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Bowen, Aidan ; Engelhardt, Jan; Gabderakhmanova, Tatiana; Marinelli, Mattia; Rohde, Gunnar

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Battery Buffered EV Fast Chargers on Bornholm: Charging Patterns and Grid Integration

Aidan Bowen, Jan Engelhardt, Tatiana Gabderakhmanova, Mattia Marinelli
Department of Wind and Energy Systems
Technical University of Denmark
Roskilde, Denmark
{s192360, janen, tatigab, matm}@dtu.dk

Gunnar Rohde
Danish Center for Energy Storage
Copenhagen, Denmark
gr@atv.dk

***Abstract*—The widespread adoption of electric vehicles (EVs) is a vital step in the reduction of emissions within the transport sector. However, the development of public fast charging infrastructure and the proper modeling of EV charging behaviours is required to enable this adoption. This paper presents charging data and patterns observed at a battery buffered fast charging DC microgrid on the Danish island of Bornholm. The charging sessions observed at this single site tend to be shorter with lower total energy transfer compared to studies with a wider scope. An atypical uptake of charges with higher than average energy transfer late in the evening is also observed. A simulation based study using this charging data to examine the effectiveness of the battery buffers at facilitating EV fast charging at reduced grid capacities is then presented. This study shows that the Bornholm DC microgrid would have been able to supply all observed EV charging at a reduced grid capacity of $11\,\mathrm{kW}$, enabling such a system to provide EV fast charging at a much wider range of locations.**

***Index Terms*—BESS, Electric vehicles, Fast charging, Charging behavior, Microgrid.**

I. Introduction

In recent years there has been a widespread adoption of electric vehicles (EVs) in an effort to reduce emissions caused by fossil fuel powered vehicles and transition towards a more renewable transport sector [1]. Lack of public charging infrastructure is one of the largest barriers to this electrification, and hence an equally widespread deployment of fast-charging stations, guided by proper modeling of the potential charging patterns of EVs, will further enable this adoption [2] [3]. The grid reinforcement required to connect this fast charging infrastructure is costly and slow to develop [4] [5], however pairing fast chargers with battery buffers can allow their installation without the need to upgrade the grid connection [6] [7]. It also reduces the stress placed on the primary grid, providing a buffer during fast, high power charging and can be exploited for additional grid services [8].

This paper presents two main contributions, firstly charging data recorded from two battery buffered HVDC fast-chargers located on the Danish island of Bornholm and the observed patterns. It then compares this recorded charging data to that previously presented in literature, particularly a study by R. Wolbertus and R. van den Hoed which present charging patterns seen across a range of EV fast charging stations in the Netherlands [9] [10]. The publishing and examination of charging data in this manor enables the modeling of charging profiles, EV user behaviour and vehicle characteristics. This facilitates analysis of the impact the increased adoption of EVs has on the power grid [3] [11].

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The second main contribution of this paper presents a study carried out on the aforementioned DC microgrid [12]. It examines the capability of the microgrid, and the buffer batteries contained within, to supply EV fast charging at low voltage distribution grids. This is done by simulating and analysing the performance of the microgrid at different grid connection limits, namely $43\,\mathrm{kW}$, $22\,\mathrm{kW}$ and $11\,\mathrm{kW}$.

The remainder of this paper is structured as follows: Section II covers the topology of the Bornholm DC microgrid, Section III the charging patterns observed at this site and the comparison to wider scope studies, Section IV the simulated testing of the the capability to perform at reduced grid capacity, Section V the results of this testing and finally Section VI concludes the paper.

II. Campus Bornholm DC Microgrid

Fig. 1 gives an overview of the Bornholm DC microgrid, which comprises two $175\,\mathrm{kW}$ EV fast chargers, a $61\,\mathrm{kW}$ PV system, a battery energy storage system and a 66 kW grid-tied inverter, connecting the DC microgird to the wider

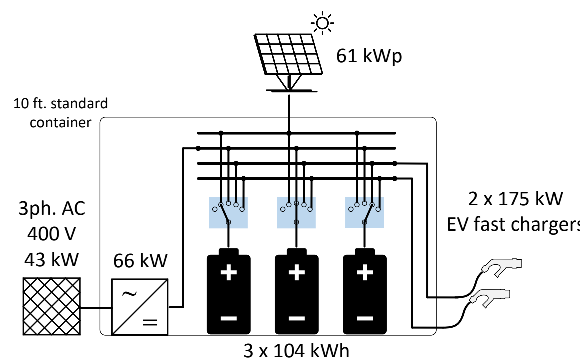


Fig. 1: Campus Bornholm DC microgrid overview [16].

Fig. 2: Demonstration DC microgrid at Campus Bornholm in use by a Tesla and Porsche Taycan.

distribution network via a $400\,\mathrm{V}$, $63\,\mathrm{A}$ $3\,\mathrm{ph}$ AC connection with a maximum power of $43.47\,\mathrm{kW}$. The battery storage system (BESS) consists of three battery dual-strings with a reconfigurable topology, each with a capacity of $104\,\mathrm{kWh}$.

The reconfigurable topology enables the strings to change operating voltage, enabling them to be connected directly to all of the four components of the system [13] [14]. Each dual-string consists of two strings, each containing 162 cells in a series reconfigurable topology each with a rated voltage and power of $3.2\,\mathrm{V}$ and $0.64\,\mathrm{kW}$. These two strings can be connected in either a parallel or series connection to, giving each of the batteries dual-strings a rated power $207.36\,\mathrm{kW}$ and the capability of supplying this power at up to $1036.8\,\mathrm{V}$ [15].

The reconfigurable topology and variable voltage means the components can only connect to battery strings and not directly to each other, hence all energy flowing through the system do so via a battery. This is a novel design that removes the need for interfacing power converters [17] [18].

These batteries act as a power and energy buffer, enabling the PV and EV systems to operate at full power capacity despite having a rated power significantly higher than the capacity of the grid connection. Fig. 2 shows the DC microgrid in use, with two EVs connected to the fast chargers and the PV system located on a nearby roof is shown in a Fig. 3.

III. Observed EV Charging Paterns

For this study into the charging patterns observed at the Bornholm DC microgrid fast charging station, 166 days of operation were examined, from 07/06/2021 to 03/03/2022, with the charging station not in operation for 105 days between these two dates. Within this period there are 360 unique charging events. Fig 4 shows the probability density functions of the arrival time, charge duration and total energy transferred during a charge for these recorded events, compared to those seen in the study of multiple fast charging stations in the Netherlands. The scope of this study covered over 1 million charging sessions recorded in 2019 at fast charging stations with a power of up to $175\,\mathrm{kW}$ from across the country [9] [10]. Only charging sessions that have a total energy transfer of over $0.5\,\mathrm{kWh}$ are considered as it was occasionally observed that an EV would terminate the charging process very quickly after it began. The charged energy plot shows the mean total energy demand of the EVs is $12.48\,\mathrm{kWh}$, with the single largest charging event requiring $62.25\,\mathrm{kWh}$ of energy. Similarly, the mean charge duration is $13\,\mathrm{Min}, 38\,\mathrm{Sec}$, with a standard deviation of $15\,\mathrm{Min}, 12\,\mathrm{Sec}$, with the low mean and high standard deviation for both values indicating a large amount of short charging sessions over which only a small amount of energy is transferred, but with a non-negligible amount of long duration, high energy charging sessions. This is a contrast to the study considering a collection of fast chargers carried out in the Netherlands, where both the charged energy and duration have a larger mean value, indicating the majority of charges tend to last longer and transfer more energy. Both studies show a similar level of exceptionally long and high energy transfer charges. The study of the Bornholm DC microgrid captures the nuances of charging patterns at that one site, especially when compared to a study that considers multiple sites as being located at a high school and education center, the Bornholm DC microgrid charging station experiences an increased amount of very short duration charges.

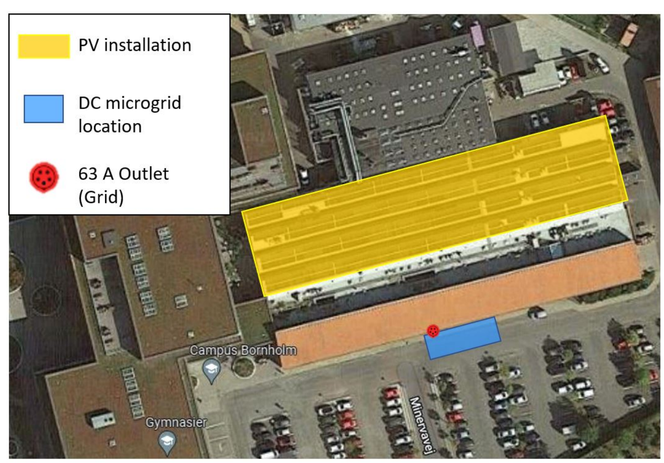


Fig. 3: Satellite view of DC microgrid location with PV system

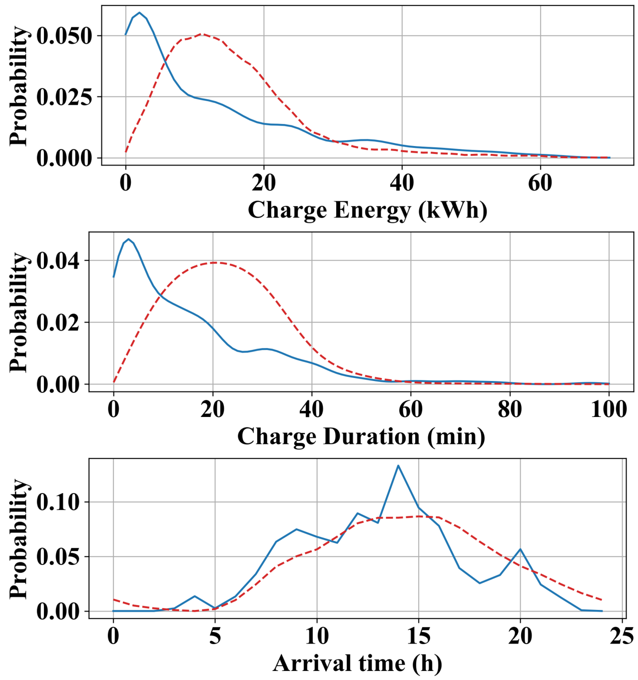


Fig. 4: Probability density functions for arrival time, charge duration and charged energy observed at the Bornholm DC microgrid fast chargers (in blue) and for multiple chargers as presented in [9] [10] (in red).

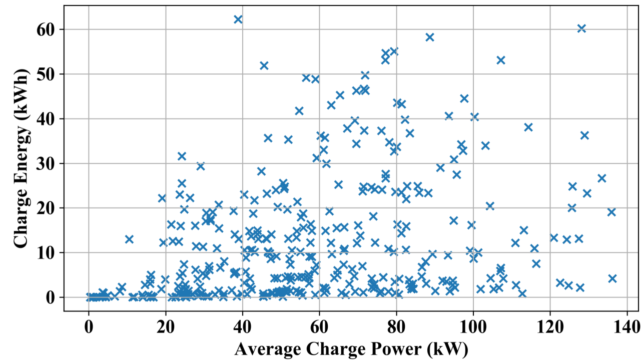


Fig. 5: Scatter plot of Charged Energy and Charge Power.

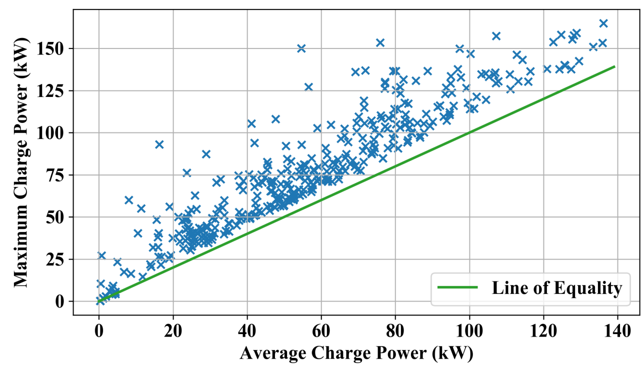


Fig. 6: Scatter plot of Average Charge Power and Max Charge Power.

The third graph in Fig 4 shows the distribution of when EVs arrive and connect to the fast chargers. Both studies show a somewhat similar pattern, little to no charging occurring in the early morning, before a steady increase towards a peak of connections at midday and the early afternoon, before steadily decreasing again in the late afternoon and evening. The Bornholm DC microgrid study again shows a more distinct pattern, in particular the peaks in number of connections at $14:00$ and 20.00, that are due to charging behaviours specific to the site and would not be present in a study with a larger scope.

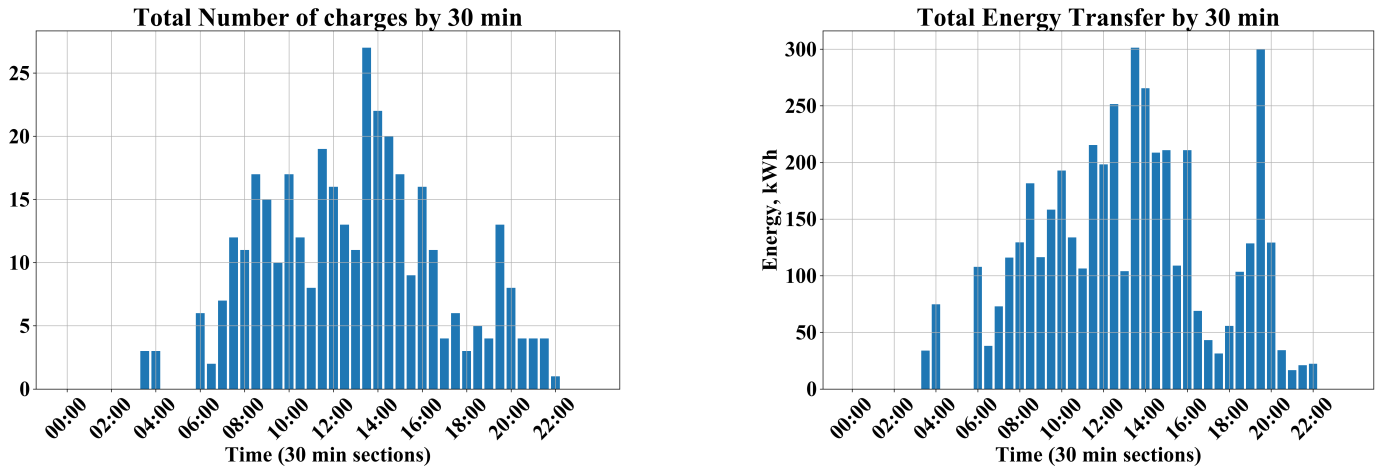
Fig. 5 compares charge power to energy transfer of the charges observed in the Bornholm DC microgrid. It shows that there is no correlation between the power of a charge and the energy transferred during that charge outside of very low energy/power charges, with the charge duration being the metric that energy transfer is most dependent on. Fig. 6 compares the average power of a charge session to the maximum of the same session. It shows that for the majority of charging events the peak power was 15% larger than the average power, though a significant number had a larger difference between the two values. It also shows that the majority of charging sessions do not utilise the full $175\,\mathrm{kW}$ capacity of the charging station.

To closer examine the charging patterns with time of day observed on the Bornholm DC microgrid, Fig. 7 shows the total number of charges and total energy transfer with the day divided into 48 $30\,\mathrm{Min}$ segments, summed considering all 166 days. These distributions show patterns of charging that are not represented in the arrival time distribution shown in Fig. 4, with the observed peak of connections in the evening $(19.30-20.30)$ transferring a significantly large amount of energy per charging session than what is observed earlier in the day, indicating that these charging sessions that occur late in the day tend to last longer. Again this is likely due to the location of the Bornholm DC microgrid, which is situated at an education center that offers evening classes.

IV. Case Study: Effect of Reduced Grid Connection

One of the major benefits of including battery storage alongside EV fast charging facilities is the capability to provide charging at powers greater than what could normally be provided by the local distribution grid, with the battery acting as a power and energy buffer. The Bornholm DC microgrid utilises this to facilitate high power EV charging through its two chargers, each capable of supplying energy at $175\,\mathrm{kW}$ simultaneously, significantly higher than the grid capacity of $43\,\mathrm{kW}$. However these battery buffers have the potential to allow such a DC microgrid, and the associated EV charging, to operate at lower grid connection capacities. Hence a study was conducted into the impact reducing this grid capacity has on the performance of such a DC microgrid.

For this study, the DC microgrid and EMS described in section I is modelled at an energy level in Matlab Simulink, with EV demand and PV generation recorded from the site used for test data [15]. The performance of the DC microgrid



(a) Total Number of Charge Sessions

(b) Total Energy Transfer

Fig. 7: Distribution of charging throughout the day in 30 minute windows.

was tested at grid connection limits of $43\,\mathrm{kW}$, $22\,\mathrm{kW}$ and $11\,\mathrm{kW}$. Each grid connection was subject to a series of six tests with each test consisting of a 24 hour simulation. Each test had an EV demand profile defined as either average, high or stress and a PV generation profile defined as average or high.

The 'high' EV demand profile was seen at the DC microgrid on $02/08/21$, with a total of $112.58\,\mathrm{kWh}$ of energy demand across 16 charging events, it is the day with the 4th largest total energy demand. The 'Average" EV demand profile is taken from $26/10/21$, with a total of $84.45\,\mathrm{kWh}$ of energy demand across 5 charging events while the 'stress' EV scenario was created by including 37 unique charging events into a single day of charging, with each event beginning and ending at the same time of day as when recorded and being represented by the average power demand of the charge. This resulted in a profile with a demand of $319.96\,\mathrm{kWh}$, designed to test the capabilities of the DC microgrid in a scenario more stressful than any recorded day. The PV profiles used were generation recorded at the Bornholm DC microgrid on $07/06/21$ for the 'high' profile and $16/09/21$ for the 'average' profile, with each having a total energy generation available of $410.38\,\mathrm{kWh}$ and $146.13\,\mathrm{kWh}$ respectively.

The performance of the DC microgrid at each grid connection across these tests was assessed primarily using four metrics, as follows:

- **EV success rate** (EV_{SR}), the percentage of the EV demand requested that was successfully delivered.
- **PV success rate** (PV_{SR}), the percentage of the available PV generation that was successfully harvested.
- **Self Sufficiency**(E_{SS}), a measure of how well the DC microgrid is able to supply local load with local generation [20].
- **System Efficiency**(η_{sys}), the measure of total system efficiency, calculated as per [15], where the change in energy storage can be considered either an input or output of energy to the system.

V. Results of Testing

Tables I, II and III show the results of these series of six tests for each of the three grid connection capacities considering these metrics. Fig. 8 plots the EV demand, PV generation and Grid connection power over the course of a simulated 24 hour test with a $22\,\mathrm{kW}$ grid connection using the "high" EV demand profile that was recorded $02/08/21$ and the "average" PV production recorded on $16/09/21$.

TABLE I: Test results at a grid capacity of $43\,\mathrm{kW}$

Grid Cap: 43.47 kWh	Metric			
	$\mathbf{EV_{SR}}$	$\mathbf{PV_{SR}}$	$\mathbf{E_{SS}}$	$\eta_{\mathbf{sys}}$
Ave. EV, Ave. PV	100%	100%	77.55%	86.85%
Ave. EV, High PV	100%	100%	93.96%	88.60%
High EV, Ave. PV	100%	100%	82.75%	85.49%
High EV, High PV	100%	100%	97.03%	88.13%
Stress EV, Ave. PV	100%	100%	38.80%	82.77%
Stress EV, High PV	100%	100%	80.02%	86.64%

TABLE II: Test results at a grid capacity of $22\,kW$

Grid Cap: 22 kWh	Metric			
	$\mathbf{EV_{SR}}$	$\mathbf{PV_{SR}}$	$\mathbf{E_{SS}}$	$\eta_{\mathbf{sys}}$
Ave. EV, Ave. PV	100%	100%	79.52%	87.07%
Ave. EV, High PV	100%	90.15%	94.60%	81.46%
High EV, Ave. PV	100%	100%	84.35%	85.89%
High EV, High PV	100%	91.85%	98.11%	82.27%
Stress EV, Ave. PV	100%	100%	40.59%	91.51%
Stress EV, High PV	100%	100%	85.76%	90.42%

These primary result of these tests is that the Bornholm DC microgrid was able to completely fulfill all scenarios based on observed charger at all grid capacities, with an EV success rate of 100% in all but two cases. The only scenarios where the microgrid could not completely fulfill the charging demand was when subject to "stress" EV conditions with a $11\,\mathrm{kW}$ grid connection, a scenario with a total energy demand more than twice as large as any observed day. Even in these extreme

TABLE III: Test results at a grid capacity of 11 kW

Grid Cap: 11 kWh	Metric			
	$\mathbf{EV_{SR}}$	$\mathbf{PV_{SR}}$	$\mathbf{E_{SS}}$	$\eta_{\mathbf{sys}}$
Ave. EV, Ave. PV	100%	100%	81.22%	87.17%
Ave. EV, High PV	100%	77.13%	96.21%	89.95%
High EV, Ave. PV	100%	100%	88.47%	85.76%
High EV, High PV	100%	74.65%	98.23%	89.10%
Stress EV, Ave. PV	96.25%	100%	51.46%	88.63%
Stress EV, High PV	99.9%	91.25%	89.49%	88.65%

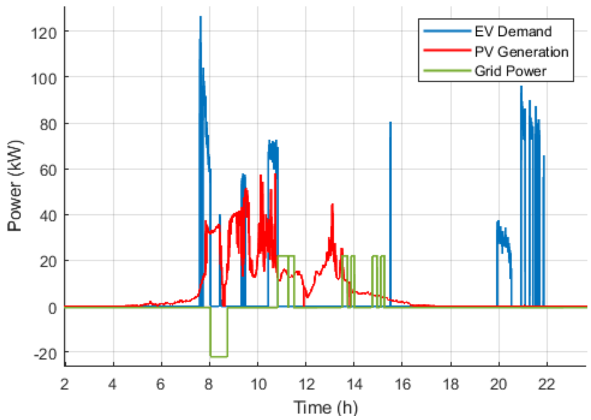


Fig. 8: EV demand, PV generation and Grid energy for 22 kW grid connection, High EV (02/08/21) & Average PV (16/09/21).

scenarios, only 0.1% & 4.75% of the total charge demand was not supplied, equivalent to 1 & 2 charging sessions being ended prematurely by the microgrid.

It is also shown that while at a grid capacity of 22 kW or 11 kW the microgrid is not always able to completely harvest all available PV energy, with the PV success rate falling below to 90% & 75% respectively during high PV generation equivalent to that of a clear summer day, with the generation increasing beyond the ability of the microgrid to export and store energy.

The measured self sufficiency is depended on the definition and calculation used [20]. The self sufficiency in this study is largely dependent on the condition scenarios used, particularly the PV scenario, with higher generation resulting in a value of E_{SS} in a range of $93\% - 98\%$ in scenarios with observed EV charging. The value of E_{SS} also increases marginally as the grid capacity decreases, with a 3% increase seen between a grid capacity of 43 kW and 11 kW, similarly the system efficiency tends to incrase by 1% with the decreased capacity.

VI. Conclusion

Developing public fast charging infrastructure is an important step in enabling the widespread adoption of EVs, but this requires understanding, and mitigating, the strain the increased demand will place on the grid electricity grid. By examining the charging patterns of a single EV fast charging station that forms part of a demonstration DC microgrid on the Danish island of Bornholm details and nuances of the charging patterns seen at the site become apparent where they would not in a study with a wider scope. The Bornholm DC microgrid charging station sees a larger number of short, low energy transfer charging sessions, particularly when compared to wider area studies. It was found that there is a correlating between the time of day at which EVs connect to the charger and the average energy transferred, with the Bornholm DC microgrid experiencing an increase in larger energy demand charging sessions in the early evening, around $20:00$, resulting in an atypical charging pattern caused by the nature of the site that would not have been captured in a study of a wider scope.

The capabilities of the Bornholm DC microgrid to operate at a reduced grid capacity was then tested through simulation, assessing the effectiveness of the battery storage at acting as a grid buffer, enabling the fast charging of EVs at a power much higher than the local distribution grid could provide. These tests showed that the Bornholm DC microgrid would be able to supply all observed days of EV charging with a grid connection as low as 11 kW. This is testament to the effectiveness of a battery buffer system enabling the charging of EVs at a power of up to 175 kW at a significantly lower grid capacity, while lowering the impact of charging on the power grid. Lowering the grid connection from 43.47 kW to 11 kW also saw a marginal increase of self sufficiency and efficiency, of 3% and 1% respectively. It was also observed that the DC microgrid was unable to completely harvest all PV generation at lower grid connections, as the rate of generation increased beyond the capacity of the microgrid to export energy. Hence accounting for grid connection capacity when sizing the generation systems of similar microgrids is of paramount importance to ensure all available energy is harvested.

The studies presented in this paper show that the there is value in studying charging patterns at individual charging stations as they capture nuances that would be lost in wider area studies. It has also been shown that a DC microgrid with a battery buffer and local renewable generation is capable of supplying sufficient fast charging infrastructure at a drastically reduced grid connection capacity. This allows such charging infrastructure to be provided without the costly and time consuming grid reinforcement normally required to supply these high powers. DC microgrids like the demonstration site at Campus Bornholm also allow a large degree of flexibility, the modular containers can be moved and rearranged as charging needs develop. Further development of the energy management systems used in such microgrids, particularly the creation of a dynamic system that accounts for locally seen charging patterns, could further increase there capabilities through better utilisation of available capabilities.

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