Potential of battery storage systems to increase the self-consumption of photovoltaics in charging of electric vehicles in residential buildings

Mahmoud Shepero*, Reza Fachrizal †,
Joakim Munkhammar‡, Joakim Widén§
Department of Engineering sciences, Uppsala University
Uppsala, Sweden
Email: *mahmoud.shepero@angstrom.uu.se, †reza.fachrizal@angstrom.uu.se,
‡joakim.munkhammar@angstrom.uu.se, §joakim.widen@angstrom.uu.se

***Abstract*—Electric vehicles (EVs) and photovoltaics (PV) are swiftly being adopted to improve sustainability in both the transportation and the electricity sectors. Residential buildings might benefit from self-consuming the locally produced PV electricity to charge the EVs of the residents. However, the temporal mismatch between midday solar power production and late afternoon EV charging reduces the self-consumption (SC) potential. Here, we investigate the potential of battery storage in improving this SC. The batteries are intended to be used to store the PV energy, from midday, to charge the EVs during the late afternoon. Here we estimate the SC with various battery capacities. This work might be of value to grid operators interested in temporal load matching using battery storages. The results indicate that the houses benefit the most from a 5 kWh battery capacity in comparison with 10 kWh or larger. Using a 5 kWh battery, the SC and self-sufficiency (SS) of the median house without an EV improved by 40% and 14%, respectively. With EVs, the same scores improved by 38% and 11%, respectively. This indicates that the batteries were predominantly used to cover the load of the house and were rarely used to supply the load of the EVs.**

***Index Terms*—electric vehicles, photovoltaic, self-consumption, battery storage, residential buildings**

I. Introduction

The increase in environmental awareness along with a reduction in technology prices has accelerated the installation of photovoltaics (PV) panels and the switching to electric vehicles (EVs). In residential buildings, EVs are expected to charge in the evenings, while the PV yield peaks around noon. The adoption of battery storage systems to shift the midday solar yield to the evening EV charging might be of value.

Several papers have investigated the potentials of batteries to improve the temporal matching between PV generation and the load. The temporal matching was often measured using the self-sufficiency (SS) and the self-consumption (SC) [1].

In [2], the effectiveness of a 2 kWh battery in improving the SS of houses in the UK was simulated. The results showed that without batteries the SC ranged between 15%–93% and averaged at 51%. The average SS was, however, 31%. Adding batteries resulted in an average increase of 6%.

Three battery charging strategies were evaluated in [3] on houses in Germany. The first charging strategy aimed at increasing the SC, the second aimed at limiting the feed-in to the grid, and the third strategy smoothed the daily feed-in peaks. The results indicated that on average the SC increased by 19%, 16% and 28%; and the SS increased by 28%, 16%, and 27% for the three strategies, respectively.

Satsangi et al. [4] estimated the temporal matching between PV, the load, and a battery system in a microgrid in India. The battery in their study was assumed to be as a backup in case the grid and the solar were not sufficient to supply the load. The battery was used during an 8 days grid failure, where an islanded microgrid was created. The solar yield from the microgrid was used to charge the batteries and supply the load. During nights or when the PV yield was not sufficient, the load was supplied by the batteries. During 4 instances, in 8 days, the batteries were fully depleted and the load was completely shut down until the morning when the PV yield was enough to supply the load and recharge the battery.

As regards studies including economic aspects, Pena-Bello et al. [5] optimized the battery charging and discharging to reduce the total electricity bill. The authors compared various battery technologies and capacities on single dwellings with PV installations in Geneva and Texas. The results showed that the levelized cost of energy (LCOE) was lowest for the houses that cycle the batteries more. Moreover, the higher the electricity prices were, the higher the value of storage per kWh was. The economic viability of the batteries was, however, non-profitable in neither of the locations.

In addition, Koskela et al. [6] evaluated the economics of installing PV panels along with battery storage in Finland. The authors optimized the sizing of both technologies to minimize the costs. The results indicated that for detached houses, the recommended battery capacity ranged between 4–6 kWh.

Synergies between PV, EVs, thermal heat storage and electricity consumption were modelled in [7]. The authors optimized the components of the system to minimize the yearly costs of energy. The results indicate that for the optimal system adding EVs did not significantly improve the SC, $< 10\%$ by visual inspection, in most of the regions around the world. It is important to note that the optimal system varied among the regions.

In this paper, the authors complement the previous literature by simulating the impacts of employing battery storages to store the PV generated energy on the SC and the SS. Unlike in [7], no smart charging scheme was assumed here. Moreover, the integration between the space heating/cooling systems and the electricity consumption was not considered.

Section II presents the models and the data used in this paper. The results are presented in Section III. Finally, the conclusions are drawn in Section IV.

II. Methods

This section describes the data and the battery model used in this paper. In Section II-A, the household electricity consumption data and the production data used in this study are presented. In Section II-B, the EV model used to generate the charging load of EVs is presented followed by a description of the battery model in Section II-C. Finally the metrics proposed to evaluate the temporal matching are presented in Section II-D.

A. Data

The authors used the measured Australian household consumption data from [8]. The data represent the electricity consumption and solar production from 300 Australian houses measured from 2010–2013. Ratnam et al. [8] performed quality checks on the recorded data. They determined that the data from only 54 houses passed these checks. In this paper, the data from these 54 customers were used.

The PV production $P_{PV,t}$ (kW) and the house load $P_{L,t}$ (kW) at each time-step t were obtained from the recorded energy production/consumption (kWh) on 30-min basis. In this study, the house load included the controllable and uncontrollable loads of each customer. As stated in [8], some customers allowed the utility grid to control their hot water tank. In this case, the load of the hot water tank represented the controllable load.

An important metric representing the household's load and production is the PV/L ratio [1]. This ratio measures the total PV production as percentage of the total load

$$\text{PV/L} = \frac{\int P_{PV,t}dt}{\int P_{L,t}dt}, \tag{1}$$

integrated over the study time, where a PV/L > 1 means that the house is a net energy producer. Among the 54 houses used in this study, only 3 houses were net producers with PV/L ratios of 1.2, 1.3 and 1.7. The remaining 51 houses were net consumers with PV/L ratios ranging between 0.15 and 0.94, with a median of 0.41.

B. Electric vehicles

In this paper, the EV charging model developed in [9] was employed to charging load of EVs. The model uses a Markov chain to estimate the simulate the mobility of EVs. The Markov chain is trained using the Swedish travel survey [10], which reflects the travel behavior of Swedish drivers.

TABLE I
Properties of the battery used in the model.

Characteristic	Symbol	Unit
Battery capacity	E_B	kWh
Maximum charging power	C	kW
Charging/Discharging efficiency	η	-

The daily energy consumption of EVs is dependent on the energy consumed per driving distance, i.e., the specific consumption. In this paper, the specific consumption was assumed to be 0.2 kWh/km [11]. In total, 3 years were simulated for each house, and it was assumed that each house has a single EV that charges using 3.7 kW charger and charges solely at home.

The model simulated the charging load of each house on minute resolution, which was then averaged to get the 30-min resolution. For the case study that included EVs, the 30-min averaged load of the EVs was then added to the other household related loads and considered as part of the house load, i.e., $P_{L,t}$. As a result, the PV/L ratios of each house changed. With the load of the EVs added, only 2 houses were net energy positive, and the rest of the houses had PV/L ratios ranging between 0.14 and 0.87, with median of 0.32.

C. Battery model

Batteries were assumed to be charged whenever there was an excess solar yield that was not locally consumed by the house. On the other hand, batteries supplied the load, when the solar production was not sufficient to supply the load. Thus, the power flowing to/from the inverter of the battery $P_{B,t}$ (kW) can be defined as:

$$P_{B,t} = \begin{cases} \min(P_{PV,t} - P_{L,t}, C) & \text{if} \quad P_{L,t} \leq P_{PV,t}, \\ \max(-(P_{PV,t} - P_{L,t}), -C) & \text{if} \quad P_{L,t} > P_{PV,t}, \end{cases} \tag{2}$$

where C is the maximum charging/discharging powers (kW). Thus $P_{B,t}$ is positive when the battery is charging and negative when the battery is discharging.

Using (2), the change in the state of charge (SOC) (kWh) of the battery between the time-steps can be estimated as

$$\Delta SOC_t = \begin{cases} P_{B,t}\Delta t\eta & \text{if} \quad P_B \geq 0, \\ P_{B,t}\Delta t/\eta & \text{if} \quad P_B < 0, \end{cases} \tag{3}$$

where η is the charging/discharging efficiency of the battery charger or inverter. Equation (3) is, however, limited such that the SOC of the battery never exceeds the battery capacity E_B (kWh) and never goes below zero, i.e., becomes completely depleted. Table I summarizes the characteristics of the batteries used in this model.

The batteries were assumed to charge using a linear charging function, as shown in (3). In other words, constant-power charging was assumed, and the dependencies of the charging power on the SOC were neglected.

The authors reviewed the specifications of some commercially available battery storage systems, e.g., [12–14]. The

TABLE II
THE SIMULATED PARAMETERS OF THE BATTERIES. THE SYMBOLS OF THE PARAMETERS ARE DEFINED IN TABLE I.

Battery parameter	Simulated values
E_B	5 kWh,10 kWh,15 kWh, and 20 kWh
C	5 kW
η	0.9

three batteries had capacities of 10 kWh, 12.2 kWh, and 14 kWh, respectively; and charging powers of 3 kW, 12.2 kW (specified as 1C), and 5 kW, respectively.

Here, the authors chose to simulate batteries with capacities 5 kWh, 10 kWh, 15 kWh, and 20 kWh. The reason was to simulate a mixture of small optimal capacities, as shown by [6], and commercially available systems. The maximum charging/discharging powers C were chosen to be 5 kW—the middle of the range of the commercially available systems. We chose the battery charging/discharging efficiency η to be 90% [14]. Table II summarizes the simulated parameters of the batteries.

D. Temporal matching metrics

In this section, the temporal matching metrics presented before in [15] were adopted. They were, however, adapted to match the simulated battery behavior, as defined in (2).

In order to estimate the temporal matching, the self-consumed power M_t (kW) is of importance. This power can be estimated by:

$$M_t = \min(P_{L,t} + P_{B,t}, P_{PV,t}). \tag{4}$$

This, however, assumes that the batteries are not exporting electricity to the grid. Which is the case of the battery model used in this paper, see Section II-C.

The SC estimates the percentage of the self-consumed PV energy to directly supply the load, or indirectly supply it through the battery storage. The SC is defined as

$$\text{SC} = \frac{\int M_t dt}{\int P_{PV,t} dt}. \tag{5}$$

To estimate the share of the PV production supplying the load, the SS is defined as

$$\text{SS} = \frac{\int M_t dt}{\int (P_{L,t} + P_{B,t}) dt}. \tag{6}$$

High SS and SC are favoured since a high SC means that a large percentage of the PV production is self-consumed to supply the load. A high SS means that the load is mostly supplied from the locally produced PV energy.

Luthander et al. [1] proposed to combine the two temporal matching metrics into a chart which they called the “energy matching chart”. This chart will be used to present the results of this study.

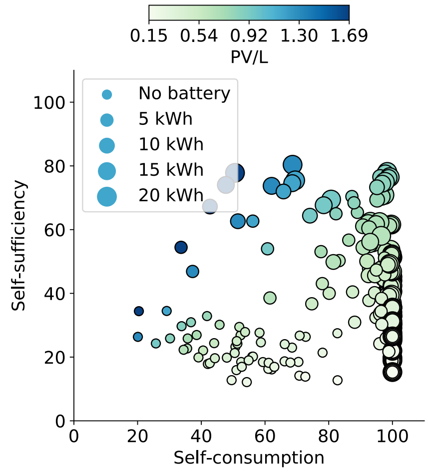

Fig. 1. The energy matching chart of the simulated 54 houses using different battery capacities.

III. RESULTS

The results of adding batteries to the existing households are presented in Section III-A. Section III-B presents the corresponding results in the case of adding the charging load of EVs to the houses.

A. Batteries and PV

The SS of the houses without battery storages was small, only 5 houses had a SS>30%. The SC was above 50% for 33 houses. However, only 2 of these houses had an SC that was higher than 80%.

The energy matching chart of the houses with various battery capacities is presented in Fig. 1. As shown, having a 5 kWh battery improves the SC significantly. In fact, the median house observed an improvement of 40% in the SC after installing a 5 kWh battery. Using the same battery, the SS score of the median house increased by 14%.

Increasing the battery capacity to 10 kWh, and comparing the results with the 5 kWh battery, showed that there was little benefit from this 100% battery capacity increase. The SS increased by more than 10% for only 5 out of 54 houses. For 44 houses, there was no significant—more than a 5% increase—impact on the SS compared with the 5 kWh battery. As regards the SC, the median house observed an increase of 3% in comparison to the case with the 5 kWh battery. However, 8 houses observed an increase of 10% or more in the SC.

Batteries larger than 10 kWh did not result in significant improvements in neither the SS nor the SC for the majority of the houses, see Fig. 1. A battery with a capacity of 15 kWh improved the SS and the SC by 10% or more for only 1 and 2 houses, respectively, when compared with the 10 kWh battery. Increasing the battery capacity to 20 kWh had no observable impact on neither the SS nor the SC. Only one house witnessed

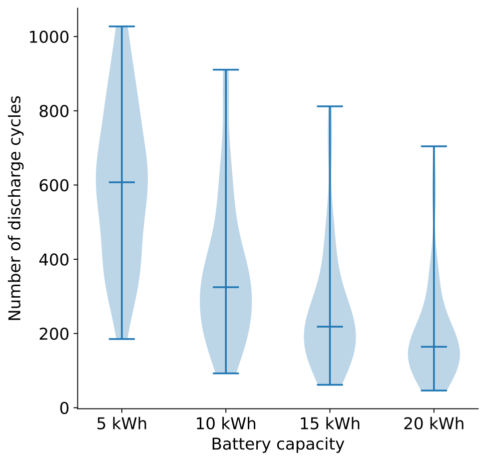

Fig. 2. A violin plot of the number of discharge cycles of the batteries installed in the houses. The center horizontal line represents the number of discharge cycles of the battery in the median house.

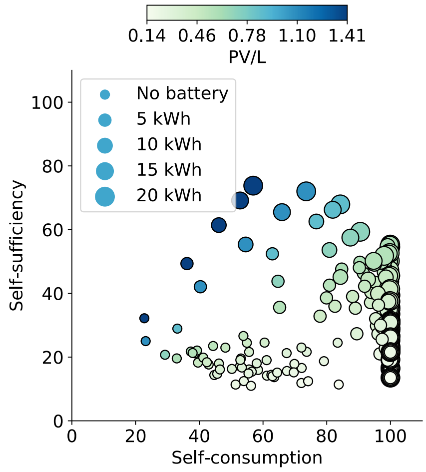

Fig. 3. The energy matching chart of the simulated 54 houses including the EV charging load and using different battery capacities.

a 5% increase in the SS and another house observed a 5% increase in the SC.

Figure 2 presents a violin plot of the number of discharge cycles of the installed batteries in the households. As expected, the smaller the battery capacity the higher the number of discharge cycles. The 5 kWh battery can be cycled up to 1000 cycles over 3 years, i.e., 0.9 times per day. The 5 kWh battery in the median house, nonetheless, was cycled approximately once every 2 days. This is of importance since batteries have a cycle-life after which the batteries reach their end-of-life.

Han et al. [16] studied various commercial Li-ion batteries used in hybrid EVs and showed that some batteries reached their end-of-life—defined as 20% loss in the battery capacity—after less than 500 cycles. Other commercially available batteries retained 85% of the battery capacity after 1000 discharge cycles. Some commercially available battery systems, however, are provided with a 10 year warranty without any limitation on the number of cycles [14], or with a one cycle a day [12] limitation, i.e., 3650 cycles.

It is important to state that in this paper, the battery degradation due to the number of cycles was not simulated. Future works might include the impacts of the battery degradation on the SC and SS estimates.

B. Batteries, PV and EVs

As stated before, adding the charging load of EVs to the load of the households results in a decrease in the PV/L ratio in Fig. 3 in comparison to Fig. 1. The decrease in the PV/L ratio ranged between 0.02 and 0.3 with a median of 0.08.

By comparing Fig. 3 to Fig. 1, it can be noticed that the impact of adding the load of EVs slightly improved the SC scores. The median house, without battery storage, witnessed a 2% increase in the SC as compared with the case without EV. This, nevertheless, came at the cost of the SS, for which the median house witnessed a 4% decrease. This, perhaps, was expected since EV charging in residential buildings increases the load in the evening. Such an evening load cannot be met by PV production without batteries.

For the case of 5 kWh battery capacity, the SC improved by 38% for the median house. This is close to the 40% increase in the SC observed by installing the same battery but without the EVs, see Section III-A. In contrast, the SS improved for the median house by 11% which is slightly lower than in the case without EVs.

Similar to the results in Section III-A, installing a battery with a 10 kWh capacity or larger did not improve the SS and SC scores when compared to the 5 kWh battery. For example, the median house observed an improvement of 0.6% and 2% in the SS and SC, respectively, by doubling the battery capacity from 5 kWh to 10 kWh.

Installing a 15 kWh or 20 kWh battery seems to be of little value to the majority of houses. Only 8 houses increased their SS by more than 1% when upgrading from a 10 kWh battery to a 15 kWh one. Furthermore, only 14 houses improved their SC by more than 1% due to the previous upgrade. Nine out of these 14 houses increased the SC by more than 2%.

Comparing Fig. 4 to Fig. 2 shows that there were unnoticeable differences in the number of cycles witnessed by the batteries in the houses. The differences ranged from a decrease by 30 cycles to an increase by 105 cycles. There were no visible patterns, and it seemed to vary among the houses.

It can be observed from the previous results that the EVs did not benefit from the battery storage. The differences in the SC scores due to installing a battery storage did not significantly differ as compared with the same house if it did not have an EV. The differences were less than 1% for the median house and 10% or more for only one house. The SS, as expected, decreased by adding the load of the EVs as the PV production could not meet this extra load.

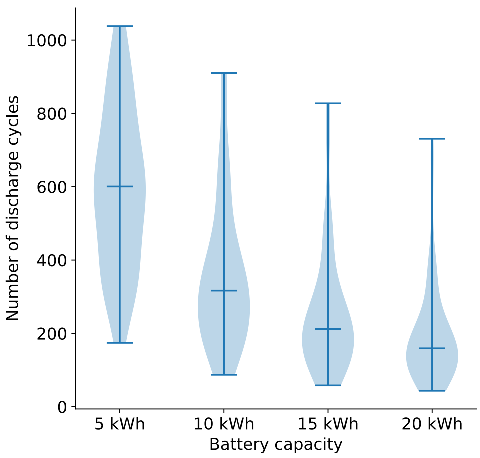

Fig. 4. A violin plot of the number of discharge cycles of the batteries installed in the houses including the charging load of the EVs. The center horizontal line represents the number of discharge cycles of the battery in the median house.

IV. Conclusions

An evaluation of the impacts of installing battery storages on the self-consumption (SC) and the self-sufficiency (SS) in Australian houses is provided. In addition, the study compares the current load of the houses to a future scenario when electric vehicles (EVs) are charged in the houses.

The results indicated that, for most of the houses, installing a 5 kWh battery provided the highest value when it comes to improving the SC and the SS. For 50% of the houses, installing a 5 kWh battery improved the SC by 40% and 38% for the cases without and with an EV, respectively. The SS increased by 14% and 11% for the same cases. Further increasing the battery capacity did not translate to a proportional increase in neither the SC nor the SS.

Adding EVs did not change the behavior of the battery storage systems as regards the SC. The load of the houses interact with the batteries, and the charging load of the EVs neither improved nor worsened these interactions.

The results in this paper are of value to grid operators aiming to explore the synergies between photovoltaics (PV), EVs and battery storages. In addition, the analyses made here can be applied to other houses in other countries. Future works are encouraged to explore the temporal matching on higher resolution data. A higher resolution, e.g., 10 min or 1 min, might result in a worse temporal matching compared with the 30 min data studied here. Furthermore, the impacts of the battery degradation on the temporal matching can be explored.

Acknowledgement

This project was partially funded by the projects "Probabilistic Forecasting for Battery Management", funded by the Swedish Energy Agency. This work was also supported by the Swedish strategic research programme StandUp for Energy. Simulations of the load of electric vehicles were performed on resources provided by the Swedish National Infrastructure for Computing (SNIC) through Uppsala Multidisciplinary Center for Advanced Computational Science (UPPMAX) under Project SNIC 2018/8-85.

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