Sizing Electric Battery Storage System for Prosumer Villas

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***Abstract*—This paper studies the electricity consumption of 5 villas in the south of Norway and estimates the effect of utilizing batteries as a means to reduce peak load for each villa. High-resolution field data on the consumption pattern for the villas is presented. A simple battery model is utilized, and a parameter sensitivity study is performed varying the energy storage capacity and the charging/discharging power limits of the batteries. Considerable potential is found for reducing the peak load by the utilization of batteries. An appropriate balance between the energy storage capacity and the power capacity of the battery is found to be beneficial for optimization of the peak load reduction.**

***Index Terms*—battery, demand response, load profile, peak-shaving, prosumer, storage, energy**

I. INTRODUCTION

Europe is currently migrating away from a paradigm where electricity flows from large centralized generation units to a set of distributed consumers through a mainly one-directional distribution grid. In its place Distributed Energy Resources (DERs) such as wind and solar are being widely installed and are making up an increasing share of the energy-mix [1]–[3]. There is also a change in the consumer behaviour away from pure consumers to *prosumers* – a customer that at times are net producers of electric energy and feed excess electricity into the grid. Alongside an ever-increasing consumption of electric energy and larger variations of loads on both daily and seasonal time scales, this places a larger strain on both the transmission and distribution grid. If this development is to be met by new investments in grid infrastructure alone this will require substantial investments. Simultaneously the price of batteries has been considerably reduced in recent years and could pose as a cost-effective alternative to grid investments [4]. The potential for a combination of PV and battery storage is not only dependent on the installed equipment and configuration, but also on the geographical location of the villa. In this paper the effect on peak-shaving is demonstrated for villas located in Southern Norway at 58° N, where the solar radiation is lower than in more favourable locations and the heating requirements are larger and main met by the use electricity.

It is desired to flatten the load profiles to reduce the peak demand the grid needs to deliver or to shift consumption to periods when electricity produced by renewable energy sources is available. Some techniques are known as peak-shaving, load shifting and valley filling [5], and can be achieved through local energy storage systems that buffer the energy demand. New building regulations call for villas to have ever smaller energy consumption, with the long-term target that they should be energy neutral. It is expected that the increasing share of DER that have less controllability will lead to larger variations in the balance between supply and demand in the energy markets.

A number of studies has been performed on battery sizing [6]–[8], although the ones citing field data mainly concerns locations with considerably more favourable conditions that the one stated here [9]. Further, economically focused models [10], technology focused models [11] and various sizing models [12] have been deployed. It is not the focus of this paper to advance the modelling of the battery itself, but rather quantify the peak demand reduction potentially available in villas in such a northerly location based on high resolution field data. Lower solar radiation and higher heating requirements impacts the gains potentially obtained by PV-battery combination.

Section II explains the data input and context of the work. The villa and battery models is explained in Section III. The analytical results are presented in Section IV. Section V and VI contain the Discussion and Conclusions respectively.

II. DATA INPUT AND CONTEXT

A selection of villas in a demo site consisting of a villa neighbourhood in the south of Norway (at 58° N) have been built according to a Zero Emission Building (ZEB) [13] standard. The solar irradiation is about 1000 kWh/m^2 per year and the average temperature is 8.4 °C [14]. These villas have been fitted with solar panels on their roofs and with geothermal heat pumps for space- and water-heating with the aim that they should be energy neutral in a yearly perspective. In addition, the villas have been monitored for a period of time with a high-resolution Power Quality (PQ) instrument that has logged the electric energy consumption and export. The logging period varied from 4 to 27 months of continuous recording, with most monitoring periods being 2+ years. This enabled the study of energy consumption in a seasonal perspective. An overview of the data is presented in Fig. 1. Note that a positive value for the active power refers to consumption in

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the villas. As can be seen, the logging interval for the 5 villas varies substantially. However, the data span multiple seasons in several of the cases. As can be seen there are both net importing and exporting time intervals for all the 5 villas. Some seasonal variations can also be observed with net consumption being larger in the winter months due to less solar irradiation and larger need for space heating. Using the energy consumption/generation data with a resolution of 1 minute, the effect of battery energy storage has been studied.

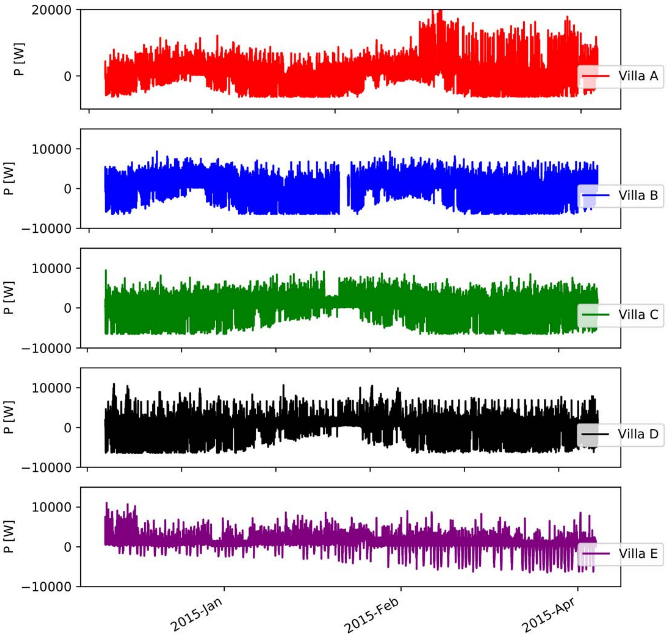

Fig. 1. Active power (P) for each of the 5 villas studied. A positive value for the active power refers to consumption in the villas.

III. VILLA AND BATTERY MODEL

In this study, a simple energy flow model is used where the battery is utilized to reduce the peak load from the villas, as seen from the grid connection point. Load peaks have been detected both on a seasonal basis, and on a daily and minute-by-minute basis. Even though the average load for a given villa is typically in the 2-3 kW range on a day-to-day basis, loads well above 20 kW have been detected for minute averages. Two characteristics for batteries have been studied in this paper a) the energy storage capacity in kWh and b) the charging and discharging capacity in kW. The power capacity for charging and discharging are assumed to be equal, and the ramping time has not been considered. The modelling does not take into account the degradation of the batteries from load-patterns, and no economic assessment of load-cycle analysis have been performed.

For each of the villas in the study, a range of battery sizes has been evaluated towards their impact on peak-shaving. The battery energy storage capacity has been varied between 1 and 50 kWh, and the battery charging/discharging capacity has been varied between 1 and 50 kW. For reference, the Tesla Powerwall battery solution has a capacity of 13.5 kWh and a power capacity of 7 (peak) / 5 (continuous) kW [15].

As noted the model allows for two battery variables; battery energy capacity E_{batt_max} and battery power capacity P_{batt_max}. At each time step there is a power consumed or generated by the house $P_{house}(t)$ and a power drawn/supplied to the grid $P_{grid}(t)$ and the battery $P_{batt}(t)$. $P_{house}(t)$ could be negative (producing energy) or positive (consuming energy) depending on the solar panel production, heating requirements and other loads/sources at each time step. The power needs to be balanced such that

$$P_{house}(t) = P_{grid}(t) + P_{batt}(t) \tag{1}$$

for each time step. The state of the battery is described by: $E_{batt}(t)$: the energy stored in the battery and $P_{batt}(t)$: the power supplied to or drawn from the battery at time t. No losses are modelled in the battery. The energy capacity requirements pose the constraints given in eq. 2 and the power limitations imposes the constraints given in eq. 3. The model is summarized in Fig. 2.

$$0 \leq E_{batt}(t) \leq E_{batt\_max} \tag{2}$$

$$\mid P_{batt}(t) \mid \leq P_{batt\_max}. \tag{3}$$

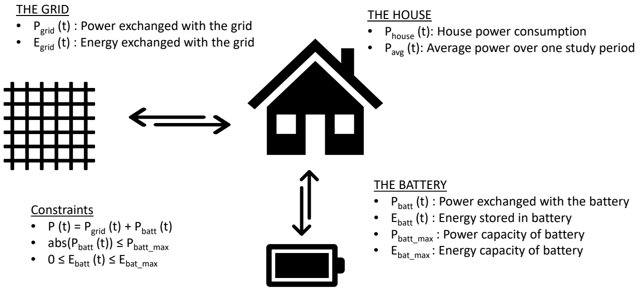

Fig. 2. Summary of the villa battery model illustrating relationships between the house, the battery and the grid.

The modelling starts by establishing the average energy consumption and power $P_{avg}(t)$ of the house for a given study period. Since the core focus of the study is peak shaving and impacts on a time scale of hours/days and not for seasonal storage, the study period has been selected to be one day. The study period has been varied between one hour and one week, and marginal variation on the results has been observed. The simulations are done with a timestep of one minute. For each timestep the difference ($P_{delta}(t)$) between house load $P_{house}(t)$ and the average power $P_{avg}(t)$ are calculated

$$P_{delta}(t) = P_{house}(t) - P_{avg}(t). \tag{4}$$

The optimum behaviour sought in this study is for the house to have a flat load curve within each study period, in this case one day. In order to obtain a flat load curve within each study period the villa should aim at importing/exporting the average power at each timestep, and use the battery as storage to level

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out the variations around this average. If $P_{delta}(t) > 0$ then the villa is using more power than average and draws this from the battery depending on the available energy in the battery and within the power constraints. Any power or energy that the battery cannot supply is drawn from the grid. If $P_{delta}(t) < 0$ the villa is using less power than average and will be charging the battery, again under the power and energy constraints posed above. The consumption of the house is evaluated for each timestep and compared to the study period average. The appropriate charging or discharging of the battery is performed and the resulting exchange with the grid is calculated.

The utilization of an average energy consumption over each study period is not realistic in real-world operation as such information would not be available at the time of decision of utilization of the battery. This is therefore a best-case scenario in the limit of perfect information. When it comes to practical implementation, good forecasting tools are needed for $P_{avg}(t)$ to deliver results close to the deterministic results presented in this study.

IV. ANALYTICAL RESULTS

In Fig. 3 the results for one selected villa are presented. The upper left-hand pane shows the minute-by-minute recorded power drawn from the grid for the villa with a minute resolution. It also shows the average power drawn for each study period (green line). Observe the large variation in the minute-by-minute data compared to the day-by-day averaged data. In red the cumulative energy drawn from the grid is plotted (right-hand y-axis). Observe that the villa has a net consumption during winter and a net production for a period during summer. It is evident that the villa is not a net zero consumer of electric energy from the grid even over the 2+ years monitored in this study. The lower left-hand figure shows the state of the battery over the monitored time period. The battery is initiated with 50% energy capacity filled. The pane shows the state of the battery and the charging/ discharging at each timestep.

The upper right-hand pane shows the electric energy exchanged with the grid by utilizing the battery as an intermediate storage. Note that the cumulative energy consumption for the villa plotted on the secondary (right-hand) y-axis does not change (red curve), but that the variation in power drawn from the grid is smaller. The horizontal time axis is the same for the two upper panes. The lower right-hand pane shows histograms of peak load drawn from the grid with and without the utilization of the battery. The particular set-up displayed in Fig. 3 has a battery with 27 kWh storage capacity and 10 kW power capacity. This is equal to two Tesla Powerwall units for one villa. From the study of the lower right-hand pane of this figure it is clear that the utilization of a battery storage system is changing the peak power consumption distribution, however the tail-end of the histogram distribution is little affected. By looking at the pane displaying the state of the battery it is clear that the battery is being fully charged/discharged significantly more frequently after the beginning of 2017. This coincides with the period of the year where the need for heating is high and the solar irradiation is low, hence the capacity of the battery is no longer sufficient to significantly reduce the peak power consumption. This could indicate that the ration between power [kW] and storage [kWh] capability is too much in favour of the power, and that the battery is too rapidly discharged. In the time interval before 2016 the battery was less frequently fully discharged, and the peak power consumption was significantly reduced.

A further study where the impact of varying the power and the storage constraints systematically have been undertaken for all the 5 villas. A selection of the results for villa A is plotted in Fig. 4 for varying energy storage and power capacities of the battery. The blue histogram is the case without battery installed and the red histogram is the case with battery installed. As can be seen there is an effect of the battery in reducing the peak power demand. The impact of the battery is more pronounced as the balance between the energy storage and power characteristics of the battery is better selected. For lower power capacities the energy in the battery is less likely to be too quickly drained and hence the impact on the tail end of the peak demand histogram (at the lower peak values) is more pronounced.

V. DISCUSSION

By looking at the 95 percentile of the peak demand distribution for each of the villas, an understanding of the impact of the battery on the peak demand is apparent. Fig. 5 illustrates that the decline in the peak demand is not linear, and varies between the villas quite considerably. A general observation is that regardless of power capacity, the peak reduction is larger for increasing battery energy capacities. Is it however also demonstrated that the battery power cannot be too great compared to the battery energy constraint, otherwise the battery will be drained too quickly, and the peak demand for a period of high demand will not be reduced by combining grid and batty power. This can also be seen in [16], [17]. There are some minor variations from this trend. These are assumed to be stochastic variations of combinations of the state of the battery and the villa's power demand. It is expected that variations would be averaged out given larger investigation periods or by averaging over multiple villas so that there is a monotonously increasing peak reduction effect with larger battery energy capacities. It is also observed that the power consumption of Villas B and C show similar characteristics as seen in Fig. 1, and that the effect of battery storage is correspondingly similar as seen in Fig. 4.

In the study presented in this paper, there is only 5 villas included, and there was a varying monitoring period for each of the villas. In Norway the energy consumption pattern varies considerably from season-to season, mainly due to electricity used for space heating. Even though the villas were reasonably similar in size and built according to the same standard, it is still questionable how directly the results can be compared. There are large qualitative differences between the 95 percentile curves found for each villa, and the difference in monitoring period, difference in usage or characteristics

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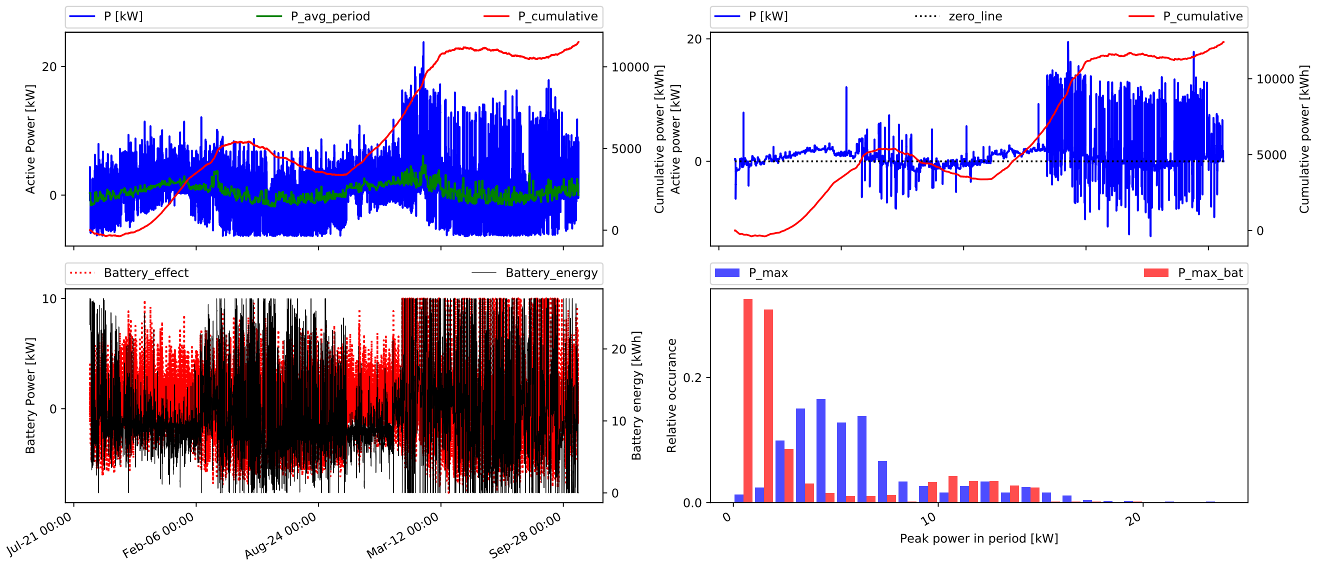

Fig. 3. Upper left-hand pane: Power consumption for villa A (blue), daily average (green) and cumulative power consumption (red) over the monitored period without battery installed. Upper right-hand pane: Power consumption (blue) and cumulative consumption (red) with battery utilization. Lower left-hand pane: The state of the battery, the charging/discharging power (black) and the energy stored in the battery (red). All three panes with a 1-minute time resolution on x-axis. Lower right-hand pane: Daily peak load distributions on a 1-minute average basis with and without battery installed at the villa.

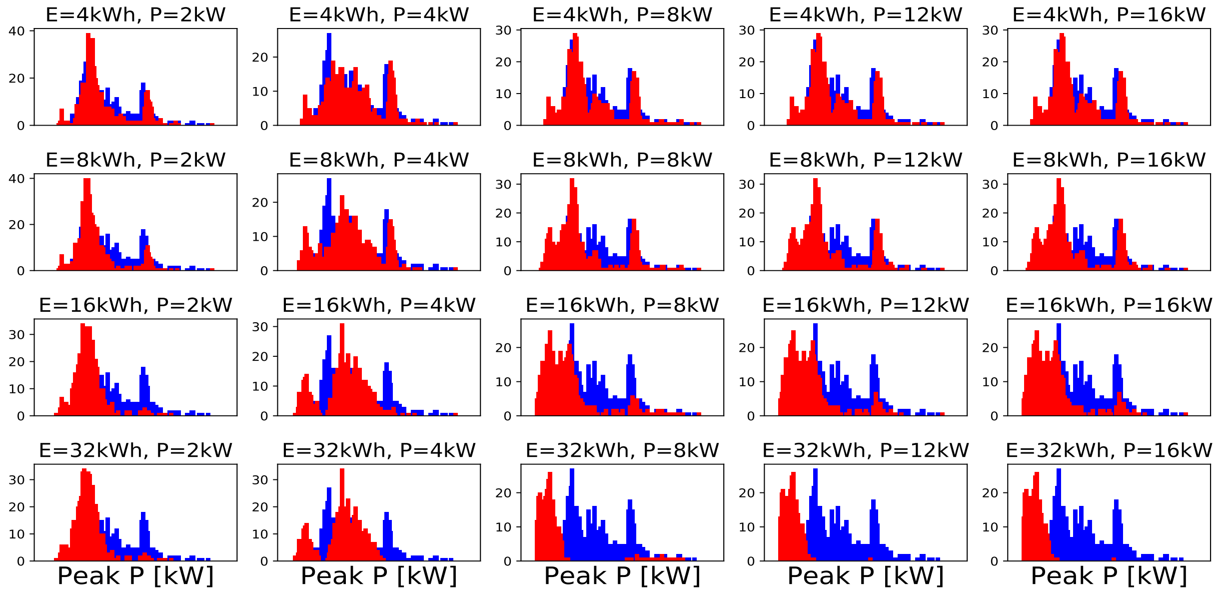

Fig. 4. Daily peak load distributions for 1-minute averaged resolutions for various battery characteristics. The blue curves are peak load distribution without battery installed and the red curves are peak load distributions with batteries installed in the range 1 to 32 kWh energy storage and 1 to 16 kW charging/discharging power capacity. See Fig. 5 for aggregated results.

of the villas (inhabitants, appliances installed, sun-orientation etc.) could cause such differences. A considerable potential for peak load reduction by the utilization of batteries as energy storage is however demonstrated for all villas. There needs to be a balance between the energy storage capacity of the battery and the power capacity in order to achieve effective peak reduction. The power capacity should not be too large for the battery to drain too quickly, as it will not be able to reduce consumption peaks after it has been depleted. It is recommended in future studies to include larger samples size of villas to study, and also to correlate with meta-data on the villas such as number/age/gender of inhabitants, area of villa, building standard, appliances installed and villa orientation. Repeating the study with a predicted average load forecast in place of the calculated one utilized in this study would give more realistic insight into the peak reductions achievable in practical operation. The ideal average load forecast utilized in this paper gives an artificially high peak reduction estimate.

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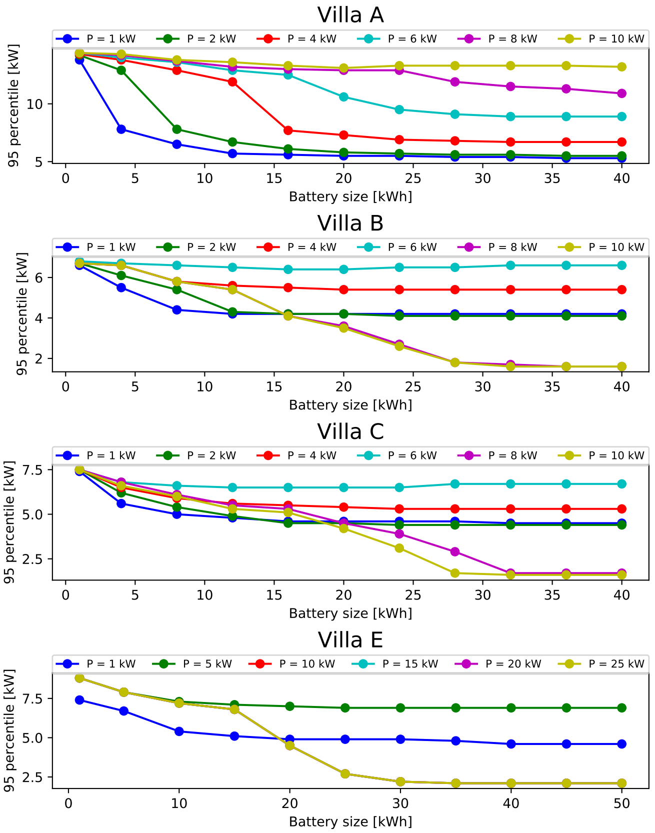

Fig. 5. Plot of 95 percentile peak power demand for each villa as a function of battery characteristics. Horizontal axis is the battery storage capacity in kWh, and the vertical axis is the 95 percentile daily peak demand on a minute-by-minute average. Each plot shows the impact of varying the power characteristic of the batteries as separate coloured curves. Note that some plots seem to be missing some curves as there is several curves that are laying on top of each other. This indicates that there is no change in peak reduction due to increasing battery power capabilities.

The price of electricity is varying over the studied period, and an optimization problem focused on optimizing the cost for the prosumer would have to take this into account.

VI. Conclusion

It has been demonstrated that the peak power demand from villas can be substantially reduced by the utilization of household batteries even at relatively unfavourable longitudes. A reduction of 50 to 80% in the 95 percentile minute-by-minute power demand has been estimated using ideal load prediction forecast. A balance between the energy storage capacity and the charging/discharging capacity of the battery is important to optimize the peak load reduction. In particular the charging/discharging capacity must not be too large compared to the energy storage capacity in order to facilitate high peak load reduction capability. Large variations in the simulated peak reduction achieved have been observed between the monitored villas for similar batteries. The battery utilization model deployed here could be improved to achieve better peak-shaving ability for the battery utilization. Utilizing a more sophisticated methodology not only being controlled though the battery capacities could be beneficial.

VII. ACKNOWLEDGMENT

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