Title

Effects of Capacity Factor on Sizing of Energy Storage Systems for Electric Vehicle Charging Plazas

ISBN
979-8-3503-2774-8

Authors

Lappalainen, Kari
Kleissl, Jan

Publication Date
2023-11-24

DOI
10.1109/isgtasia54891.2023.10372638

Effects of Capacity Factor on Sizing of Energy Storage Systems for Electric Vehicle Charging Plazas

Kari Lappalainen
Electrical Engineering Unit
Tampere University
Tampere, Finland
kari.lappalainen@tuni.fi

Jan Kleissl
Center for Energy Research and Department of Mechanical and Aerospace Engineering
University of California, San Diego
San Diego, United States

Abstract—**This paper presents a study on the effects of capacity factor of electric vehicle (EV) charging plazas on sizing of energy storage systems (ESS) for peak load reduction of the charging plazas. The study is based on one year of measurement data from four fast charging stations from southern California, USA. The capacity factor of the charging stations was varied from 10% to 40% by duplicating the measured charging sessions to occur at the same time on a different day of the same type. Moreover, the size of the charging plaza was varied between 4 and 20 charging stations. The results show that the relatively highest ESS capacity is needed, and the utilization rate of the ESS is the largest, for highly utilized small-scale charging plazas. The required grid connection power of an EV charging plaza can be decreased considerably by an ESS with relatively small power and energy capacities.**

Index Terms-- **Charging stations, Electric vehicle charging, Electric vehicles, Energy storage systems, Load management**

I. INTRODUCTION

As part of the current energy transition, the movement towards electrified mobility is making rapid progress. The increasing number of electric vehicles (EV) and their fast charging stations might lead to severe problems for electrical grids. The significant power demand of the charging stations brings on a need for grid upgrade investments. Moreover, the highly intermittent energy demand of the charging stations complicates demand forecasting and might lead to grid stability issues. Energy storage systems (ESS) can be used to reduce the required connection power of an EV charging plaza by levelling its power demand. The ESSs can also be used to smooth fast variations in the power drawn from the grid by the charging plaza and for enhancing power outage resilience of the charging plaza.

Sizing of ESSs for EV charging plazas has been studied during the past few years considering several aspects like peak load reduction [1]–[4], resilience to power outages [2], [4], and costs of the ESS [2], [3], [5] and electricity [3], [5]. Sizes of the EV charging plazas and utilization rates of the charging stations affect the requirements of the ESSs and will likely increase over time. However, their effects have not been studied thoroughly so far. ESS energy requirements for peak load reduction of a charging plaza were studied in [1] varying the number of charging stations from 2 to 10. Moreover, the earlier studies, like [1], focused only on ESS energy requirements. However, also the required power capacity and utilization rate of the ESS play a central role in ESS sizing, but these aspects have received little attention.

The earlier studies in the field were mostly based on synthetic charging demand profiles instead of actual measurements. Synthetic charging demand profiles were created based on daily EV commuting profiles [5], probabilities of EV driving behavior [2], [4], and measurement-based probability distributions of charging sessions [1]. Synthetic charging profiles and measurements were compared in [6]. Although the temporal resolution of EV charging profiles affects the accuracy of the obtained results, the temporal resolution in EV charging modeling varies typically from 10 s [7] to 2 h [8] and the choice of the temporal resolution is not justified in most studies, like [2], [5]. The effects of the temporal resolution on the peak power of a fleet of EVs were investigated in [9] and the effects on the accuracy of EV charging load modeling were investigated in [10]. The results indicate that use of too low temporal resolution distorts the obtained results.

In this paper, the effects of charging plaza capacity factor, i.e., utilization rate of the charging stations of the charging plaza, on sizing of ESSs for peak load reduction of EV charging plazas is studied. This study addresses the main drawbacks of earlier studies: the required ESS energy and power capacities and utilization rate of the ESS are studied comprehensively based on one year of high-resolution measurements from four 62.5 kW direct current fast charging (DCFC) stations. The capacity factor of the charging stations was varied from 10% to 40% by increasing the number of charging sessions. The size of the charging plaza was varied between 4 and 20 DCFC stations by generating charging profiles for virtual stations by re-ordering the measured charging sessions of the four DCFC stations. The power limit (PL) below which the power drawn from the grid was limited

---

K. Lappalainen was funded by the Research Council of Finland (funding decision 348701) and J. Kleissl was funded by TotalEnergies.

by the ESS was varied from 6% to 100% with respect to the rated charging power of the charging plaza.

II. METHODS AND DATA

A. *Measurement data*

This study is based on one year of measurements from four ChargePoint DCFC stations located on the campus of the University of California, San Diego (UCSD). Two of the stations are at the East Campus Utility Plan (ECUP) parking lot and the other two are at the Osler parking structure in La Jolla, CA 92093, USA. The rated power of each station is 62.5 kW. However, each station is paired with another DCFC station so that if only one of them is in use, then the maximum power delivery to a single EV doubles to 125 kW.

In total 4,787 charging sessions occurred at the four DCFC stations during the year 2022. Charging sessions with missing charging duration or energy were removed leading to 4,087 charging sessions which were analyzed. The utilized charging session data consists of the times when charging started and ended, and the energy dispatched. Charging sessions with power higher than 62.5 kW were modeled as if there was only 62.5 kW available by removing the excess energy. The numbers and total durations of the charging sessions, capacity factors, and total energies dispatched are compiled in Table I for the four DCFC stations. The capacity factors of the DCFC stations range from 5.6% to 9.7% with Osler DCFC 1 being the most frequently utilized charging station. In this study, the capacity factor of the charging stations was varied from 10% to 40%. The lower limit of 10% is chosen as the highest capacity factor value of Table I.

TABLE I. NUMBER OF CHARGING SESSIONS, TOTAL CHARGING DURATION, CAPACITY FACTOR, AND TOTAL ENERGY DISPATCHED FOR THE STUDIED DCFC STATIONS.

Station	**Sessions**	**Total duration (h)**	**Capacity factor (%)**	**Energy dispatched (MWh)**
ECUP 1	795	493.3	5.63	12.5
ECUP 2	721	525.0	5.99	20.6
Osler DCFC 1	1475	846.5	9.66	32.5
Osler DCFC 2	1096	638.2	7.29	25.2

The number of charging sessions was increased by the following procedure to study the effects of the capacity factor. First, a charging session was randomly picked from the dataset of a DCFC station. Then it was duplicated to occur at the same time on a different day of the same type (holiday, weekday, weekend day). If the duplicated charging session overlaps with an existing one its start time was increased to 1 minute after the end of the previous charging session, i.e., 1 minute was assumed to be the time required to switch between drivers. The capacity factor of each DCFC station was increased to up to 40% by repeating this procedure. After that, the number of DCFC stations was increased beyond 4 by creating new stations by the following procedure. The starting dates of the measured charging sessions were changed by randomly reordering the days from each day type. Since a charging session may continue to next day, this reordering may lead to overlapping charging sessions after midnight. Thus, starting from the first charging session of the year we checked for overlapping sessions. The overlapping sessions were moved to start 1 minute after the end of the previous session. Four new DCFC stations were created by this procedure from the data of each real DCFC station. Finally, a power time series with a sampling frequency of 1 Hz was generated for each DCFC station by assuming constant charging power for each charging session between the times when EV charging started and ended. Differences between power time series generated in this way and actual electrical measurements are usually small [11].

Fig. 1 presents the highest total plaza EV charging power P_{EV} as a function of the capacity factor and number of DCFC stations. At small charging plaza sizes, the highest P_{EV} is close to 100% decreasing with increasing number of DCFC stations since the aggregate charging profile becomes flatter as the charging profiles of individual stations differ from each other. For charging plazas consisting of multiple charging stations, the highest P_{EV} increases with the increasing capacity factor as the probability of simultaneous charging of multiple EVs increases. For a single DCFC station, the highest P_{EV} is constant as a function of the capacity factor as the new charging sessions are duplicated from the existing ones, i.e., the highest P_{EV} stays constant when the number of charging sessions is increased.

The average P_{EV}, i.e., required minimum connection power for a charging plaza in case of perfect power levelling, with respect to the rated charging power is presented in Fig. 2 as a function of the capacity factor. The relative average P_{EV} increases with the increasing capacity factor as there are more charging sessions. The relative average P_{EV} is the same for all studied charging plaza sizes as it is simply the relative total energy charged divided by one year.

B. *Control strategy*

In this study, the ESS is sized to limit the power that the charging plaza draws from the grid P_{grid} below the applied PL. The PL is altered from the average P_{EV}, which varies from 6% to 23% depending on the capacity factor (Fig. 2), to 100% of

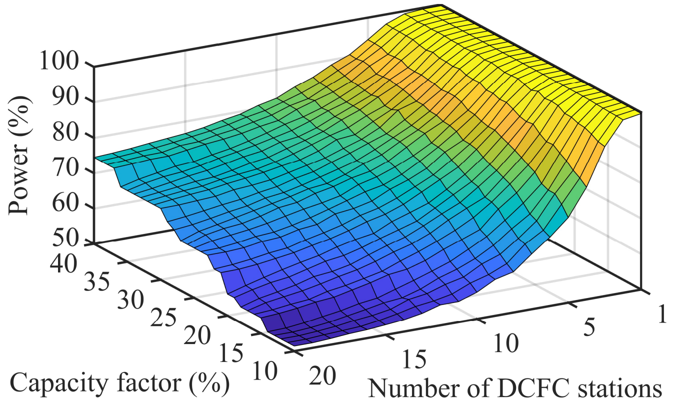

Figure 1. The highest EV charging power for a charging plaza with respect to the rated charging power as a function of the capacity factor and number of DCFC stations. The power values are calculated as averages of random DCFC station permutations limiting the number of permutations to 200.

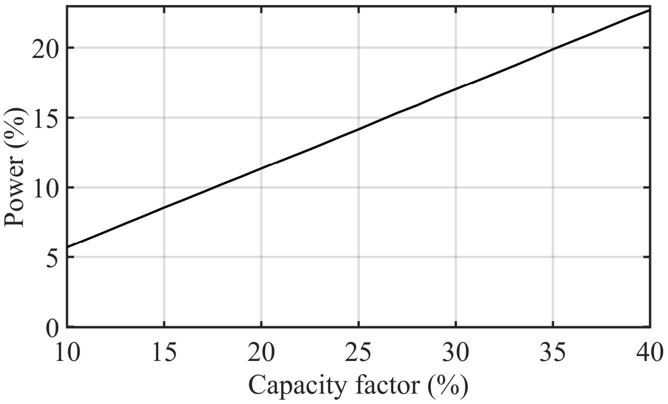

Figure 2. The average EV charging power for a charging plaza with respect to the rated charging power as a function of the capacity factor.

the rated charging power of the charging plaza. The minimum PL limit is selected based on Fig. 2 since PLs below the average P_{EV} are not feasible. The ESS was controlled as follows. The ESS discharges when the P_{EV} is more than the PL and charges when P_{EV} is less than the PL until the ESS is fully charged. The ESS was fully charged in the beginning of the studied year. Losses of the ESS and cables were not taken into account.

III. RESULTS AND DISCUSSION

Fig. 3 presents the highest power drawn from the grid, highest EV charging power, and highest power of the ESS for the charging plaza of 12 DCFC stations for capacity factors of 10% and 40% as a function of the PL. The highest (normalized) powers increase with increasing capacity factor since the frequency of simultaneous charging sessions increases. The highest P_{EV} is independent of the PL as EV charging power is not limited. At PLs lower than the highest P_{EV}, the highest P_{grid} equaled to the PL. In that PL region, the highest ESS discharging power decreases linearly as the sum of the ESS discharging power and P_{grid} equals P_{EV}. The highest ESS charging power equaled to P_{grid} for low PL values meaning that the highest ESS charging power occurred when all the power drawn from the grid was used to charge the ESS. At some PL value, the highest ESS charging power started to fluctuate until it became zero when the PL reached the highest P_{EV}. In that PL region, the highest ESS charging power occurred when P_{grid} was not used entirely to charge the ESS but part of it charged the EVs. Thus, the highest ESS charging power depends on the concurrent EV charging power. The erratic behavior of the ESS charging power is a result of using a rule-based ESS control strategy.

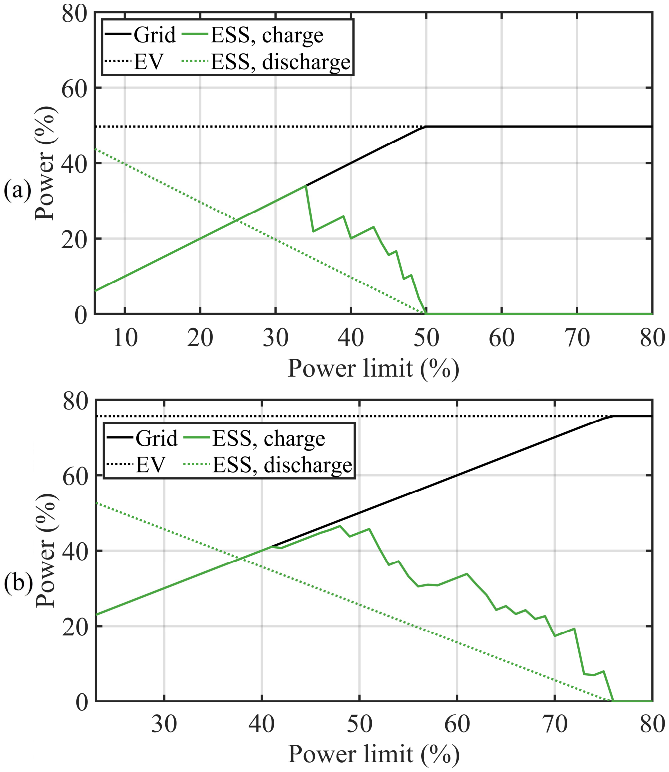

Figure 3. The highest power drawn from the grid, highest EV charging power, and highest ESS charging and discharging powers with respect to the rated charging power during the one-year period for 12 DCFC stations with capacity factors of 10% (a) and 40% (b) as a function of the power limit.

Fig. 4 presents the highest ESS power during the one-year period for several charging plaza sizes as a function of the PL and capacity factor. The highest ESS power means the ESS power capacity required to limit P_{grid} below the applied PL. The normalized powers decrease strongly with increasing charging plaza size. Moreover, they decrease with decreasing capacity factor, with greater decreases for larger charging plazas. Thus, the relatively highest ESS power capacity is needed for highly utilized small-scale charging plazas. The required power capacity changes as a function of the PL as was earlier explained by Fig. 3.

The required energy capacity of the ESS with respect to the rated charging power of the charging plaza is presented in Fig. 5 for several charging plaza sizes as a function of the PL and capacity factor. The required energy capacity decreases with increasing charging plaza size and PL. The increasing charging plaza size smooths the aggregate EV charging profile since the profiles of individual charging stations are not identical while the increasing PL reduces the need for power leveling. There are peaks at low PLs since the calculations were done with PL steps of 1%. The peaks are the higher the closer the lowest PL value is to the average P_{EV} determined by the capacity factor (Fig. 2), i.e., the required energy capacity increases strongly as the PL decreases closer to the average P_{EV}. The required energy capacity decreases with decreasing capacity factor as the occurrence frequency of simultaneous charging sessions decreases reducing the need for power leveling. The ESS energy capacities for charging plazas of 4 and 20 DCFC stations required to limit P_{grid} to 30% were 3.02 and 1.88 h, respectively, for a capacity factor of 40% while the corresponding values for a capacity factor of 20% were 0.85 and 0.27 h. For 20 DCFC stations, an ESS energy capacity of 3.34 h is sufficient for power leveling even with the highest studied capacity factor (40%) and a strict PL of 25%.

The utilization rate of the ESS can be illustrated by the energy cycled through the ESS which is also an indicator of the lifetime of the ESS that is typically rated in number of charge–discharge cycles. Fig. 6 presents the share of total EV charging energy cycled through the ESS for several charging plaza sizes as a function of the PL and capacity factor. Like

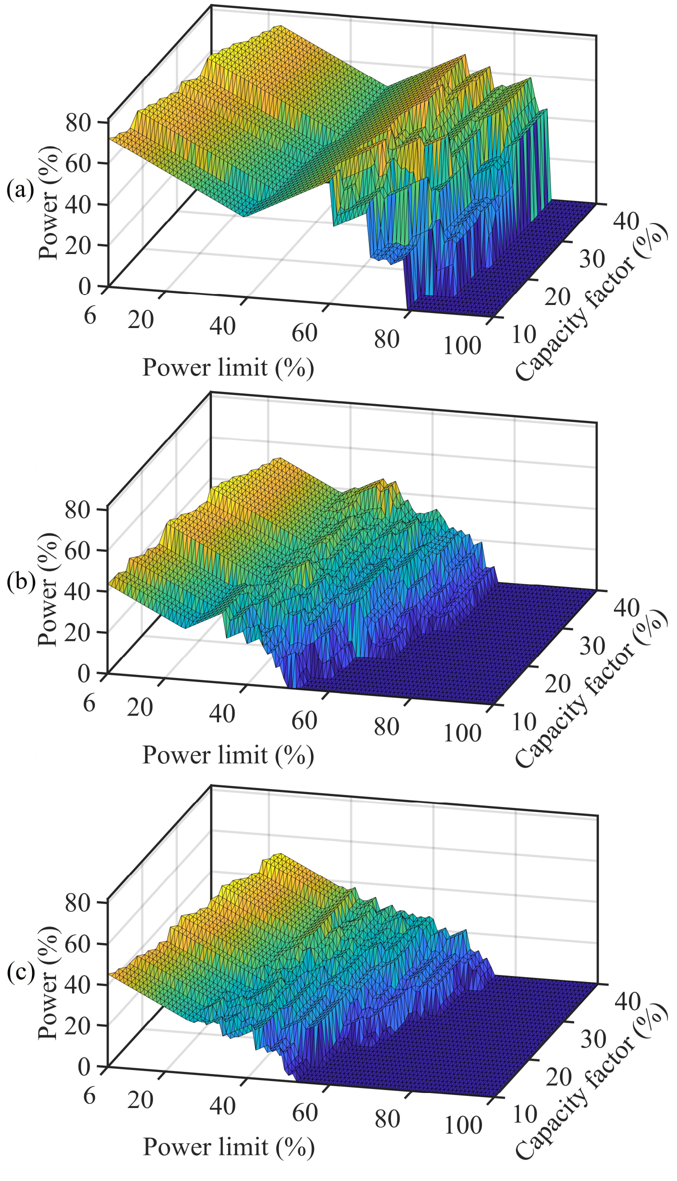

Figure 4. Required power capacity of the ESS with respect to the rated charging power during the one-year period for 4 (a), 12 (b), and 20 (c) DCFC stations as a function of the power limit and capacity factor.

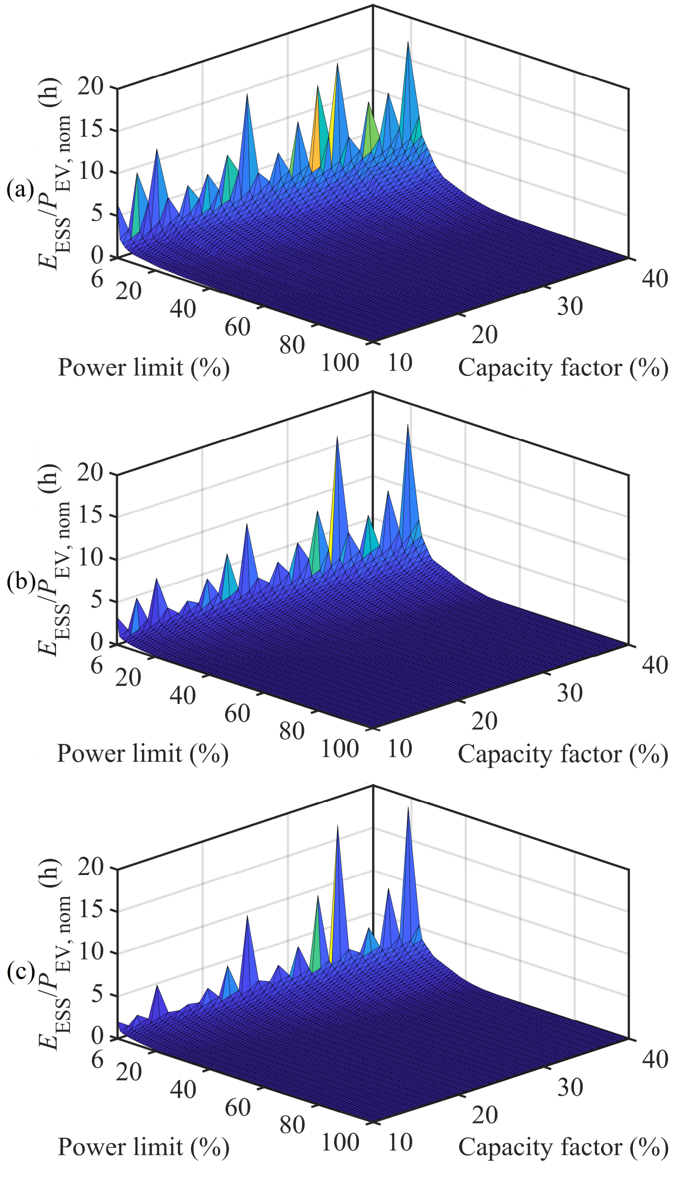

Figure 5. Required energy capacity of the ESS with respect to the rated charging power during the one-year period for 4 (a), 12 (b), and 20 (c) DCFC stations as a function of the power limit and capacity factor.

relative power and energy requirements in Figs. 4 and 5, also the share of energy cycled through the ESS decreases with increasing charging plaza size and PL and with decreasing capacity factor. At PLs higher than 40% or so, only a small share of the EV charging energy is cycled through the ESS, i.e., the utilization rate of the ESS is low, while the share of cycled energy increases strongly at lower PLs. With a PL of 30%, depending on the capacity factor, between 5.4% to 22.6% of the EV charging energy is cycled through the ESS for the charging plaza of 4 DCFC stations while the corresponding range is from 0.05% to 12.6% for 20 DCFC stations.

The results show that the utilization rate of an EV charging plaza has a major effect on the requirements and the utilization rate of an ESS used for peak load reduction of the charging plaza. The relative ESS power and energy requirements and the utilization rate of the ESS increase as the PL and the charging plaza size decrease and the utilization rate of the plaza increases. The required grid connection power of an EV charging plaza can be decreased considerably relative to the rated power of the charging plaza by an ESS with relatively small power and energy capacities especially in the case of EV charging plazas with many DCFC stations or low utilization rate.

IV. CONCLUSIONS

In this paper, the effects of the capacity factor of EV charging plazas on sizing of ESSs for peak load reduction of the charging plazas were studied based on one year of measurements from four DCFC stations. The capacity factor of the DCFC stations was varied from 10% to 40% by duplicating measured charging sessions to occur at the same

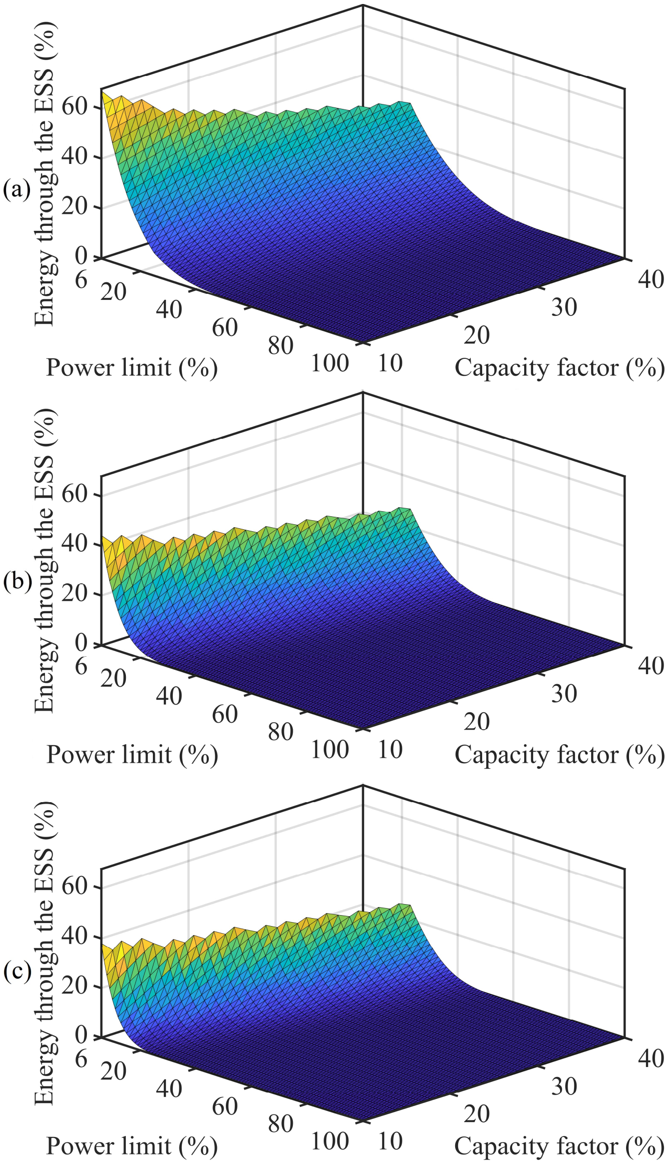

Figure 6. Share of total EV charging energy cycled through the ESS during the one-year period for 4 (a), 12 (b), and 20 (c) DCFC stations as a function of the power limit and capacity factor.

time on a different day of the same type. Moreover, the size of the charging plaza was varied between 4 and 20 DCFC stations by generating charging profiles for virtual stations by re-ordering the measured charging sessions.

The relative ESS power and energy requirements and the utilization rate of the ESS increased as the PL and the charging plaza size decreased and the utilization rate of the plaza increased. The results mean that the relatively highest ESS capacity is needed, and the utilization rate of the ESS is the largest, for highly utilized small charging plazas. The increasing charging plaza size smooths the aggregate EV charging profile as the charging profiles of individual charging stations differ from each other while the decreasing capacity factor decreases the occurrence frequency of simultaneous charging sessions reducing the need for power leveling. The required grid connection power of an EV charging plaza can be decreased considerably by an ESS with relatively small power and energy capacities. For example, ESS power and energy capacities of 45.7% and 2.19 h, with respect to the rated EV charging power, are high enough to limit the peak power of a charging plaza of 12 DCFC stations to 30% of the rated EV charging power of the charging plaza even with the highest studied capacity factor of 40%.

REFERENCES

[1] Y. Ligen, H. Vrubel, and H. Girault, “Local Energy Storage and Stochastic Modeling for Ultrafast Charging Stations,” *Energies*, vol. 12, 1986, May 2019.

[2] A. Hussain, V.-H. Bui, and H.-M. Kim, “Optimal Sizing of Battery Energy Storage System in a Fast EV Charging Station Considering Power Outages,” *IEEE Trans. Transportation Electrification*, vol. 6, pp. 453–463, Jun. 2020.

[3] P. Antarasee, S. Premrudeepreechacharn, A. Siritaratiwat, and S. Khunkitti, “Optimal Design of Electric Vehicle Fast-Charging Station’s Structure Using Metaheuristic Algorithms,” *Sustainability*, vol.15, 771, Jan. 2023.

[4] A. Y. Ali, A. Hussain, J.-W. Baek, and H.-M. Kim, “Optimal operation of static energy storage in fast-charging stations considering the trade-off between resilience and peak shaving,” *Journal of Energy Storage*, vol. 53, 105197, Sep. 2022.

[5] A. Hussain, V.-H. Bui, J.-W. Baek, and H.-M. Kim, “Stationary Energy Storage System for Fast EV Charging Stations: Optimality Analysis and Results Validation,” *Energies*, vol. 13, 230, Jan. 2020.

[6] G. Pareschi, L. Küng, G. Georges, and K. Boulouchos, “Are travel surveys a good basis for EV models? Validation of simulated charging profiles against empirical data,” *Applied Energy*, vol. 275, 115318, Oct. 2020.

[7] H. Kikusato *et al.*, “Electric Vehicle Charging Management Using Auction Mechanism for Reducing PV Curtailment in Distribution Systems,” *IEEE Trans. Sustainable Energy*, vol. 11, pp. 1394–1403, Jul. 2020.

[8] N. Sadeghianpourhamami, J. Deleu, and C. Develder, “Definition and Evaluation of Model-Free Coordination of Electrical Vehicle Charging With Reinforcement Learning,” *IEEE Trans. Smart Grid*, vol. 11, pp. 203–214, Jan. 2020.

[9] M. Shepero and J. Munkhammar, “Spatial Markov chain model for electric vehicle charging in cities using geographical information system (GIS) data,” *Applied Energy*, vol. 231, pp. 1089–1099, Dec. 2018.

[10] T. Simolin, K. Rauma, A. Rautiainen, P. Järventausta, and C. Rehtanz, “Assessing the influence of the temporal resolution on the electric vehicle charging load modeling accuracy,” *Electric Power Systems Research*, vol. 208, 107913, Jul. 2022.

[11] M. Majidpour, C. Qiu, P. Chu, H. R. Pota, and R. Gadh, “Forecasting the EV charging load based on customer profile or station measurement?,” *Applied Energy*, vol. 163, pp. 134–141, Feb. 2016.