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Impact of Electricity Prices and Tariffs on Smart Charging: A Comparison Between Norway and Denmark Using Receding Horizon Optimization

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ABSTRACT: With the growing number of electric vehicles (EVs) in Denmark and Norway, the need for efficient control of charging stations increases. This paper compares smart charging strategies using a receding horizon optimization method, focusing on the different electricity pricing systems in both countries. By optimizing EV charging based on hourly electricity prices, we aim to reduce costs for charging point operators (CPOs). The results show that being a CPO in Norway is 1.4 times more profitable in terms of operational costs than in Denmark, with on average 1116 € more profit for Norway per year in more favorable scenario with high energy delivery rate for EVs.

KEY WORDS: smart charging, receding horizon optimization, electric vehicles, pricing mechanisms.

1. INTRODUCTION

Norway and Denmark are the leading countries in Europe in terms of electric vehicles (EV) adoption. The Norwegian EV sales share surpassed 90% last year with an EV stock share reaching 30%. The next in line is Denmark having an EV sales share of 46% and stock share of 11%.(1) While the electrification of the transport sector brings positive improvements for emissions reductions globally and locally, it also puts stress on existing power network infrastructure with uncontrolled EV charging. To reduce the need for costly grid upgrades, there is a possibility to deploy smart charging algorithms that can schedule charging time and control power levels of charging decreasing consumption during peak hours.(2) One of the leading power network loading control mechanisms is price-based incentives. The price-based mechanisms are considered implicit demand side management. Following low prices, which usually correspond to off-peak hours, is often mutually beneficial for both charging stations and grid. However, Norway and Denmark have different energy mixes with dominance of hydropower in Norway and a variety of different generation, dominated by wind in Denmark. Besides different spot prices, these countries have distinct tariff schemes, with capacity tariffs for Norway and time-of-use tariffs in Denmark.

In this study, smart charging is deployed using receding horizon price optimization for charging stations. The aim is to compare the profitability of charging station operators (CPOs) in Norway and Denmark. Most of the smart charging economic assessment studies are done for pricing in a particular country. For example, Martinenas et al. conduct study EV charging under dynamic pricing in Denmark.(3) Another study focuses not only on cost-effective smart charging but also offering demand response for Norwegian network.(4)

This study aims to compare the economic performance of receding horizon optimization smart charging under different pricing schemes of two EV-leading European countries.

2. METHODOLOGY

2.1. General model structure

The destination charging station setup is shown in Fig.1.

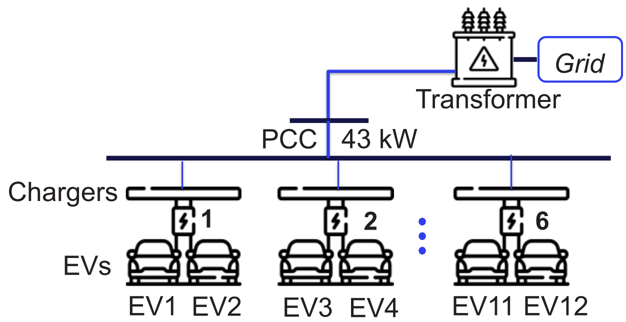


Fig. 1 Destination charging station setup.

The charging station consists of six chargers with two plugs, each with the ability to host twelve EVs. The station has a point of chargers' connection (PCC) with a capacity of 43 kW and a grid connection through a transformer.

The smart charging model structure is illustrated in Fig. 2. The algorithm consists of two levels: the upper-level model solves price optimization and allocates the power reference for the whole charging station. The lower-level model dispatches the power reference to each EVs and has an opportunity to communicate an aggregated power request from the EVs to the upper-level for improving the delivery of energy requests. The presence and absence of this feedback loop highly influence the delivery of requested energy to the EVs. When the feedback is on, the priority of the model is to deliver the requested energy. However, when it is off, the model fully focuses on electricity purchasing costs optimization. The algorithm runs every five minutes with foreseeing electricity prices of six hours. A more detailed description of model the methodology can be found in the previous papers about the model.[5], [6]

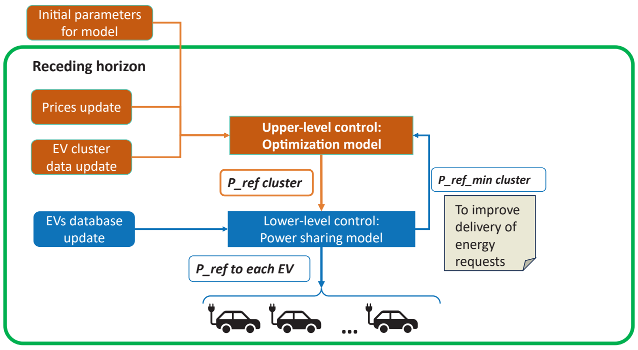


Fig. 2 Receding horizon optimization model scheme.

The energy allocated for the cluster to be dispatched within a day is 150 kWh with an assumption that EVs are present at the charging station between 6:00 – 20:00. The energy allocation and time presence of the cluster are the average of energy and most probable hours obtained from historical data. The simulated EVs data are recorded charging sessions at a public charging station of the Technical University of Denmark in Lyngby, Denmark. The lower-level model receives information about EVs only when they connect. The model has been run for one week in each season for the year 2023: January 9-16, April 10-17, July 9-16, October 10-17. The model results presented in the results section are based on two system setups with and without feedback loop from lower-level control. The graphical representation of EVs data used in the model is shown in Fig.3. The four plots, each for week of one of the seasons, show the EVs plug-in duration at the charging station and energy request for EV to charge.

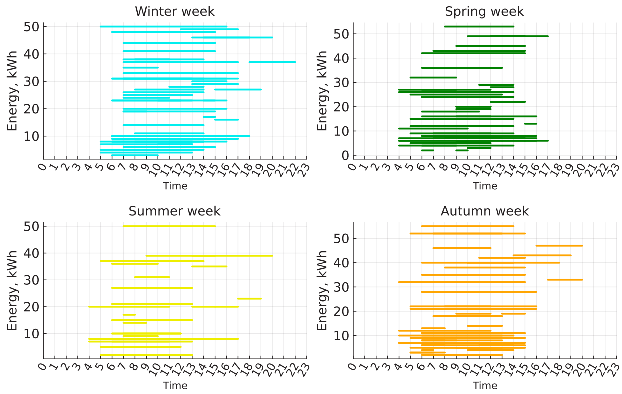


Fig. 3 Distribution of EVs charging station plug-in duration and their energy request for each of considered weeks of the year.

2.2. Norway and Denmark electricity pricing

Spot prices used in this study are taken from Norway's pricing bidding zone NO2 and Denmark zone DK2. The choice of zones is made based on historical data availability for these zones and that they are both part of the Nord Pool energy market.[7] The spot prices of NO2 and DK2 for the year 2023 are shown in Fig.3. Spot prices in NO2 are less variable than in DK2. They have less spikes and rarely have a negative price. The variability of DK2 spot prices comes from the large share of variable RES in Danish energy mix. Norway's electricity tariffs are taken from Lede power network company, DSO.[8] A distinctive feature of Norway's electricity tariffs is the capacity-based part. The capacity tariff is calculated based on the average of three consumption peaks during the month. For the charging station studied, the peak would be 43 kW, which corresponds to 1397 NOK/month (123 €/month). In addition, there are also other charges related to connectivity cost

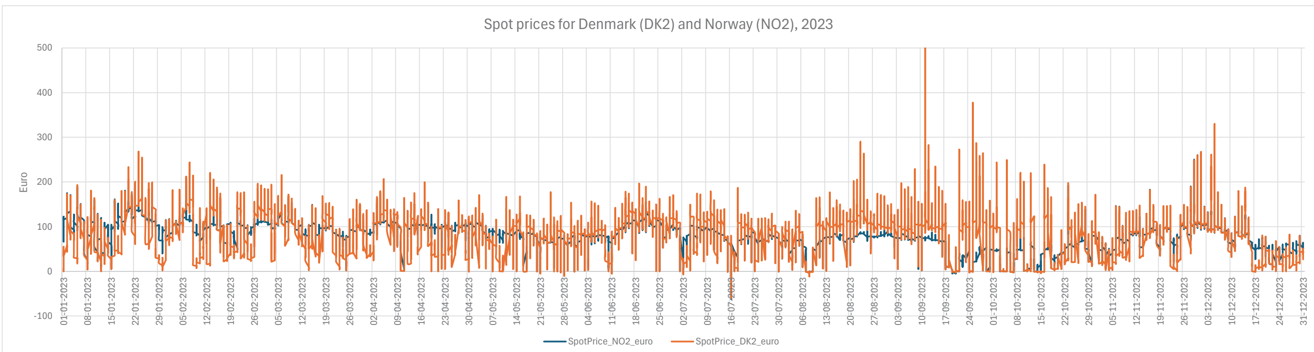


Fig. 3 Spot prices NO2 (blue) and DK2 (orange)

and energy usage. In Denmark there are no payments for capacity, but extensive Time-of-Use (ToU) tariffs. The prices for the Danish case are taken from the DSO network company Trefor.[9] For the considered charging station, respective tariffs apply for a connection at low-voltage with commercial consumption, so-called B-low. The variability of tariffs comes from the seasonality, time of day and if it is a workday or weekend. The charging station only pays for energy consumption and connectivity costs. The schematic representation of tariffs difference in Norway and Denmark is shown in Fig. 4, where for Norway the tariff costs are constant, while in Denmark they vary during the day.

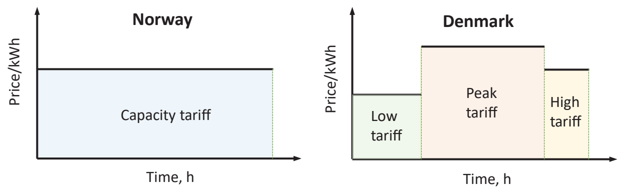


Fig. 4 Schematic of tariff differences in Norway and Denmark.

The prices that the EVs should pay to the charging station are taken from common charging station operators in Denmark – Clever [10] and in Norway – MER[11].

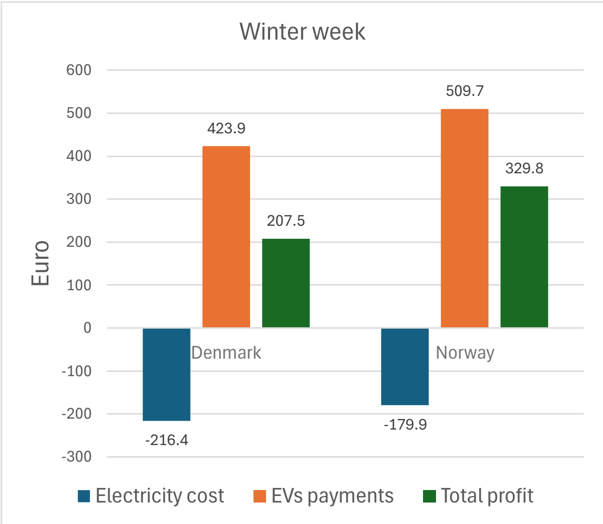
3. RESULTS AND DISCUSSION

The results of this study are shown in Fig. 5 and Fig. 6. Both figures show the economic assessment for charging stations in Denmark and Norway: Fig. 5 presents the results for the model setup with feedback loop from the lower level control, Fig. 6 - without. Electricity purchase costs are represented as negative values, while payments received from EVs are shown as positive values. This convention clearly distinguishes the money the CPO pays to the grid from the revenue generated, making the financial flow more intuitive. The total profit, from the CPO's perspective, is calculated as the sum of EVs payments and the electricity costs paid to the grid. Using this approach, positive values of total profit represent a gain, while negative values indicate a loss, ensuring a clear and consistent financial interpretation.

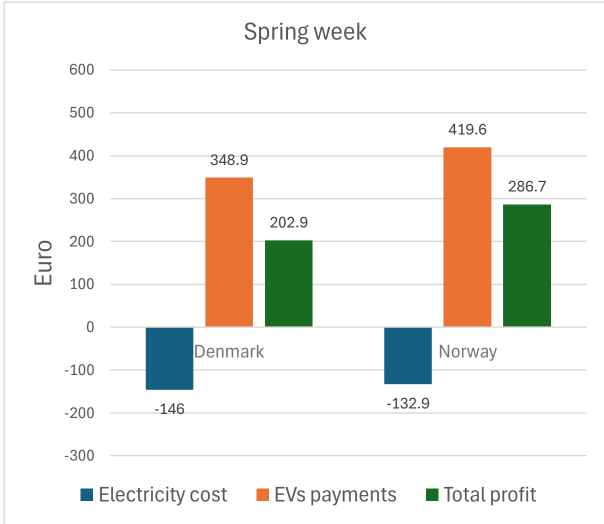
For the model setup with enhanced delivery by feedback loop presented in Fig. 5, a CPO in Norway is more profitable compared to a Danish CPO, independent of season. This results both from less electricity purchase costs and larger payments received from EVs. It is important to stress that delivery of requested energy is the same for Denmark and Norway in every season case and always above 95%. This means that the difference in economic profitability comes solely from different electricity pricing and EV charging rates in these two countries. According to the studied weeks, a Norwegian CPO is on average 93 € more profitable than a Danish CPO within one week and on 1116 € within a year. Also, it is worth mentioning that during the winter week electricity prices are higher and more EVs are charged, bringing more EVs payments. In this setup, the feedback constrains the charging power to be allocated even during non optimal electricity price hours. Making it more stiff and less flexible to exploit prices variability. To discover variability opportunities the setup of removed feedback is presented in Fig. 6. Here it is clearly seen that Danish electricity costs are now less than Norwegian in almost all seasons except for autumn. This shows the electricity costs of consumption in optimal hours are lower for more variable pricing of Denmark than for more stable one in Norway. However, due to the removing delivery restriction of feedback, the delivery in this setup does not overcome 57% and on average is 39%. Thus, the revenues from EVs are highly reduced compared to the setup with feedback present. The delivery varies for different seasons, but almost the same for both countries for the same season. Norwegian CPO receives more revenue from EVs due to higher selling prices for EVs. The total profits of a Norwegian CPO are almost higher than Danish CPO's, even though the electricity purchase cost is higher for Norway case. The pricing for EV charging outweighs the electricity cost reduction.

4. CONCLUSIONS

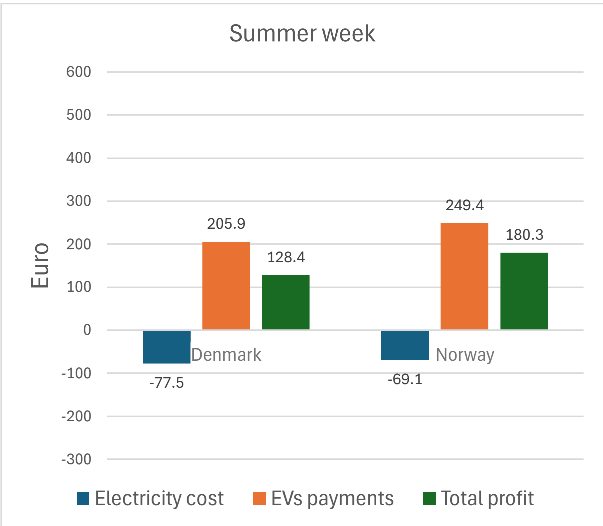
From the results presented there are a few conclusions to be made. First, from a CPO perspective it is better to have a higher delivery rate in both countries as the EVs revenues are much higher than in low delivery cases, and they outweigh the electricity cost payments to the grid. Second, forced consumption in economically non-optimal electricity cost hours is cheaper for Norway than in Denmark. Third, relaxed consumption allocation in optimal hours is cheaper in Denmark than in Norway due to high price variability. Fourth, the Danish price variability and Time-of-Use tariffs can be more valuable for more predetermined consumption and for the cases where the electricity costs reduction is the primary goal. Last, being a CPO in Norway is on average 1.4 times more profitable than being a CPO in Denmark due to higher prices for selling electricity to EVs and more stable prices and tariffs, while ensuring high delivery. Further research is aimed at exploring different network companies and CPO companies in both countries to build a more representative picture. Another potential study is on grid requests for limiting the power consumption of a charging station to see how it affects electricity



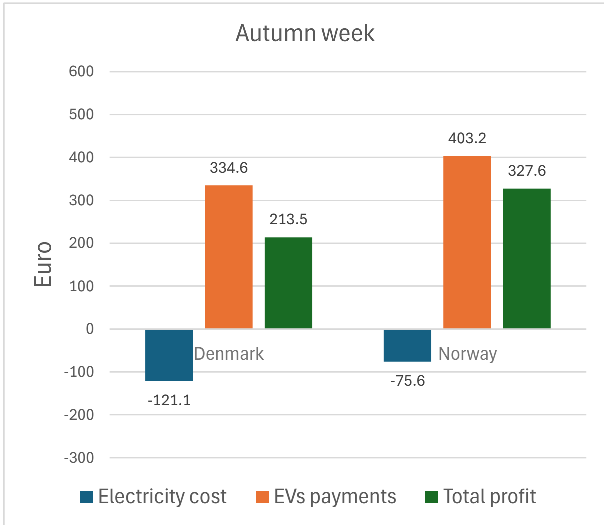
(a) Winter week case simulation



(b) Spring week case simulation



(c) Summer week case simulation



(d) Autumn week case simulation

Fig. 5 Economic assessment results for each season with feedback from lower-level control

costs based on capacity tariffs in Norway and delivery of requested energy of EVs.

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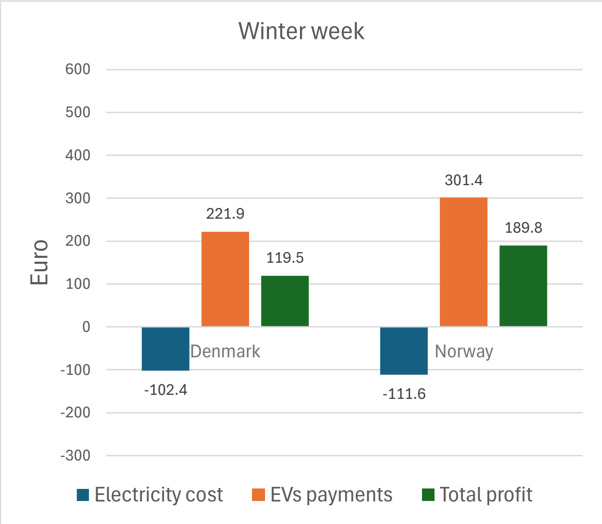

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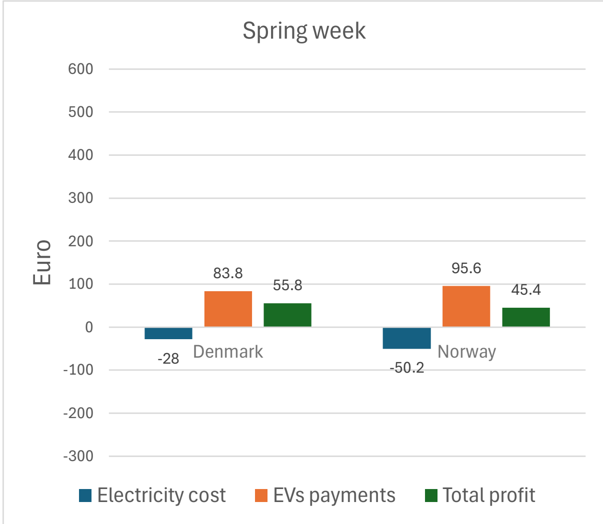
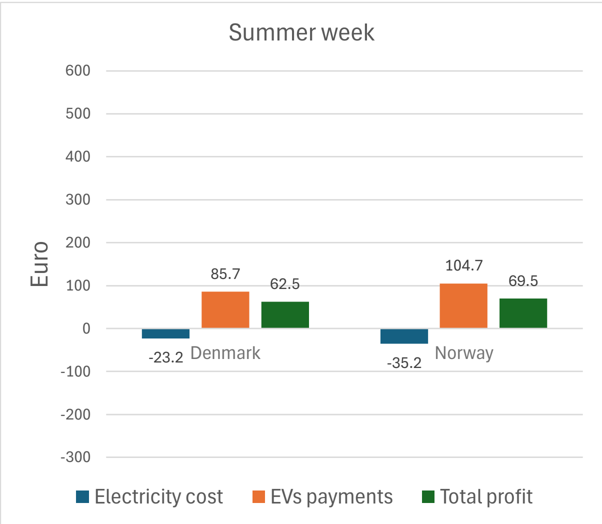
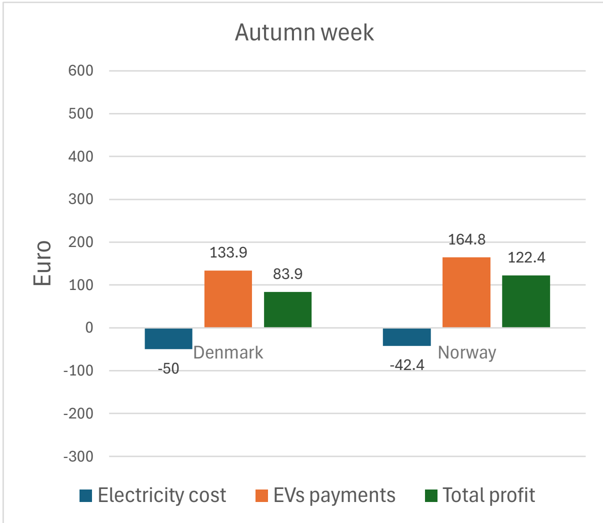


(b) Spring week case simulation



(c) Summer week case simulation



(d) Autumn week case simulation

Fig. 6 Economic assessment results for each season without feedback from lower-level control

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