CASE STUDY: ECONOMIC EFFICIENCY OF SMART CHARGING IN LUT GREEN CAMPUS

Henri Makkonen
LUT Energy – Finland
henri.makkonen@lut.fi

Tikka Ville
LUT Energy – Finland
ville.tikka@lut.fi

Juha Haakana
LUT Energy - Finland
juha.haakana@lut.fi

Jarmo Partanen
LUT Energy – Finland
jarmo.partanen@lut.fi

Pertti Silventoinen
LUT Energy – Finland
pertti.silventoinen@lut.fi

Lappeenranta University of Technology
Department of Energy
Finland

ABSTRACT

The aim of this paper is to describe the smart charging methods and discuss about the economic efficiency of electric vehicle charging optimization methods in Lappeenranta University of Technology (LUT) Green Campus Smart Grid (GCSG). By utilizing the communication interface which the GCSG provides, different charging optimization methods are carried out for a pilot electric vehicle (EV). Analysing optimization results shows the economic efficiency of smart charging as well as the most potential optimization method.

INTRODUCTION

While the electric vehicle has been elevated to be the next step of transportation, there are growing number of EV charging researches and concept developments searching new control and communication strategies, such as [1].

Typical control strategy is time based charging control, for instance charging the vehicle during night. However, some cases the charging event must be done during the day or the charging during the day is most welcome (case of negative electricity prices).

However, increased control over the charging event requires additional information from the electric vehicle, as the current standards provides inadequate information for smart charging purposes. Hence, the common ground for smart charging studies is to implement communication interface between the smart charging system and electric vehicle. The Green Campus Smart Grid environment provides the necessary interface between the smart charging system and electric vehicle with a compatible interface on-board.

GREEN CAMPUS SMART GRID

The Green Campus Smart Grid is a combination of different electricity appliances, connected together with an existed low voltage customer network and communication network. Addition to control system (energy management system, EMS), GCSG contains measurement units, controllable loads, wind turbine, solar panels, energy storages and electric vehicles. Figure 1 presents the basic concept of GCSG environment.

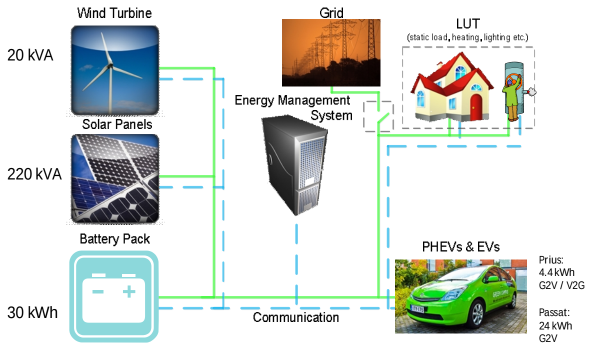

Figure 1. The basic concept of Green Campus Smart Grid.

The GCSG is a smart grid environment, designed to allow easy implementation of energy resources and appliances. With flexible data system and optimization, the GCSG is effective research platform for smart grid related research.

The GCSG control system (EMS) consists of several separate but fully compatible software. The software allows multiple client connections, enabling direct connection from all the GCSG appliances and also enabling connecting multiple optimization algorithms. The structure and operation of the EMS is more thoroughly explained in [2].

Connecting multiple optimization algorithms to optimization socket applies also to different optimization strategies, including smart charging system. Hence, the smart charging system can easily to be modified to obtain various inputs and use diversity of optimization approaches, for example price or load optimization.

SMART CHARGING

Even though the optimization system allows multiple optimizations methods being executed at the same time, there can be contradictories between the methods as the beneficiaries can be different actors. For instance, using price optimization for smart charging can give economic benefit for both customer and electricity retailer but can form problems for DSO (distribution system operator). Furthermore, the economic effect of different optimizations can vary greatly between different actors.

Smart Charging Actors

Because of the different approaches and goals between different actors, the optimization method is strongly depended on objective of the actor. By combining the optimization algorithms from different actors, the system can form a charging period with minimal total cost. However, the combined algorithm can lead to losses for certain actors. By giving priorities to different actors, the optimization system can form algorithm which prioritizes certain values and inputs to achieve compromise between the actors, while still giving some actors vantage. For instance, economic optimization for customer, electricity retailer and DSO could be simplified to:

$$min \int_{t0}^{t1} \Big(k_{customer} \big(C_{e\,customer}(t) \big) + k_{retailer} \big(C_{e\,retailer}(t) \big) + k_{dso} \Big(C_{investment}(t) + C_{loss}(t) + C_{intr}(t) + C_{oper}(t) \Big) \Big) dt \qquad (1)$$

where,

$k_{customer}$	=	Priority factor for customer
$C_{e\ customer}$	=	Cost of electricity for customer
$k_{retailer}$	=	Priority factor for retailer
$C_{e\ retailer}$	=	Cost of electricity for retailer
k_{dso}	=	Priority factor for DSO
$C_{investment}$	=	Cost of investments
C_{loss}	=	Cost of losses
C_{intr}	=	Cost of interruptions
C_{oper}	=	Cost of operation
Δt	=	Planning period

The presented formula optimizes charging based on electricity cost for customer and electricity retailer while including DSO's costs of transferring the electricity, thus producing optimal time frame for charging period according to priority factors. Furthermore, by adding additional optimization methods, the system can be modified to prioritize certain methods or actors.

Customer Objective

Customer's objective is to minimize the cost of charging events of the EV, charging or discharging (if possible). Hence, the objective consist from two main parts:

- Charging
  - Minimize cost of electricity
- Discharging
  - Maximize cost of electricity or refund (compensation for discharging)
  - Minimize cost of discharging batteries

While charging, the cost of batteries have no impact compared to normal charging, only the time when the charging period occur differs. Hence, only cost of the charged electricity varies between normal and smart charging. However, normal charging procedure does not support discharging (V2G) and therefore discharging has additional cost from discharging the batteries, thus shortening the life time of the battery pack. However, energy supplied by discharging batteries is being refunded following price of electricity or some other agreed method.

The cost and refund of electricity is determined by the electricity contract with the electricity retailer. The contract also defines if the cost or refund has any time variable like day and night tariff or market price based tariff. Hence, if the electricity contract has static tariff, customer's costs have no effect from the charging moment, making optimization redundant. However, if the tariff is market price based, the objective of the customer is similar with the electricity retailer's objective.

In this study, the electricity price of the customer is based on the day and night tariff and only the charging objective is used. Hence, the optimization algorithm objectives can be simplified to minimize the static hours of lower electricity price (night tariff), specified in the electricity contract between the customer and electricity retailer. Therefore, the optimization algorithm can be written from consumer perspective as follows:

$$min \int_{t0}^{t1} Electricity(t)\, dt \qquad (2)$$

where,

$Electricity(t)$	=	time depended fixed electricity price
Δt	=	Charging period

Electricity Retailer Objective

Electricity retailer's objective is to buy as cheap electricity as possible from the electricity markets or electricity producers and sell it further with a profit margin and competitive price to a customer. Hence, the smart charging objective for retailer is to be able to charge electric vehicles during the lowest price hours. However, as the electricity markets have multiple different electricity products, it might also be beneficial to charge during higher price hours to balance out fixed or day-ahead electricity contracts, thus avoiding balancing markets.

In this study, the objective for electricity retailer is simplified to follow the day-ahead transaction price (Elspot) of Nordic electricity markets. Hence, the optimization objective can be presented in two parts:

- Charging
  - Minimize cost of electricity
- Discharging
  - Maximize cost of electricity
  - Take into account cost of refunding (compensation to customer)

During the charging period, electricity retailer aims to avoid higher price hours and shifts the charging period to lower price hours. In addition, while optimizing possible discharging period, electricity retailer calculates net gain from supplying power from the customer EV at high price hours against the compensation to customer for discharging the EV's batteries. Only if the net gain is positive and profit margin is high enough for the retailer, discharging period is realized. Furthermore, electricity retailer can gain additional revenue by providing load shifting service for other actors (such as DSO).

In this study, the optimization objective for electricity retailer is based on day-ahead transaction prices and only charging objective is used. Thus, the objective is to shift the charging period to lower Elspot prices, minimizing the cost of charging event. Hence, the objective can be simplified to following formula:

$$min \int_{t0}^{t1} Elspot(t)\, dt \qquad (3)$$

where,

$Elspot(t)$	=	time depended day-ahead electricity price
Δt	=	Charging period

Distribution System Operator Objective

DSO's main objective is to minimize costs of distribution grid by minimizing investment, loss, operational and interruption costs. Translating objective to correspond charging events means avoiding unnecessary reinforcement investments and avoiding interruptions. However, requirement of reinforcement investment are dependent on behaviour of peak power on specific feeder. Hence, DSO objective is to avoid or delay the increase in peak power produced by charging events such as illustrated in Figure 3.

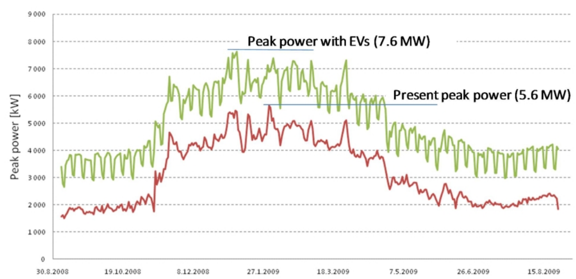

Figure 2. One-year load curve with EVs (topmost). The bottom curve illustrates the powers without EVs. The curves include the peak powers of each day; the minimum loads of the days are not presented. Figure presented in [3].

Therefore, unlike customer and electricity retailer objectives, the DSO objective is dependent on size of the peak power increment, with a defined marginal cost (€/kW) for the specific distribution network, in addition to interruption costs:

- Charging
  - Minimize load during peak hours
- Discharging
  - Minimize load during peak hours
  - Minimize interruption costs

In this study, the DSO objective is simplified to minimize load during charging period, shifting charging event to lowest load hours. Thus, the objective can be presented with the following formula:

$$min \int_{t0}^{t1} P_{forecast}(t)\, dt \qquad (4)$$

where,

$P_{forecast}(t)$	=	time depended load forecast
Δt	=	Charging period

Smart Charging Method

The economic efficiency of the optimization methods are tested with smart charging pilot, functional PHEV (Plug-in Hybrid Electric Vehicle), capable of charging and discharging according to smart charging system control. The smart charging system controls the pilot vehicle realizing given charging period.

Optimization algorithm forms a charging period for the vehicle by utilizing information gained from the pilot PHEV and the actors involved with the optimization. The necessary information for performing the optimization is:

- PHEV
  - State of Charge (SOC)
  - Battery capacity
  - Charging power
  - Time of departure
- Customer
  - Cost curve of electricity price
- Electricity retailer
  - Cost curve of Elspot price
- Distribution system operator
  - Load forecast

The optimization uses SOC, battery capacity and charging power to calculate the duration of the charging event in minutes. Utilizing provided time of departure, optimization forms a charging window where the charging event should occur. Applying the different actor objectives, the optimization distributes the necessary charging minutes along the charging window.

In this study, two different charging windows are used. Time of departure in both charging windows is the same, next day at 7am. However, the smart charging optimization is executed on two separate times, 12am and 2:30pm.

The first charging window has only current day Elspot prices available, thus the charging window starts at 12am and ends at 12pm current day. The second charging window has also next day Elspot prices available in addition to static customer prices and 24 hour load forecast, therefore being able to form charging window between 2:30pm current day and 7am next day. The load forecast is based on gathered data of load consumption of LUT, taking average of two previous weeks. In addition, the smart charging optimization uses floating average of 10 minutes to prevent short periods of charging.

Costs of Actors

The customer optimization uses electricity tariff with different fixed prices for day and night, 5.5 cent/kWh (55 €/MWh) and 4.9 cent/kWh (49 €/MWh) respectively. The night tariff starts at 10pm and ends at 6am. By applying the prices along the charging window, smart charging optimization algorithm forms a cost curve for the customer. The cost curve for customer during first charging window is presented in Figure 4 and during second charging window in Figure 5.

The optimization of the electricity retailer is fully dependent on Elspot. Therefore, the curve formed by smart charging optimization is based on available future Elspot prices. The cost curve for electricity retailer during the first charging window is presented in Figure 4 and during the second charging window in Figure 5.

While the optimization of DSO is based on minimizing load with the load forecast, the optimization method does not have well-defined cost for different load values. In this study, cost of load variation is determined by using maximum and minimum values of the load forecast, neglecting base load. Furthermore, the cost is defined as service payment for load shifting, maximizing the payment for shifting load to minimum load. The maximum service cost in this study is set to 25 €/MWh, roughly half of the typical distribution fee in Finland. Hence, the DSO objective formula can be written:

$$min \int_{t0}^{t1} \frac{C_{service}\left(\max\left(P_{forecast}(t)\right) - P_{forecast}(t)\right)}{\max\left(P_{forecast}(t)\right) - \min\left(P_{forecast}(t)\right)}\, dt \qquad (5)$$

where,

$P_{forecast}(t)$	=	time depended load forecast
$C_{service}$	=	Cost of service
Δt	=	Charging period

By utilizing formula (5), the smart charging optimization algorithm forms a cost curve for DSO. The cost curve for the first charging window is presented in Figure 4 and the second charging window in Figure 5.

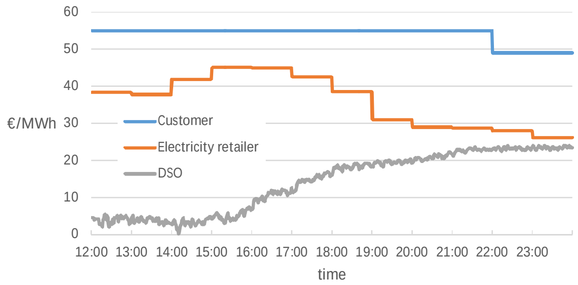

Figure 3. Cost curves of customer, electricity retailer and distribution system operator during the first charging window.

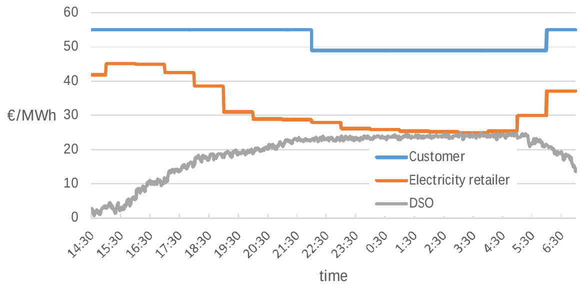

Figure 4. Cost curves of customer, electricity retailer and distribution system operator during the second charging window.

Smart Charging Optimization

The smart charging optimization utilizes the cost curves presented in Figure 4 and 5 to form the most economical charging periods for the given charging window. The optimization is based on the previously presented formula (1), minimizing costs of different actors. However, the optimization does not take into account of the presented costs of DSO in the formula (1). On the contrary, optimization algorithm uses formula (5) to represent the objective of the DSO. Applying the modification in addition to formulas (2) and (3), the optimizing formula to minimize the costs of the actors can be presented as:

$$min \int_{t0}^{t1} \Bigg(k_{customer} Electricity(t) + k_{retailer} Elspot(t) - k_{DSO} \left(\frac{C_{service} \times \left(\max\left(P_{forecast}(t)\right) - P_{forecast}(t)\right)}{\max\left(P_{forecast}(t)\right) - \min\left(P_{forecast}(t)\right)} \right) \Bigg)\, dt \qquad (6)$$

Before the optimization algorithm runs the presented formula (6), the algorithm fetches necessary information of the PHEV from Green Campus database to form the charging window. The information is presented in Table I.

Table I. Necessary information of PHEV for smart charging optimization to form a charging window.

SOC [%]	Capacity [Wh]	Charging power [W]	Time of departure
41	4200	1000	2015-01-16 07:00:00

The optimization algorithm calculates length of charging window (149 minutes in this case) and allocates the charging period in charging window using formula (6) with the floating average of 10 minutes. The formed smart charging period and the cost efficiency curve in addition to a normal charging period (starting from 4pm) is presented in Figure 6 for first charging window and in Figure 7 for second charging window.

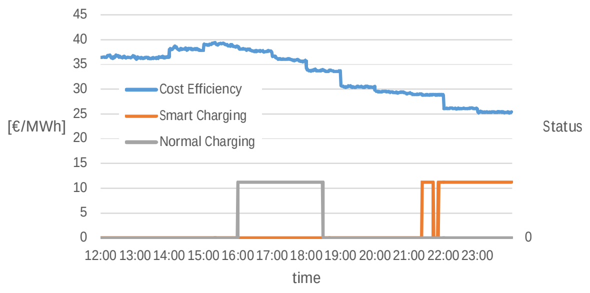

Figure 5. Normal charging and smart charging periods for first charging window. Smart charging period is formed by minimizing cost efficiency curve. Cost efficiency curve priority factors are $k_{customer}$ = 0.4, $k_{retailer}$ = 0.4 and k_{dso} = 0.2.

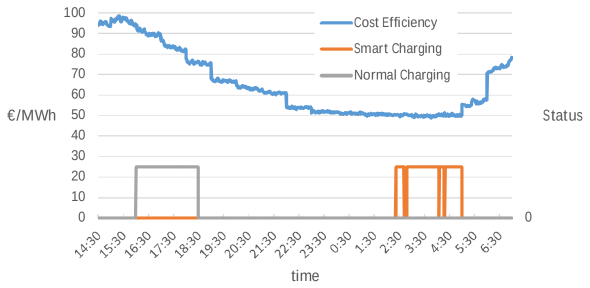

Figure 6. Normal charging and smart charging periods for first charging window. Smart charging period is formed by minimizing cost efficiency curve. Cost efficiency curve priority factors are $k_{customer}$ = 1.0, $k_{retailer}$ = 1.0 and k_{dso} = 1.0.

As illustrated in Figure 6 and 7, the smart charging period is allocated during the lowest values of the cost efficiency curve. The charging periods are fragmented in both cases because the optimization is allocating charging minutes according to the DSO cost curve's minimum values.

Smart Charging Results

The cost efficiency of the smart charging is determined by comparing it to normal charging (PHEV is plugged in at 4pm). The customer's and electricity retailer's costs are compared with the costs of the charging events. However, the DSO cost curve is not fully comparable as DSO service payments were a replacement for the original costs, a method to take load variation into account in the optimization algorithm. However, by calculating relative costs between charging methods, an indicative estimation of the load shifting cost efficiency can be given for the DSO. The costs of smart charging compared to normal charging for actors in both charging windows are presented in Table II.

Table II. The cost difference between normal and smart charging for actors in first and second charging windows.

	Charging window 1		Charging window 2	
	Cost [€]	Cost [%]	Cost [€]	Cost [%]
Customer	-0.012	-8.79	-0.015	-10.91
Retailer	-0.038	-35.90	-0.044	-41.19
DSO	0.024	69.66	0.028	86.32

The charged energy was 2480 Wh in both charging windows. As can be seen from the Table II, the profit gained from smart charging compared to normal charging as a single charging event is low. However, the relative difference between the costs are significant.

Furthermore, the second charging window has lower costs compared to first charging window based on the low electricity price hours, which were not available during the first charging window. In the second charging window customer's costs have decreased almost 11%, convergent between day and night tariffs. With Elspot based tariff, the customer could have achieved the same cost reduction than the electricity retailer, 41% respectively.

In both charging windows, the DSO has high relative cost. Hence, it indicates that the shifting of the charging event from day hours to night hours is beneficial for the DSO.

CONCLUSION

The key target of this study has been to present the economic efficiency of smart charging in smart grid environment. With necessary information available, charging event of the electric vehicle can be optimized to minimize the charging costs for multiple actors.

By utilizing available data, cost curves for different actors are formed. The cost minimizing optimization is applied based on the cost curves, forming a charging period. With the smart charging optimization, the economic efficiency of a charging event can be increased for customer, electricity retailer and distribution system operator.

In the future studies, discharging possibility is taken into account in the optimization algorithm. With the discharging capability, the pilot PHEV provides research platform for more complex optimization tools.

REFERENCES

[1] Green eMotion, [Online] [16 January 2015] http://www.greenemotion-project.eu

[2] H. Makkonen et al., 2014, "Demonstration of Smart Charging Interface in Green Campus", *Proceedings EPE'14-ECCE Europe conference*, Lappeenranta, Finland.

[3] J. Lassila et al., 2011, "Network Effects of Electric Vehicles - Case from Nordic Country", *Proceedings CIRED conference*, Frankfurt, Germany.