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Control of EV Charging and BESS to Reduce Peak Powers in Domestic Real Estate

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Abstract – *The paper discusses the effects of electric vehicle (EV) charging and battery energy storage systems (BESS) on monthly peak powers in domestic apartment buildings. The introduced control method for both EV charging and BESS utilizes real-time measurements and memorized peak power consumptions to determine the available power before exceeding the previous peak power. This kind of control method could lead to cost savings if the power-based distribution tariff of distribution system operators (DSO) includes a price component based on monthly peak power. Some Finnish DSOs have also launched this kind of power-based distribution tariff for small-scale customers. Simulations indicate that EVs can likely be charged without increasing the monthly peak powers of real estate when EV penetration is relatively small. Higher EV penetration would lead to a higher risk of some EVs to not fully charge. There are also indications that BESS can be effective in limiting monthly peak powers when utilizing the peak saving control method.* **Copyright © 2009 Praise Worthy Prize S.r.l. - All rights reserved.**

***Keywords**: BESS, EV Charging, Peak Load Management, Power-Based Distribution Tariff*

Nomenclature

$\eta_{B,C}$	BESS charging efficiency
$\eta_{B,D}$	BESS discharging efficiency
η_{CP}	Charging point efficiency
η_{I}	Inverter efficiency
$E_{B,max}$	Maximum state of charge of BESS
$E_{B,SOC}$	State of charge of the BESS
$E_{EV,miss}$	Missing energy of EV before becoming fully charged
$P_{B,C}$	BESS charging power
$P_{B,C,max}$	Maximum BESS charging power
$P_{B,C,max,p}$	Maximum BESS charging power which has already taken battery SOC into account
$P_{B,D}$	Battery discharging power
$P_{B,D,max}$	Maximum BESS discharging power
$P_{B,D,max,p}$	Maximum BESS discharging power which has already taken battery SOC into account
$P_{CP,max}$	Maximum power of a charging point
P_{EV}	Charging power of a single EV
$P_{EV,C,max}$	Maximum charging power of EV
$P_{Grid,f}$	Power taken from the grid
$P_{Grid,max,f}$	Limit for the power taken from the grid due to the main fuse
$P_{Grid,f,mm}$	Maximum measured peak power of the ongoing month
$P_{Grid,t}$	Power injected to the grid
$P_{Grid,max,t}$	Limit for the power injected to the grid due to the main fuse
$P_{I,max}$	Maximum output power from inverter
$P_{I,out}$	Power from PV system after inverter losses
P_{Load}	Total load of the building and EV charging
$P_{Load,ab}$	Power consumption of the apartment building
$P_{Load,EV}$	Total EV charging power
$P_{Local,out}$	Total power output from PV system and BESS
P_{PV}	Power from PV system

I. Introduction

The interest in EVs has increased globally. For example, the Finnish government has set a target for Finland to acquire 250 000 EVs by 2030 [1]. With the current relative growth of EVs, this target might be achieved much sooner. Although the target EV count is equivalent to an EV penetration of less than 10%, the importance of smart charging should not be overlooked. Over the last few years, a lot of research has centered on controlling EV charging. Some work has been made, e.g., in [2] and [3], where the EV charging power is limited based on the limits of the feeder. EV charging peak load–related studies are presented, e.g., in [4], [5], [6], and [7], in which the principle for mitigating the increase of peak load is based on scheduling the EV charging. In [8], a valley-filling control method has been introduced, making the increase of peak powers negligible. However, the research lacks studies of peak power–related problems and their solutions in the internal networks of domestic real estate with charging station groups.

In recent years, there has been ongoing discussion in Europe on shifting DSOs' distribution tariffs in a power-based direction. This means that in addition to or instead of traditional basic (€/month) and volumetric charges

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(€/kWh), there would be a tariff component (€/kW) based on peak power of some time period, i.e., the latest year or month. It is worth noting that as peak power is the highest average power taken from the grid in any 1-hour time period, momentary power consumption can be higher. Power-based distribution tariffs are enabled by a rollout of smart meters. In Finland, the electricity consumption of >99% of network customers including households is measured by smart meters [9]. As some distribution system operators in Finland have already started using power-based distribution tariffs for small-scale customers, suboptimal control of EV charging could cause an unnecessary increase in operational costs for EV owners or their apartment buildings. Therefore, it is reasonable to investigate options to reduce peak powers.

BESS and photovoltaic (PV) system could be utilized for the whole building's load if the energy community model is used; the apartments form an energy community, which makes only common contracts with the energy retailer and DSO when all electricity purchased by the building from the grid or grid feed is measured with one meter. The problem is that the law requires that every customer have the possibility to tender out energy retailers. The energy community model is possible if all apartment owners accept and they have the possibility to resign from the community. This also requires each apartment to have its own electricity meters in addition to the common meter so the customers can divide the cost.

This paper investigates a simple peak-shaving control method in which the free power capacity of the feeder before exceeding the current peak power of the ongoing month is continuously calculated in order to determine the necessary actions. This control method can be applied to EV charging, where charging power is lowered if needed, and to BESS, which can be charged when free capacity is positive and discharged when free capacity is negative. The developed control method maximizes EV charging power while preventing unnecessary peak power increase. This could bring operational cost savings for apartment owners if a peak power-based distribution tariff component is used and the apartment building forms an energy community. To evaluate the viability of the introduced control method, potential cost savings will be calculated, and possible limitations are discussed.

The paper is organized as follows. In section II, the control method is introduced and discussed. In section III, the necessary initial data for the case study simulations are presented. Section IV represents the simulation results, and Section V finalizes the paper by presenting the conclusions and future work proposals.

II. The Control Method

Without a proper control method for EV charging, monthly peak powers, for example of an apartment building, could increase notably. The monthly peak power will likely be a popular basis to charge the power-based fee by DSOs in the future. The idea of this control method is that the total load of the whole real estate is measured in real-time, and the highest peak load of the ongoing month is memorized by the control system. The free capacity before exceeding the current peak load can then be continuously calculated to determine if EV charging power should be decreased or increased, or if BESS should be charged or discharged.

The main principle of the system structure is illustrated in Figure 1. According to the standard IEC 61851-1, this kind of control method is possible in mode 3 EV charging, where the charging station can restrict and adjust the maximum AC charging current (per phase) between 6 A and 80 A. Figures 2 and 3 illustrate the control method operation when applied to EV charging or BESS, respectively. The feeder limit shown in Figure 2 is there to ensure that the charging power would not exceed the limits of the fuse or the cable of the EV charging feeder. The highest memorized peak power should be reset at the beginning of each month so that previous months would not affect the peak power of the ongoing month.

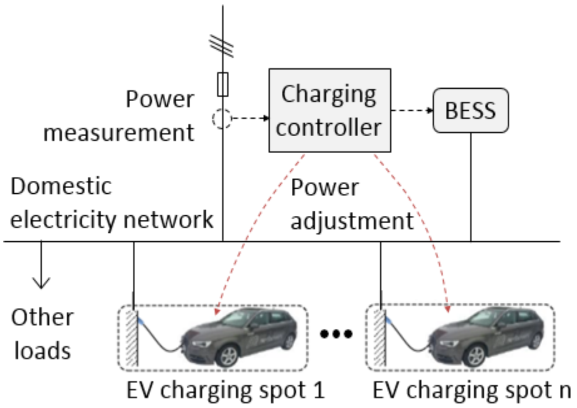

Fig. 1. The basic setup of the control method.

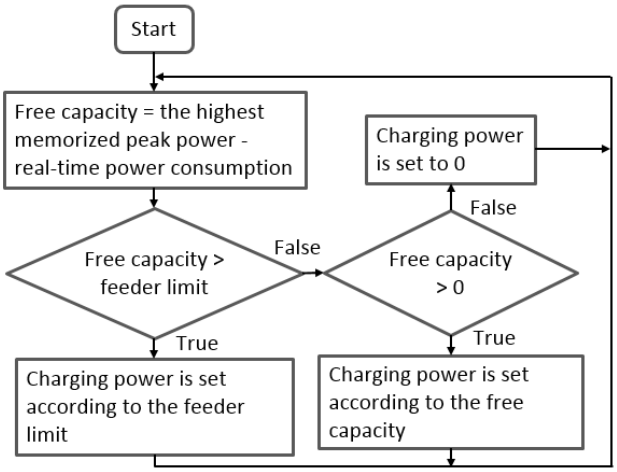

Fig. 2. Simplified block diagram of the control method for EV charging.

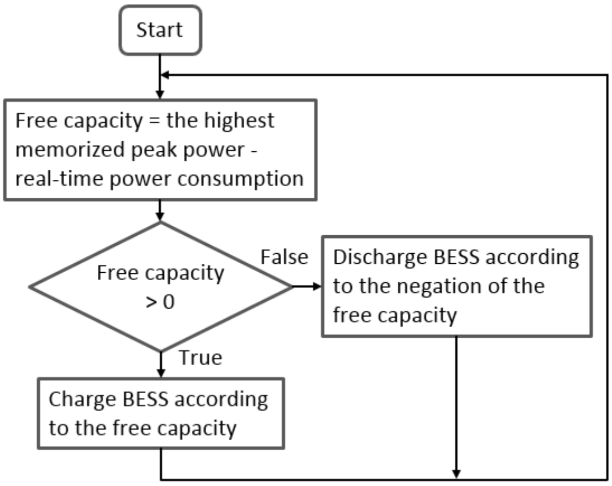

Fig. 3. Simplified block diagram of the control method for BESS.

As shown in Figure 3, BESS should be charged when the free capacity is positive and discharge when the free capacity is negative. Charging power should be limited according to the free capacity to increase the state of charge (SOC) of BESS as fast as possible without increasing monthly peak powers. Discharging power should be limited according to the free capacity to avoid increasing monthly peak powers while keeping the remaining SOC as high as possible. In addition to these, battery properties like the maximum charging and discharging powers and the maximum and the minimum SOC levels should also be taken into account.

In simulations of this case study, the total power consumption of the final hour of the previous month is used as a starting value for the memorized peak power of the new month. Another simple option would be to reset the memorized peak power of the new month to 0. However, preliminary simulations indicated that the selected method would result in lower monthly peak powers and lower uncharged energy of the EVs on average.

III. Simulation Data and Modeling

III.1. Case Description

The investigated case is called "Tammela," which is an apartment building built in 1980 in Finland. Between 2013 and 2015, various renovations have been made, which have resulted in a 67% reduction in purchased energy. However, the share of electrical energy has increased and resulted in electrical energy consumption to increase by around 30%. This is caused by the installation of exhaust air heat pumps, where produced heat energy replaces the purchase of energy from district heating. In the simulations, the models included eight charging points, a PV system, and a BESS for "Tammela." These eight charging points are modeled for daily use and equal to a local EV penetration of approximately 15%. Simulations were carried out based on long-term electricity consumption measurements made in the apartment building and electricity production measurements of a 30 kW PV system. Consumption data were measured in 2013–2016 in one-hour intervals, and the PV production data was measured in 2017 in five-minute intervals.

Figure 4 illustrates the modeled system. The BESS is modeled so that it can be charged with energy from the PV system or from the grid. In the simulations, the BESS' usable energy capacity, maximum charging/discharging power, and charging/discharging efficiencies are selected to be 35 kWh, 10 kW, and 0.96, respectively. These parameters are based on a BESS found on the market [10] but multiplied by four (except the efficiency) to make it more impactful for the apartment building. Lithium-ion batteries typically have a high efficiency of 0.95–0.98 [11]–[13]. The selected BESS power and energy capacity is a few times larger than the ones meant for a single household mentioned in [11], [14], and [15]. Therefore, the BESS is assumed to be reasonable and yet its control method is expected to have an impact on the peak powers of the apartment building.

The simulation focuses on a charging power of 3.7 kW per charging point, which should be roughly suitable for almost every commercial EV. As EV charging presumably takes place mostly at night, there is no urgent need for a higher charging power. Furthermore, simulations investigate scenarios where the total charging power of the whole charging station group can be limited to 11 kW, or to 11 kW and according to the control method. By limiting the maximum total power of the EV charging system, cheaper feeding cables and smaller network connections can be used. This can result in lower investment costs and in some cases in smaller distribution fees without a notable effect on EV charging times. Even though the total charging power limit of 11 kW is under half of the combined power of all eight charging points, the simulations do not indicate that it has a negative impact on EV charging. This is likely due to long-available charging times and the reasonable energy demands of EVs, as presented in the following subsection.

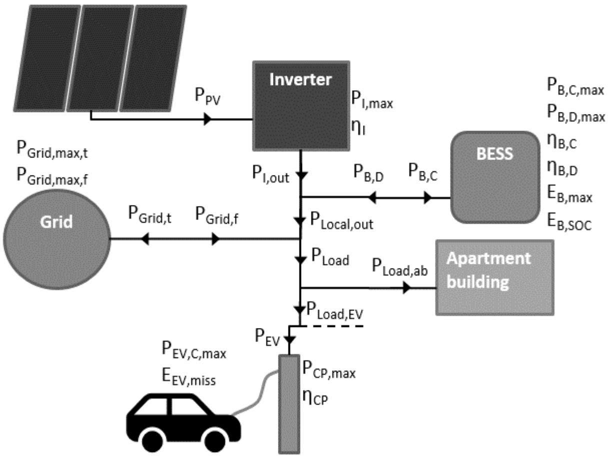

Fig. 4. System arrangement behind the simulations.

III.2. EV Load Modeling

According to Statistics Finland, the average travel distance per passenger car in Finland was 14 000 km/a in 2017 [16], which would be around 38.4 km/day on average. Assuming that a typical EV energy consumption is 0.25 kWh/km, this would lead to a daily charging energy need of 9.6 kWh, which is also close to the typical battery capacity of most common plug-in hybrid EVs in Finland. If charging losses in an EV are assumed to be 10%, the average daily energy needed from the charging point will be around 10.7 kWh. The investigated case is an apartment building, and EV charging is therefore assumed to occur in the afternoon and night.

To add variety to daily charging sessions, they are simulated to start between 16.30 and 20.00 and end between 6.00 and 8.30. The energy needed for the charging sessions has also been multiplied with factors of 0.5–2.0 in a way that the average energy need of an EV remains at 9.6 kWh. The schedule for the use of each charging point (CP) has been presented in Table I. Possible bigger energy needs for full electric vehicles (FEV) are left out of this study.

TABLE I
DAILY CHARGING SCHEDULE OF EVS

EV	Arrival	Departure	Missing energy (Wh)
1.	18:30	6:45	10416
2.	19:45	6:15	17904
3.	16:45	8:00	5040
4.	19:00	7:15	11424
5.	17:45	7:45	8256
6.	19:15	6:00	6384
7.	18:15	8:30	10560
8.	17:15	7:15	6816

III.3. System Modeling

The introduced control method discharges BESS when power taken from the grid is about to exceed the current month's highest peak power. The BESS is also controlled to discharge to allow a higher EV charging power when needed. If power taken from the grid is below the peak power, BESS will be charged. Power used for battery charging $P_{B,C}$ can be calculated according to (1),

$$P_{B,C} = \min(P_{B,C,max,p}, \max(0, P_{I,out} - P_{Load} + P_{Grid,f,mm})) \tag{1}$$

where $P_{B,C,max,p}$ is the maximum power that BESS can receive, $P_{I,out}$ is power from the PV system after inverter losses, P_{Load} is the sum load of the building and EV charging, and $P_{Grid,f,mm}$ is the measured maximum peak power of the ongoing month. Power discharged from BESS $P_{B,D}$ can be calculated according to (2),

$$P_{B,D} = \min(P_{B,D,max,p}, \max(0, -P_{I,out} + P_{Load} - P_{Grid,f,mm})) \tag{2}$$

where $P_{B,D,max,p}$ is the maximum power that BESS can discharge.

Power needed from the grid $P_{Grid,f}$ can be calculated according to (3),

$$P_{Grid,f} = \min(P_{Load} - P_{Local,out}, P_{Grid,max,f}, \max(P_{Grid,f,month,max}, P_{Load,ab} - P_{Local,out})) \tag{3}$$

where $P_{Grid,max,f}$ is the limit of power taken from the grid due to the main fuse, $P_{Load,ab}$ is the consumption of the apartment building, and $P_{Local,out}$ is power coming from the PV system and BESS. Simulations use a time step of 15 minutes, which allows a whole year to be simulated within a reasonable amount of time. In order to use the measured consumption data of the apartment building in the simulations, an interpolation was necessary to change the time step of 1 hour to 15 min. This was done by simply dividing each of the 1-hour energy consumptions evenly for four parts.

IV. Simulation Results

To evaluate the effects of different settings, simulations have been carried out for 11 scenarios. These scenarios have been listed in Table II. Each simulation is done for a period of one year so that we can examine monthly peak powers for every month. At first, all scenarios are calculated using the newest consumption data of the apartment building (2016) in subsections IV.1.–IV.3. In subsection IV.4., simulations are carried out using consumption data of the apartment building during 2013 – 2016 to ensure that the results are repetitive.

TABLE II
SIMULATION SCENARIOS

Scenario	Explanation
1.	Only apartment building
2.	Uncontrolled EV charging with 3.7 kW CPs
3.	Uncontrolled EV charging with 1.8 kW CPs
4.	EV charging with 3.7 kW CPs, where the total EV charging power is limited to 11 kW
5.	EV charging with 3.7 kW CPs, where the total EV charging power is limited to 11 kW and the introduced peak saving control method is in use
6.	Apartment building with 30 kW PV system
7.	Scenarios 5 and 6 combined
8.	Apartment building with 35 kWh / 10 kW BESS, which is controlled with the control method
9.	Scenarios 5 and 8 combined
10.	Scenarios 6 and 8 combined
11.	Scenarios 5 and 10 combined

Each scenario includes the consumption for the apartment building.
CPs = Charging points

IV.1. EV Charging Scenarios

It is well known that uncontrolled EV charging can cause significant peaks in power consumption [4]–[6]. Figure 5 illustrates the EV charging load curves of scenarios 1–5. It can be seen that both the peak power of apartment building and that of an uncontrolled EV charging occur in the evening, resulting in increased peak power in the day, presented in Figure 5. In scenario 5, EV charging power is limited to the peak power of the ongoing month. This peak power is 30.9 kW in Figure 5, which causes EV charging to drop around 20:00–21:00.

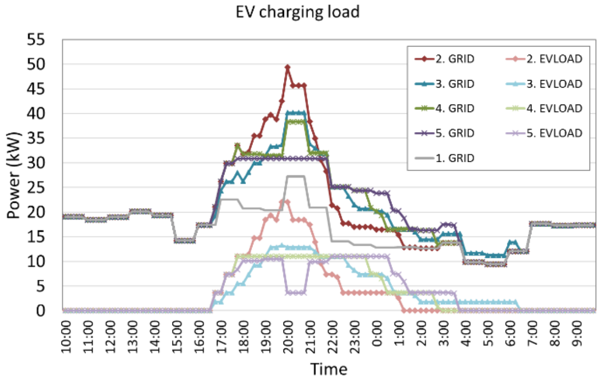

Fig. 5. Simulation results of scenarios 1–5.

As seen in Figure 6, scenario 2 results in quite a high increase in monthly peak powers, whereas in scenario 5, monthly peak powers will stay the same. For scenarios 2–5, the average relative increase in monthly peak power compared to scenario 1 is 23.9%, 13.1%, 16.6%, and 0.0%, respectively.

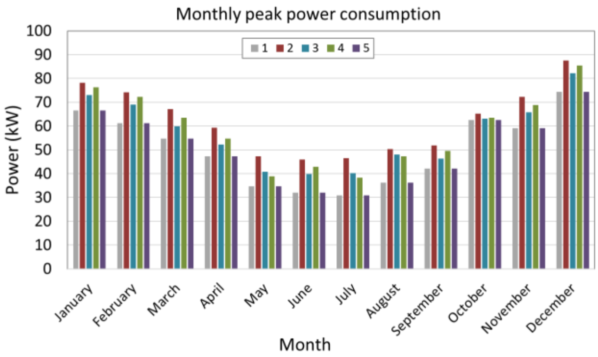

Fig. 6. Simulation results of scenarios 1–5.

IV.2. Effects of PV and BESS on Peak Powers of the Apartment Building

Figure 7 illustrates the effects of PV and BESS on the monthly peak powers of the apartment building. These scenarios (1, 6, 8, and 10) do not include EV charging and are therefore comparable to each other. The average relative decrease in monthly peak powers compared to scenario 1 is 4.6%, 17.2%, and 22.0% for scenarios 6, 8, and 10, respectively. Although the PV system is more often seen as a way to reduce energy consumption, it can also reduce monthly peak powers in the summer. However, from the DSO's point of view, this might not be very useful as the grid must be planned according to the worst-case scenario, which is more often during the winter in Finland.

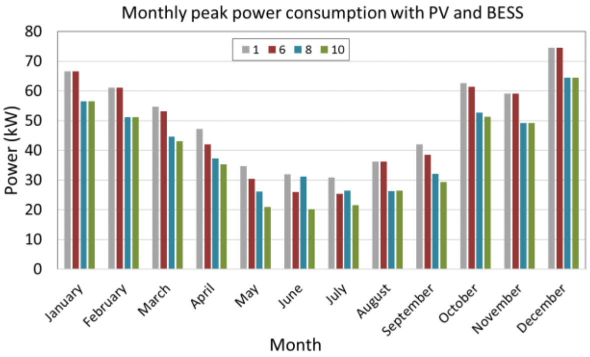

Fig. 7. Simulation results of scenarios 1, 6, 8, and 10.

IV.3. Effects of PV and BESS on Peak Powers of the Apartment Building with Controlled EV Charging

Figure 8 illustrates the effects of PV and BESS on the monthly peak powers of the real estate, which includes apartment buildings and controlled EV charging as in scenario 5. The average relative decrease in monthly peak powers compared to scenario 1 are 4.5%, 17.5%, and 21.5% for scenarios 7, 9, and 11, respectively. These results are close to the ones without EV charging that were stated above, which indicates that controlled EV charging would be possible without a notable increase to peak powers in real estate.

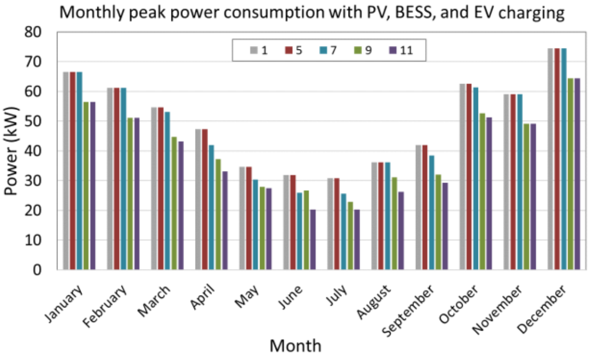

Fig. 8. Simulation results of scenarios 1, 5, 7, 9, and 11.

IV.4. Economic Effects of Different Scenarios

According to Figures 9 and 10, simulations give similar results when using different base power consumptions for the apartment building. The economic effect of each scenario can be calculated using the sum of monthly peak powers. If the cost of the increase in monthly peak power is 3.72 €/kW (including VAT 24%) [17], the average cost increase in a month for scenarios 2–5 compared to scenario 1 would be 47.3 €, 24.9 €, 30.5 €, and 0.0 €, respectively. As a side note, scenarios 2 and 3 would also require more expensive investment costs on the feeding cable as they allow higher maximum power for EV charging.

As seen in Figure 10, the PV system would also reduce the monthly peak powers by about 2.02 kW on average, which results in cost savings of 7.5 €/month. In turn, BESS would similarly reduce peak powers by 7.97 kW/month on average, which would result in a cost savings of 29.7 €/month. Again, combining the PV system and BESS would result in an average of 10.07 kW/month and 37.4 €/month. It can be noticed that combining PV and BESS seems to reduce peak powers slightly more than the sum of using only the PV system and BESS. It is also worth noting that using this control method, BESS seem to be very effective in reducing peak powers. This can be deduced from the fact that BESS, with a maximum discharging power of 10 kW as used in the simulations, can reduce monthly peak power by no more than 10 kW. Therefore, the average peak power reduction of 7.97 kW/month would be quite good.

One reason for the high effect of BESS might be the usage of saunas in the examined apartment building, which is likely to cause high and relatively short peaks in power consumption. If the used BESS has enough capacity, it might be able to mitigate the peak power consumption taken from the grid in these occasions and therefore lead to noteworthy results.

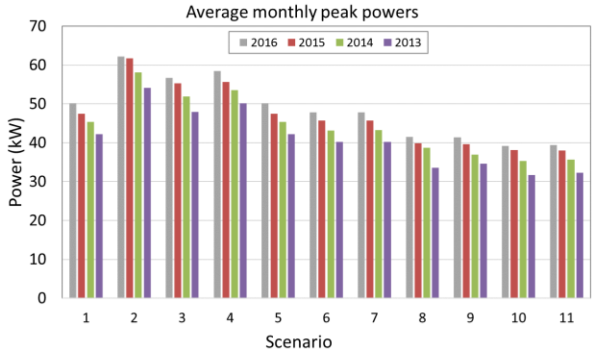

Fig. 9. Simulation results when using apartment building consumption data from 2013–2016.

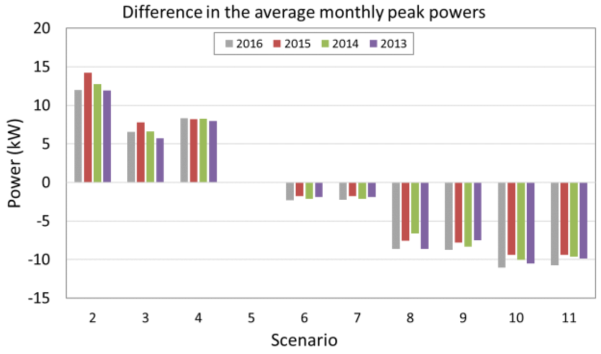

Fig. 10. Simulation results when using apartment building consumption data from 2013–2016.

IV.5. Limitations of the Control Method for EV charging

Figures 9 and 10 show that EV charging can be done without increasing the monthly peak powers of the real estate. The main downside of the introduced control method is the risk of EVs not being fully charged after a night of being plugged into a charging point. When using measured consumption data of the apartment building in 2013–2016, 11 of the 16 scenarios that used the control method for EV charging (scenarios 5, 7, 9, and 11) left some energy capacity of the EVs uncharged. The largest amount of uncharged energy occurred when simulating scenario 9 using the consumption data from 2013 for the apartment building. This energy was 11.2 kWh, which equals to 0.036% of the yearly total capacity of possible EV charging. This also means that an EV would still be completely uncharged 1.17 times per year on average after a night of being plugged into a charging point.

In the simulations, scenarios 9 and 11 use BESS to allow for higher power for EV charging. To execute this, the controller requires information from BESS about the available power that can be discharged. Besides that, this peak saving control method does require only smart metering of the real estate and charging points. Charging points require smart metering due to the fact that in mode 3 charging, the controller can only set the maximum current for a charging point, and the EV itself chooses a charging current below the limit. Therefore, the controller might not know the real power consumption of EV charging without smart metering.

V. Conclusion and Future Work

In conclusion, it can be stated that EV charging can be conducted alongside an apartment building without significantly increasing the monthly peak powers of the whole real estate. The control method, which uses memorized peak power for the ongoing month and real-time power measurements, can also be quite effective for controlling a BESS to reduce monthly peak powers. By assuming that the apartment building forms an energy community and distribution tariff includes a component based on monthly peak power, this kind of control method could bring operational cost savings.

The problem with the control method for EV charging is the risk of EVs remaining uncharged after a night of being plugged into a charging point. Although the uncharged energy seems to be relatively small in the simulated scenarios, it might raise concerns among the users of the EV charging system. The control method, as it is presented in this paper, will be particularly unfavorable for operators of FEV.

To avoid this problem with increased penetration of EV or FEV, the control method should allow peak powers to increase if necessary. The allowed increase of peak powers should be executed in a way that results in the EVs being fully charged while peak powers remain as low as possible. This might be a challenge as there are multiple unknown factors like EV departure time and energy demand of the EV, which the EV charging system controller might not be able to use for the optimization of the charging system. It should also be noted that in order to fully charge a typical full electric vehicle in one night, a charging power of 3.7 kW would most likely not be enough. It might be enough, however, to carry on the next day.

Future work could investigate different options to allow higher energy to be charged with a minimal increase in peak powers in case of a higher energy demand of EVs. Also, a more detailed analysis of the method, which resets the memorized peak power, could be conducted as it seems to have an impact on the uncharged energy according to preliminary simulations. Future work could include a thorough techno-economic analysis for both EV charging and BESS as well. Furthermore, a more comprehensive investigation of the impacts of different variables, like charging point power, feeder limit, BESS attributes, or the time step of the simulations, might be useful.

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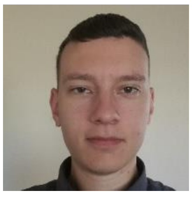

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