# SEASONALLY VARIANT DEPLOYMENT OF ELECTRIC BATTERY STORAGE SYSTEMS IN ACTIVE DISTRIBUTION NETWORKS

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## ABSTRACT

*Due to the aging of network infrastructure, the increasing load demand in distribution networks together with the increased installation of PVs (Photovoltaic) in the MV and LV network, there is a need for network reinforcement. As load growth congests the grid, the strategic placement of electric storage systems can be an alternative to or contribute to a deferral of grid investments. To study this, an optimization problem solving the dual-purpose deployment of prosumers' level battery storage system has been formulated and will be presented in this paper. The MV/LV substation loadings are compared for the 0% prosumers and 100% prosumers scenarios with PV-battery system. The results of the analysis show that the absolute peak at secondary substation decreases by 8.74% and the average day peak drops by 17% while the total annual energy drawn from the grid reduced by 8.41% with the 100% prosumers scenario. Furthermore, by using household level battery systems for peak shaving of local loads one can achieve a deferral of overloading by 3 years at MV/LV substation.*

## INTRODUCTION

Due to the aging of network infrastructure and the ever-increasing load* demand in distribution networks together with the increased installation of PVs in the MV and LV network, there is a need for network reinforcement. At low levels of variable renewable energy sources (VRES) penetration in a strong grid, electricity storage is not crucial, but as load growth congests the grid and VRES penetration increases, the strategic placement of electric energy storage systems (EES) may be more viable than the construction of new transmission and generation capacity [1]. In the Northern hemisphere, however, the yearly household load profile and the respective rooftop PV output are negatively correlated. The off-peak production in low insolation area impedes the benefits of photovoltaic system [2]. In fact, PV generation rarely coincides with peak demand periods in the residential LV network and hence PV fails to contribute to supporting the network through reducing peak demand [3]. For utilities to utilize electric battery storage systems as alternative to network reinforcement investments, its optimal utilization has to be justified. Especially when the need for peak load shaving and the need for self-consumption converges.

In this study, seasonally variant deployment of battery storage control systems is proposed as a solution. The control objective for battery energy storage is self-consumption in summer and load levelling in winter. Currently in Norway, self-consumption is more valuable than feed-in to the grid. However, the relevance of the objectives can vary depending on the variation of tariffs, incentives and global battery prices.

There are strong indications that the installation of solar (PV) panels will be increasing in the coming years in Norway. At the consumption side, although most appliances are becoming energy efficient, their short time power demand is increasing – contributing to reduced utilization time of the distribution grid. In addition, grid-connected PV may cause major challenges for the voltage quality and thermal capacity, especially in LV weak rural grids [4]. Future smart distribution network, however, envisions better utilization of existing grid infrastructure by extending longevity and leveraging capacity; making the right investment decisions based on up-to-date information; have optimized operations with fewer manual processes and increase customer experience.

The Norwegian research project 'Flexibility in the future smart distribution grid' (FlexNett, 2015-2017) aims to contribute to an increased flexibility in the future smart distribution grid by demonstration and verification of technical and market based solutions. This paper presents some of the results based on measurements from residential households and prosumers at demonstration sites, focusing on the role of energy storage systems to increase the capacity of distribution network as well as enabling the deferral of network investment needs.

In this study, we will investigate the potential electric energy storage systems offer to load smoothening, which ultimately defer the needed network investment in distribution grid. Furthermore, the potential that exists by using storage elements at different locations and sizes will be evaluated as an alternative to grid investments.

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* Unless it is specifically specified, 'load' refers to both peak load and total energy consumption

The storage battery types analyzed are (also see Fig. 1):

1. Prosumer owned battery at household level (Size: small scale distributed)
2. Community owned (Size: medium scale)
3. Utility owned battery at MV/LV substation level (Size: large scale)

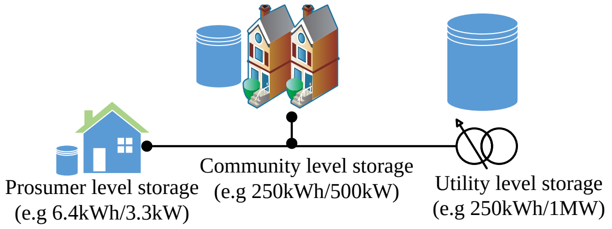


*Fig. 1. Different level placement of storage systems*

The prosumer owned batteries and their impact are investigated based on a prosumer located in a weak distribution grid in Central Norway. This work makes preliminary conclusions and recommendations on regional (located at MV/LV substation), neighbourhood (collectively owned by prosumers and ordinary consumers), and prosumer level battery storage.

## TRENDS IN PEAK POWER AND ENERGY CHANGES

The reduced utilization of network infrastructure due to increased peak loading is likely to continue of being a challenging factor in future distribution grids. The expensive investment required to mitigate only brief peak hours results in inefficient utilization of infrastructure which eventually increase the grid tariff on the general public. The change in peak hour of the year kWh/hour and the change in yearly kWh consumption are presented for the analysis period 2007 to 2015, based on hourly data from 100 residential customers located in Central Norway (see Fig. 2).

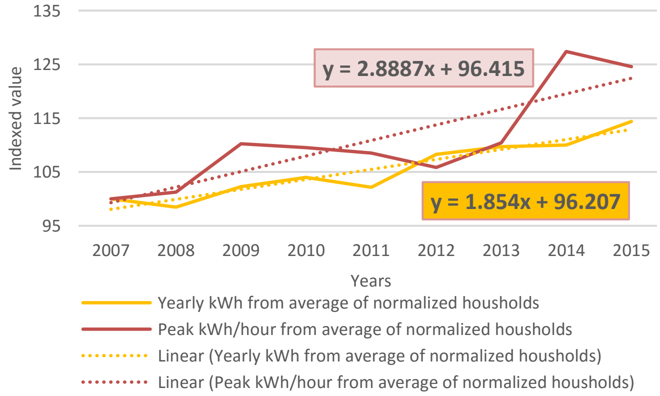


*Fig. 2. Comparison of the change in total normalized kWh yearly consumption with the change in the maximum hourly peak of the year for years between 2007 and 2015*

When we refer to peak consumption, it is the peak kWh/hour and hence it is normalized with temperature before making comparison of the rate-of-increase with yearly consumption. This also means that the absolute peak power can be higher than the hourly peak consumption, as our measurements do not capture the dynamics within one hour.

From base year of 2007 the percentage increase of the yearly consumption and the peak hour consumption is growing at different rate. Each year the percentage change of yearly consumption from 2007 value is increasing by 1.85% and increasing by 2.89% for peak-hour. Finally, in 2015 compared to 2007, the yearly consumption has increase by 14.38% and by 24.57% for peak hour of the year

## OPTIMAL DUAL PURPOSE BATTERY UTILIZATION METHOD

The highly uncorrelated PV-output and household load in Norway demands for optimal utilization of prosumer level battery (see Fig. 3). Naturally, the utilization of battery for peak shaving in winter time and self-consumption in summer time could lead to economical justifiable installations of storages.

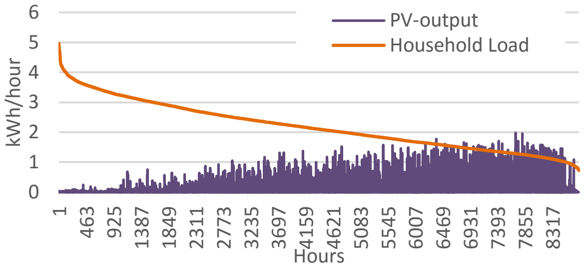


*Fig. 3. The descending order of one year hourly kWh consumption and the respective PV-output (Location: 63° 56′ 14″ N, 11° 25′ 26″ E).*

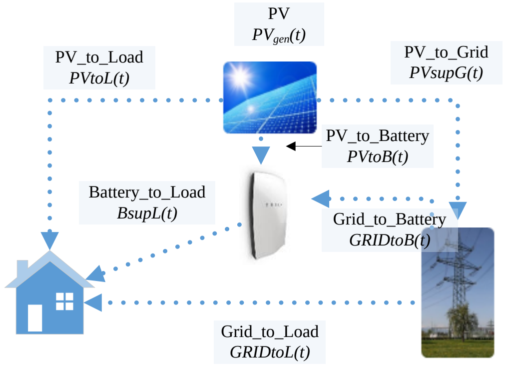


*Fig. 4. Multipurpose utilization of storage batteries inside PV integrated households*

In general, the energy exchange among the grid, the household loads, the PV and the battery is depicted in Fig. 4. The PV-output is mainly used to supply the load *(PVtoL(t))* and excessive power can be supplied back to the grid *(PVsupG(t))* or can be stored in the battery *(PVtoB(t))*. The grid can supply the household load

*(GRIDtoL(t))* or it can also supply the battery storage system *(GRIDtoB(t))*. The output (discharge) from the battery is used only to supply the household load *(BsupL(t))*. With forecasted 24-hour ahead load and weather conditions, the formulations (1) – (12) will optimally decide the optimal power exchange values for the 24-hours ahead.

**Objective#1:** Self-consumption *[If PV >25% of Load]*

$$Minimize\left(\sum_{t=1}^{24} Egrid(t)\right) \qquad (1)$$

**Objective#2:** Peak-shaving (Load levelling) *[If PV ≤25% of Load]*

$$Minimize\big(Max(Egrid(t)) - Min(Egrid(t))\big) \qquad (2)$$

### A. Battery stored energy conservation

$$Bstored(t+1) = Bstored(t) - BsupL(t) + PVtoB(t) + GRIDtoB(t) \qquad 1 \le t \le 24 \qquad (3)$$

### B. PV output, load and grid supply conservation

$$PV(t) = PVtoL(t) + PVtoB(t) + PVsupG(t) \qquad 1 \le t \le 24 \qquad (4)$$

$$L(t) = PVtoL(t) + GRIDtoL(t) + BsupL(t) \qquad 1 \le t \le 24 \qquad (5)$$

$$Egrid(t) = GRIDtoL(t) + GRIDtoB(t) \qquad 1 \le t \le 24 \qquad (6)$$

### C. Battery maximum storage and minimum discharge limits

$$Bstored(t) \le \alpha * Bmax \qquad 1 \le t \le 25 \qquad (7)$$

$$Bstored(t) \le \gamma * Bmax \qquad 1 \le t \le 25 \qquad (8)$$

### D. Initial stored battery energy level

$$Bstored(t) \le Bprevious\_day \qquad t=1 \qquad (9)$$

### E. Avoiding charging and discharging happening at the same time

$$\big(PVtoB(t) + GRIDtoB(t)\big) * BsupL(t) = 0 \qquad 1 \le t \le 24 \qquad (10)$$

### F. Battery maximum power constraint

$$BsupL(t) \le Pmax \qquad 1 \le t \le 24 \qquad (11)$$

$$PVtoB(t) + GRIDtoB(t) \le Pmax \qquad 1 \le t \le 24 \qquad (12)$$

Where *Egrid(t)* is the total supply from the grid, *L(t)* is the total load in kWh, *Bstored(t)* is the total stored energy of the battery system in kWh at time *t*, *Pmax* is the maximum power of the battery, maximum charging and discharging level in % are $\alpha$ and $\gamma$ respectively, and *Bmax* is the maximum capacity of battery.

The method followed in the study of optimal battery utilization is essentially a deterministic one. That means both the household load and PV output are determined prior to the optimization of battery charging and discharging cycles. For the household load, we used the average time-series load profile of the hourly kWh measurements of group of households. For the time series PV-output, we used weather forecasts (solar irradiation and ambient temperature) in the area of the households. The process of the analysis is depicted in Fig. 5. According to [5], for optimal sizing of the PV power and the storage capacity a resolution of 60 minutes is found to be sufficient. Hence, in this study, the analysis is essentially based on 1-hour resolution measurement.

## CASE STUDIES

Three case scenarios are simulated and compared in their impact in reducing MV/LV substation level peak loads. The first case is a battery storage system at household level (e.g. Powerwall), the second case is community ownership of battery storage and the third case is utility owned and operated battery storage system. The considered secondary substation is a typical substation of 22/0.23 kV, 315 kVA supplying 60 households [6].

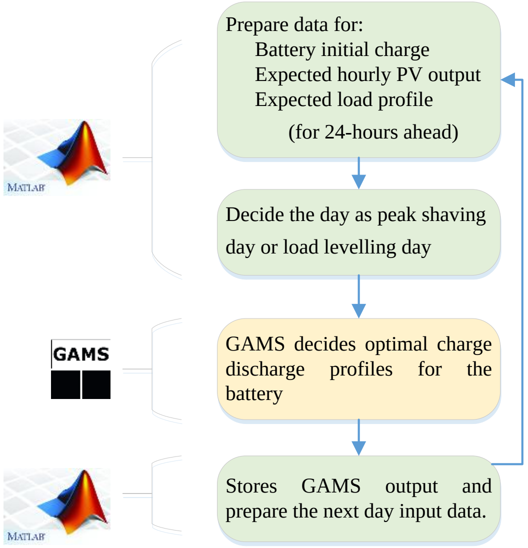


*Fig. 5. Work flow for a day-ahead hour-by-hour battery operation scheduling*

However, before conducting deeper analysis, we evaluated if it is enough to take the average household load profile of a group of households to run a single optimization on and multiply by their number to get the total effect. The time-series load profiles of 10 households (i.e. smart meter 1-hour resolution measurement for one year) was used to make this initial analysis. The sum of the results from 60 optimizations using the 60 individual time series load profiles are compared with 60 times the result from the average load profile of the 60 households. As one can see in Fig. 6, the mean absolute error is 12.63 kWh while the yearly average one-hour consumption from the grid is 125.81 kWh (i.e. ±10% error from average hourly value). This is significant and hence we shall run the optimization for individual households under secondary substation when we want to see the orchestrated impact it will have on the loading of the secondary substation. Nevertheless, the results from average household consumption are presented when it is needed to show the impact of the optimization program at household level loading (see Fig. 7).

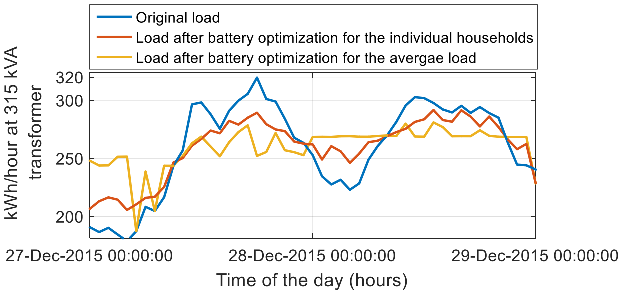
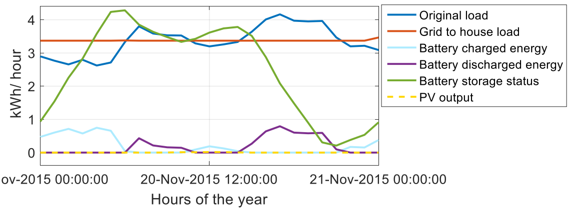


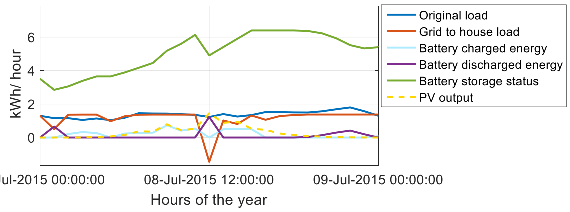
*Fig. 6. The load profile on a day with the peak hourly consumption of the year at the MV/LV substation (315kVA) supplying 60 households.*

## CASE#1: Household level battery storage system

In Case#1, we investigated the impact on MV/LV substation load when individual households owning a 3.06 kWp PV system with 6.4 kWh/ 3.3 kW battery are running alternatively dual objective for optimization while utilizing their battery storage system.



*(a)*



*(b)*

*Fig. 7. Load profiles of single household at winter (a) and summer (b) day optimization*

In Case#1 analysis, the peak kWh/hour of the year is decreased by 8.74% when all households own PV-battery system. The results of the analysis also show that average day peak drops by 17% while the total annual energy drawn from the grid reduced by 8.41% with the 100% prosumers scenario (see Figs 7 and 8).

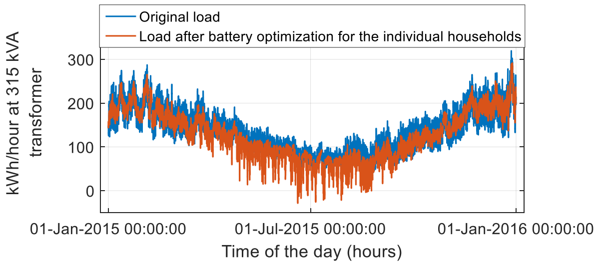


*Fig. 8. Comparison between MV/LV substation load of 100% consumers and 100% prosumers with integrated PV-battery system.*

## CASE#2: Community owned battery storage system

In Case#2, we simulated community ownership of battery storage system managing the PV-production and consumption of households in the same neighborhood. For equivalent comparison, we divided the MV/LV substation area supplying 60 households into four regions each owning 15×(6.4kWh/3.3 kW, 3.06kWp) system. (i.e 96kWh/49.5kW, 45.9 kWp).

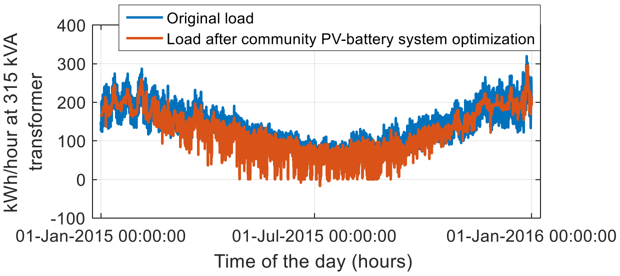


*Fig. 9. Comparison between MV/LV substation load of 100% consumers and with our four community owned* 96kWh/49.5kW *battery system with* 45.9 kWp *PV-system.*

In Case#2 analysis, the peak hourly consumption (kWh/hour) of the year is decreased by 7.68%, which is slightly, lower than the PV-battery system ownership and optimization at individual households (see Fig. 9).

## CASE#3: Utility level battery storage system

Utility owned battery storage systems are sometimes beneficial alternative to conventional reinforcement. For example, in Wettringen, Germany a Distribution System Operator owned and operated storage asset is selected over 10-kV cable reinforcement to be used as a temporary solution [7]. In order to make a comparison between distributed household level storage system to aggregated substation storage system, we conducted simulation for 384 kWh (60 x 6.4kWh) and 198 kW (60 x 3.3 kW).

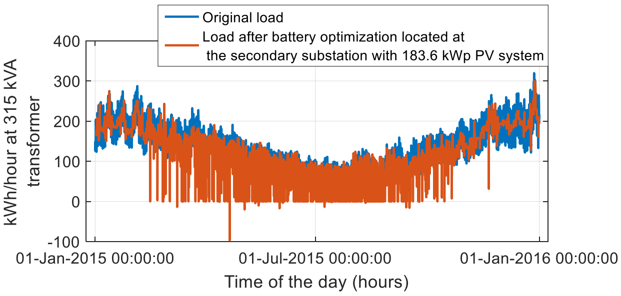


*Fig. 10. Comparison between MV/LV substation load of 100% consumers and with 384kWh/198 kW battery system with 183.6 kWp PV-system.*

In Case#3, the peak load of the MV/LV substation has decreased by 6.35%, which is lower than the 8.74% decrement observed with distributed ownership of PV-battery system (see Fig. 10).

## DISCUSSION

The determination of the size and placement of battery storage system in the distribution network is dependent on the purpose the storage system is going to be utilized for. As the results in the above three cases demonstrate, distributed energy storage systems at household level might be attractive solutions to reduce the size of the peak demand as seen by the distribution network (see Fig. 11). However, for other services such as increasing reliability by abating the impact from unexpected outages of large generating units, centralized storage systems might be effective. The study has been focusing on the consumption, storage and generation of electricity on an hourly basis, and not including any economical evaluation.

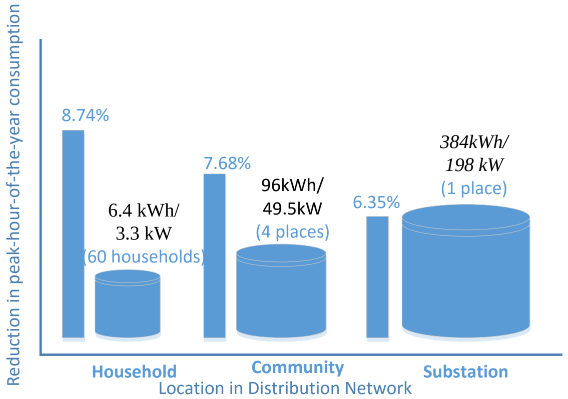


*Fig. 11. Comparison among three level placement of battery storage system in distribution network*

Assuming an increase in peak hour consumption by 2.89% each year as shown in Fig. 2, distributed household level battery storage system could defer grid investment needs at MV/LV substation by 3 years compared to the year investment would have been needed if no optimal PV-battery system utilization is implemented.

## CONCLUSIONS

The benefits of battery storage system are assessed for Northern hemisphere environment using actual households' hourly level load measurements and their respective geographical location solar irradiation measurement. A scenario dependent dual objective battery utilization is proposed and demonstrated to justify the use of battery storage system optimally for load levelling during winter and increased self-consumption during summer, in cases where PV-output is negatively correlated to load.

## Acknowledgments

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