_b^{loss} resistive battery losses. Table 1 summarizes the vehicle data and usage pattern. In order to avoid a mixed-integer optimal control problem, the model does not account for the idle energy consumption of the vehicle, i.e. to power control units, when the vehicle is ”awake” during charging.

Table 1: Vehicle data and usage pattern.

Vehicle Parameter	Symbol	Value
Plug-in time	t_{PlugIn}	18:00
Plug-out time	$t_{PlugOut}$	06:00
Plug-in SoE	SoE_{init}	0.65
Plug-out SoE	SoE_{end}	0.80
Battery capacity	E_b^{max}	110 kWh
Max Charge Power	P_{wb}^{max}	11 kW
Min Charge Power	P_{wb}^{min}	0 kW

2.2 Electricity Price Model

In this paper the focus is on the Swedish electricity market, where each consumer has two different contracts. The first contract is with the DSO who owns the local electrical grid and is responsible for the

delivery of the electrical energy. The DSO charges a fixed monthly fee and a transfer fee per kWh of bought energy, c_{tf}. The power tariff fee, c_{pt}, is proportional to the peak power that is consumed during a specified time interval. The most common DSO implementation is to define the peak power as the average of the three peak hours during each calendar month. The second contract is with an electricity retailer who acts as a broker towards the electricity producers. It can have either a flat rate, i.e. constant kWh-cost over the duration of the contract, or follow the hourly spot prices, c_{sp}, on the Scandinavian power exchange market, which is operated by *Nord Pool* [8]. In addition to the cost from the DSO and the retailer there is a Swedish energy tax and a value added tax (VAT).
In this paper it assumed that the DSO contract is with *Gothenburg Energy (Göteborgs Energi)* [9] and that the retailer contract follows the hourly spot prices set by *Nord Pool*. Table 2 summarizes the different taxes and DSO cost components that are used in the paper and Figure 1 illustrates hourly electricity spot prices, on Nordpool, during January 2023.

Table 2: Electricity cost components due to tax and DSO fees, during 2024.

Electricity Price Component	**Symbol**	**Value/Description**
Value Added Tax	r_{vat}	0.25
Energy Tax	c_{et}	0.428 SEK/kWh
Retailer Contract	c_{sp}	Hourly spot prices
DSO Contract		*Gothenburg Energy*
Fixed Fee		125 SEK/Month
Energy Transfer Fee	c_{tf}	0.204 SEK/kWh
Peak Power Tariff Fee	c_{pt}	35 SEK/kW

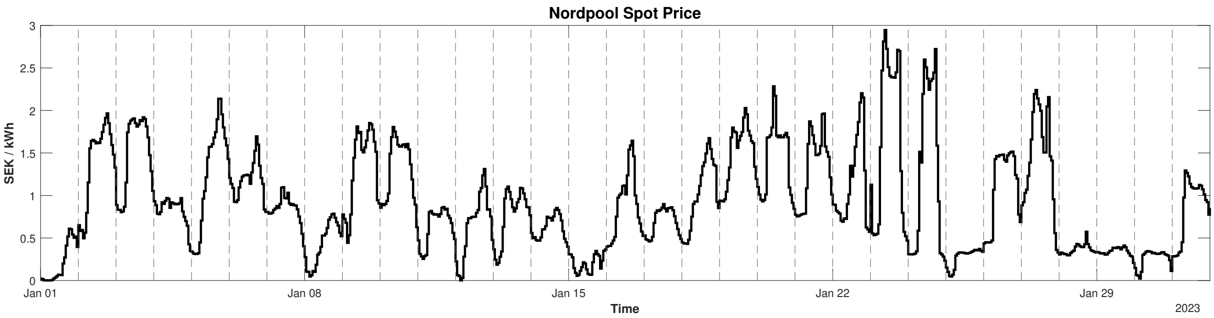

Figure 1: *Nord Pool* spot price, c_{sp}, during January 2023. The dashed vertical lines represents midnight each day.

3 Smart Charging Optimal Control Problem

The objective of the smart charging optimal control problem is to minimize the overall charging cost over a calendar month, $\mathcal{M}$,

$$J(.) = (1 + r_{vat}) \cdot c_{pt} \cdot |P_{wb}(t)|_\infty + \int_{t\in\mathcal{M}} (1 + r_{vat}) \cdot (c_{sp}(t) + c_{tf} + c_{et}) \cdot P_{wb}(t)\, dt, \tag{8}$$

where the power tariff fee is approximated by the infinity norm of the grid power, $|P_{wb}(t)|_\infty$, i.e. the peak power rather than the average of the top three hours with highest power. The constraints for the corresponding daily sub-problem can then be expressed as,

subject to:

$$\frac{d}{dt} SoE(t) = -\frac{P_b(t)}{E_b^{\max}}, \tag{9a}$$

$$P_b(t) = -P_{wb}(t) + P_{obc}^{loss}(P_b(t)) + R_b(T_b)\frac{P_b^2(t)}{U_b^2(SoE(t))}, \tag{9b}$$

$$P_{wb}(t) \in [P_{wb}^{min},\ P_{wb}^{max}], \tag{9c}$$
$$SoE(t) \in [0, 1], \tag{9d}$$
$$SoE(t_{PlugIn}) = SoE_{init}, \tag{9e}$$
$$SoE(t_{PlugOut}) = SoE_{end}. \tag{9f}$$

To solve the problem over the full calendar month, $\mathcal{M}$, the daily sub-problems, $\{1, 2, \ldots, n\} \in \mathcal{M}$, are stacked after one another and solved numerically as a single large non-linear optimal control problem using CasADi [10]. Figure 2 depicts the resulting optimal battery SoE state trajectories for the month of January 2023, when the power tariff is considered.

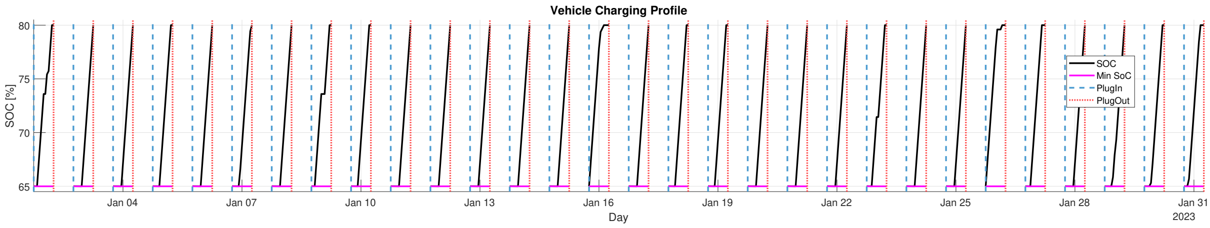

Figure 2: Smart Charging SoE trajectories for January 2023, when the power tariff is considered.

4 Results

The Smart Charging Problem formulation presented in the previous section was solved for each month from January 2023 up until February 2024, based on historical hourly spot prices for electricity in price area SE3 in Sweden [8]. To illustrate the impact of the power tariff, the optimal control problem was solved both with and without the power tariff, i.e. by setting c_{pt} to 35 SEK/kW and 0 SEK/kW respectively. The results are summarized in Table 3 and are shown in Figures 3-4. The economical cost is calculated with the actual cost for the power tariff, even when it was neglected in the optimal control problem.

The peak charging power per month saturates at the OBC max power of 11 kW when the power tariff is neglected. However, when the power tariff is considered it peaks at around 2-2.5 kW. It is clear that the optimal peak charging power is reduced significantly when the power tariff is introduced, i.e. in alignment with the behavior that is desired by the DSO.

A second-order effect of the reduced charging power, when the power tariff is considered, is that the average charging efficiency decreases somewhat, leading to a 0.7% increase in the total amount of energy that is bought from the grid. However, the slightly increased energy cost (+27 SEK) is by far offset by the significantly lower costs for the power tariff (-5,364 SEK). Hence, considering the power tariff leads to 27.5% lower overall charging cost, as compared to the case when the power tariff is ignored.

However, it is worth to stress that these numbers will overestimate the benefit of considering the power tariff as vehicle idle consumption is neglected in the charging model. The reduced charging power will increase charging time by about six hours per day. If the idle consumption is about $\sim$100 W, then this will correspond to an increased consumption of $\sim$250 kWh, for the investigated time period, with an associated cost of $\sim$400 SEK. Not a negligible number, but still not enough to change the overall result from a cost perspective, since the power tariff cost reduction is about an order of magnitude higher.

Table 3: Summary of results for the optimization study, from January 2023 to February 2024.

Results	**No Power Tariff** ($c_{pt} = 0$)	**With Power Tariff** ($c_{pt} = 35$)
Peak monthly charging power	10.9 - 11 kW	1.9 - 2.4 kW
Total Grid Energy	7,011 kWh	7,060 kWh (+0.7%)
Energy Tax	3,751 SEK	3,777 SEK (+0.7 %)
DSO Fixed Fee & Energy Transfer	3,973 SEK	3,991 SEK (+0.5 %)
DSO Power Tariff	6,730 SEK	1,366 SEK (-79.7 %)
Spot Price Energy	3,053 SEK	3,552 SEK (+16.3 %)
Total Cost	**17,507 SEK**	**12,686 SEK (-27.5 %)**

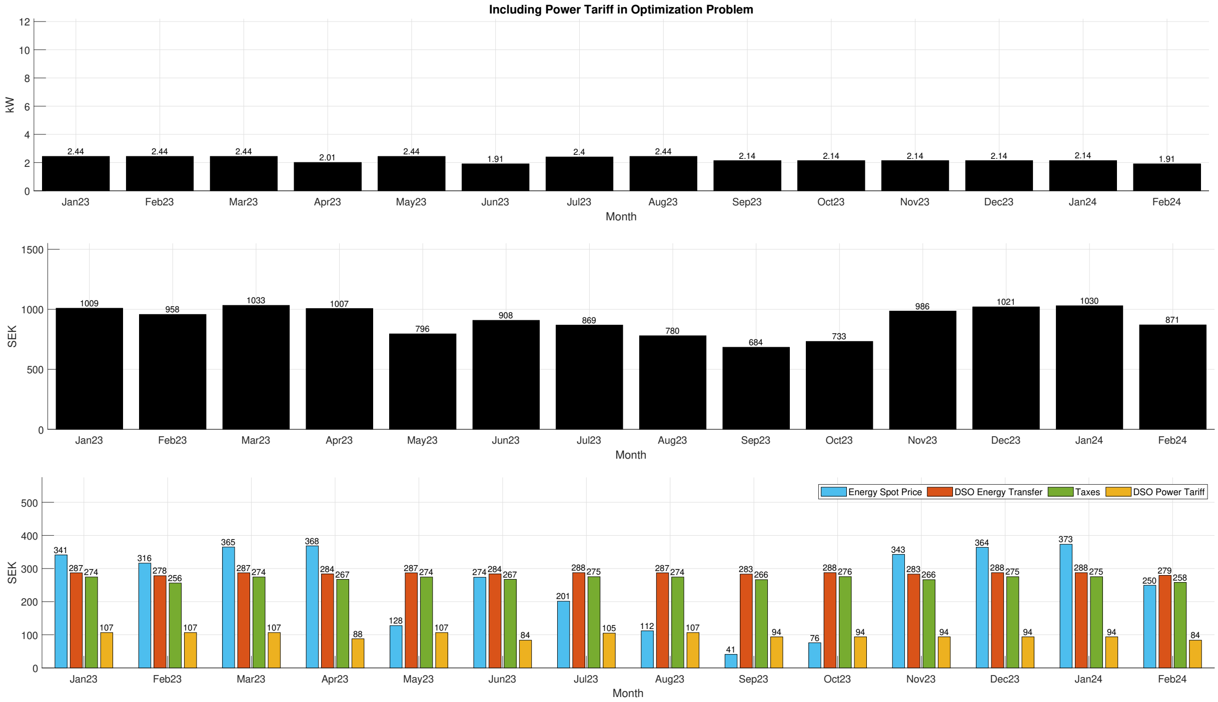

Figure 3: Peak charging power (top), total charging cost (middle) and cost breakdown (bottom), when the power tariff is considered ($c_{pt} = 35$) in the optimization.

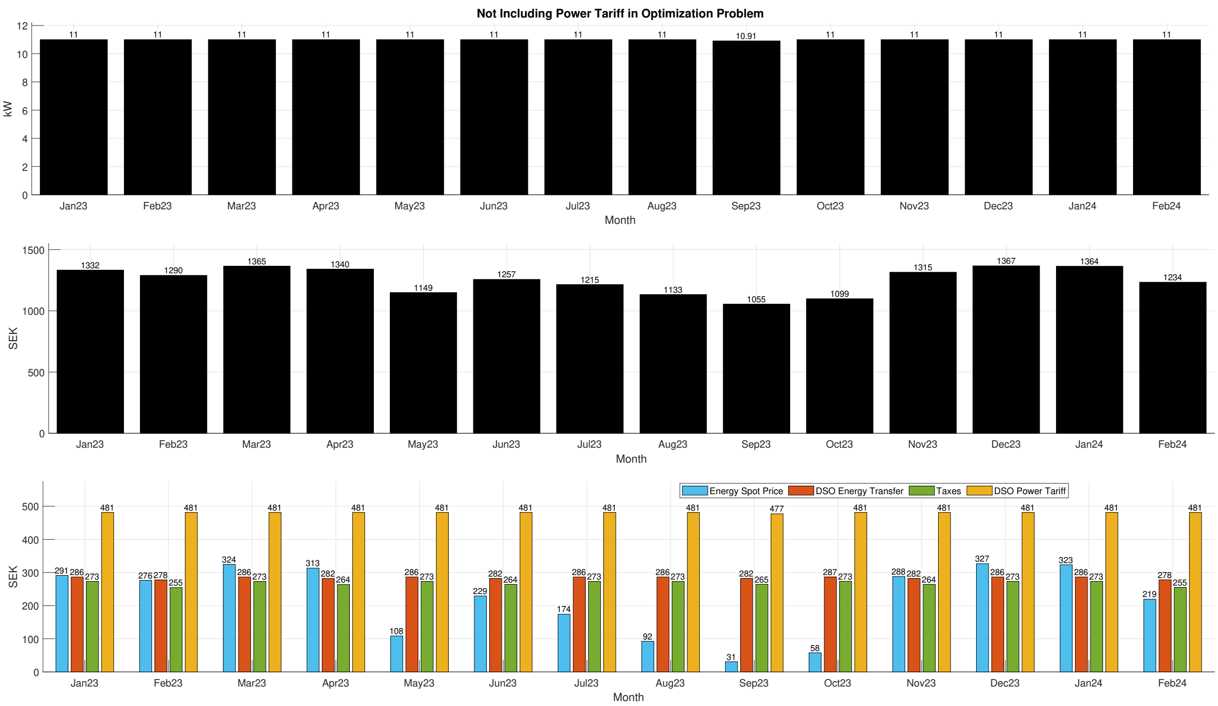

Figure 4: Peak charging power (top), total charging cost (middle) and cost breakdown (bottom), when the power tariff is not considered ($c_{pt} = 0$) in the optimization.

5 Conclusion

This paper has investigated the impact of a peak power tariff fee on smart charging of electric vehicles. The results indicate that the optimal charging behavior changes dramatically, with peak charging power decreasing from 11 kW to about 2 kW. However, the results are expected to be highly dependent on the DSO price model for the power tariff and vehicle idle losses. The price model considered in the paper features a DSO power tariff that is flat and applies to all days and hours of the year. Another, and perhaps more likely model, is a power tariff that is divided into peak and off-peak hours; where the cost is significantly lower, or even zero, during off-peak hours. For this type of power tariff the optimal peak charging power will likely remain at, or closer to, the max OBC or wallbox charging power.
The main challenge, from a smart charging implementation point of view, is that there is no uniform price model for power tariffs among the DSO's, not even within Sweden. This makes it more difficult to build scalable solutions that can be deployed across multiple regions and markets. Furthermore, another complicating factor is that Swedish power tariffs typically are defined per calendar month, meaning that it is non-trivial to optimize for both spot price and power tariff on a daily basis, i.e. since spot prices are only known for the next day and not for the upcoming month.
Finally, a potential topic for a future study is to investigate a complete Home Energy Management System (HEMS), including home loads, solar panels and a stationary residential battery.

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Presenter Biography

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