AALBORG UNIVERSITY
DENMARK

Maximizing the self-consumption of Solar-PV using Battery Energy Storage System in Samso-Marina

Ponnaganti, Pavani; Bak-Jensen, Birgitte; Pillai, Jayakrishnan Radhakrishna

Maximizing the self-consumption of Solar-PV using Battery Energy Storage System in Samsø-Marina

Ponnaganti Pavani
Department of Energy Technology
Aalborg university
Denmark.

Birgitte Bak-Jensen
Department of Energy Technology
Aalborg university
Denmark.

Jayakrishnan R Pillai
Department of Energy Technology
Aalborg university
Denmark.

Abstract—**Samsø is a medium sized Danish island located in the sea of Kattegat. Almost 90% of the island's production comes from renewable energy sources (RES) including wind and solar-photovoltaics. The fluctuating nature of these resources leads to its reduced utilization. Installing battery energy storage systems (BESS) at local communities or residences in the island not only improves the utilization efficiency but also increases the revenue to the utility/RES owners. This paper proposes a method for maximizing the self-consumption of RES using BESS installation at the Ballen-Marina site in the Samsø island. The reported simulation studies are carried out for summer months i.e., mid-July to mid-September based on real data from the Marina site.**

I. Introduction

Samsø island produces more energy than it consumes owing to offshore and onshore wind power [1]. There is not yet a curtailment issue of renewable generation in the energy system of the island since it is interconnected to the danish main land power system. There are many opportunities for better management of the local generated energy, taking flexibility of the local demand into account. A PV-BESS system is being newly installed in the island's Marina and the load is mainly consisting of yacht boats, two service buildings and harbor master's office building. One of the limitation for injecting the RES production into the grid is that the selling price of local renewable energy production is very less than the price of energy that is bought from the grid. In addition, considering the grid stability issues involved with high injection of renewable energy into the distribution grid, the new policies [2] in many countries support the increase in the self-consumption of solar-PV [3].

BESS plays a key role for maximizing the energy consumption locally by intelligently defining the charging/discharging patterns of BESS with respect to the production of Solar-PV [4] and the demand. In [5], an optimized storage control for the BESS is proposed for improving the self-consumption. Due to its fast response characteristic of BESS, it can charge/discharge in order to support the frequency control in the grid. Revenue can also be generated with increase in the self-consumption of solar-PV along with BESS to the RES owner/utility by participating in the balancing markets or day-ahead markets [6]. Demand side management with the help of flexible loads is also another option for increasing the self-consumption of solar-PV system [7]. Moreover for the

individual households, there is increased benefits in the form of both revenue and independence from the grid by maximizing the self consumption of their solar-PV installations [8].

The present work proposes an intelligent charging/discharging strategy of BESS for maximizing the self-consumption of the solar-PV. Without interrupting the supply to boat loads, energy balance is established by both the PV-BESS system and the grid. The idea is to create a real-condition smart grid system with renewable energy sources, storage and electric loads. The flagship case concerns the boats in the marina, where the boats are to be charged with the electricity from renewable energy sources (RES) by an intelligent charging/discharging system. The paper is organized as follows, in Section II the proposed strategy is explained, which is illustrated with the help of an algorithm and its mathematical formulation. In Section III, the electrical set up of the Marina site is described and the simulation studies in Section IV followed by conclusions in Section V.

II. Marina Description

A 40 kWp solar-PV along with a 240 kWh Lithium-ion based BESS with an inverter capacity of 50 kW is being installed at the Marina site and the illustration of electrical set-up for the energy system is as shown in Fig. 1. The electricity consumers are all behind one energy meter to the public grid. More specifically, the legislation only allows the produced electricity from the RES to be consumed locally avoiding the need for paying usual high electricity tax [9]. The Marina has got many piers with more than 200 electrical sockets. The main consumption of the Samsø-Marina load consists of boat charging and two service buildings. The service building contains electrical loads such as washing machine, electrically heated sauna and hot water showers for the convenience of tourists.

Fig. 2 and Fig. 3 represents the 2018 real data for both the marina load and solar-PV production, respectively and is used for carrying out the current work. The solar-PV system can directly inject into the local Marina grid to meet the load and deliver to the battery whenever there is excess energy available. It is to be observed from Fig. 2 that the maximum load occurs in July because it is generally the peak time for tourism in the island. It can also be observed from Fig. 2 that the load is very high when compared to the solar-PV
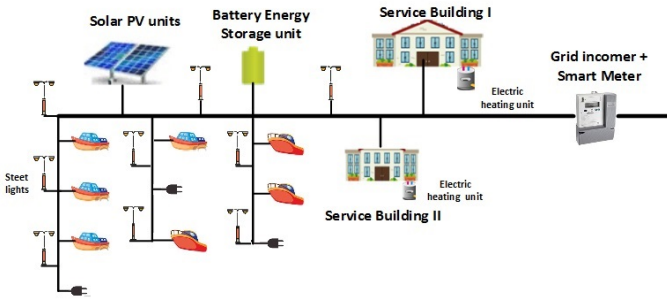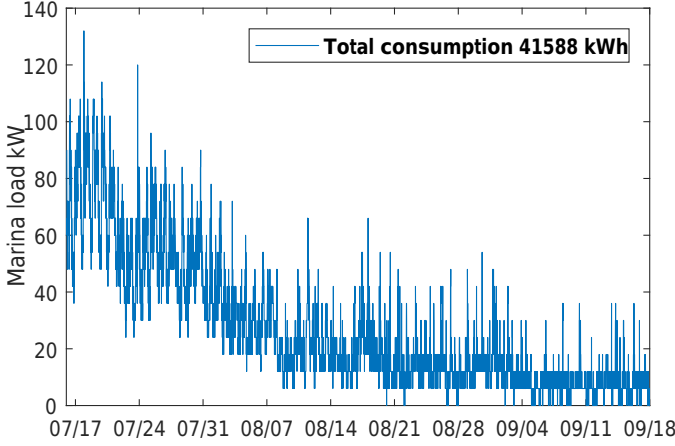
Fig. 1. Samsø-Marina site
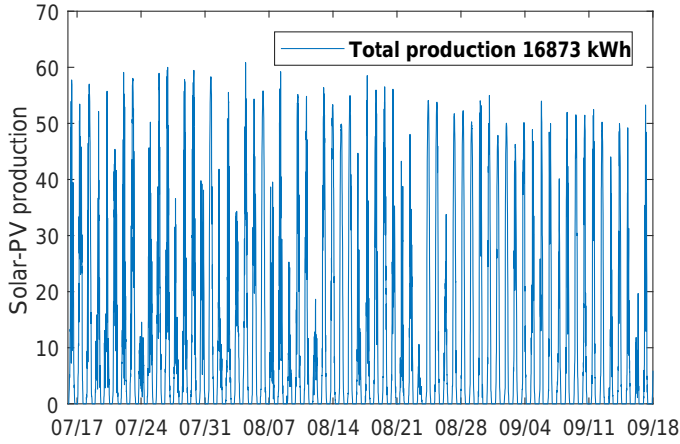

Fig. 2. Samsø-Marina load

Fig. 3. 60 kWp Solar-PV production

production as seen in Fig. 3 and possibly leaving no excess power for the battery to charge. This may be a case where BESS can be charged from grid during off-peak hours, so that BESS can support the Marina load at nominal price during peak hours.

III. METHODOLOGY

The vision is to make Samsø island free of fossil fuels by 2030, which shall be done by using only local wind turbines and photovoltaic (PV) systems together with the use of local

biomass resources for meeting the local demand. To apply the new ideas, the marinas on the island are chosen, one of which is the Samsø-Marina site that has been used in the current work. For leveling out the fluctuations of the renewable sources, battery energy storage system (BESS) is installed with a capacity that is sufficient to buffer the day-to-day local energy consumption.

The main objective of the proposed strategy is that the production from the solar-PV should be either consumed by the local loads or stored in the BESS. This maximization problem is formulated here as minimization of the amount of power injection from Solar-PV into the grid. The BESS not only charges from solar-PV but also just before peak hours to avoid high electricity costs during peak hours. A non-linear optimization problem is formulated for finding the charging/discharging strategy of the BESS for the following constraints: almost no interruption of supply to local boat loads and meeting BESS operational limits. Also, another important constraint is that BESS cannot directly inject into grid according to the island's current legislative framework [9].

The formulation is as follows:

Minimize P_{inj}^t

subject to

$$SOC_{min} \leq SOC \leq SOC_{max}$$
$$BESS_{charge} \leq Inverter_{cap} \geq BESS_{discharge}$$
$$P_{sol}^t - P_{load}^t > 0, BESS_{charges}$$
$$P_{sol}^t - P_{load}^t < 0, BESS_{discharges}$$
$$P_{sol}^t + P_{BESS}^t - P_{load}^t < 0, (A)$$
$$P_{sol}^{(t+1)=t_{peak}} + P_{BESS}^{(t+1)=t_{peak}} - P_{load}^{(t+1)=t_{peak}} < 0,$$

$$(1)$$

where, P_{inj} is the power injection from Marina site into the grid, t represents the time step of 15 mins interval for a summer period i.e., mid July-mid September, t_{peak} represents peak hours of the day i.e., 18-22 hrs in the present case. SOC_{min}, SOC_{max} is the minimum and maximum state of charge of BESS respectively, P_{sol} is the power produced by the solar-PV, P_{load} is the total Marina load and P_{BESS} is the power delivered from the BESS through its inverter. The constraint (A) denotes that whenever the PV-BESS system cannot meet the Marina load, then the grid is responsible for obtaining the load balance. In addition the last constraint is considered where BESS gets also charged from the grid say at 17 hrs i.e., before peak hours (18-22 hrs) during which the Marina site witnesses high number of boat loads (referred as $P_{load,peak}$,) and hike of electricity prices. This step needs the intelligence of both the harbor master and near accurate load forecasting for getting optimal benefits from the proposed operating strategy of the PV-BESS system.

The proposed intelligent operation of the BESS is described with the help of an algorithm.

- *State of Charge (SOC) is between min 10% & max 90% of the total BESS capacity.*
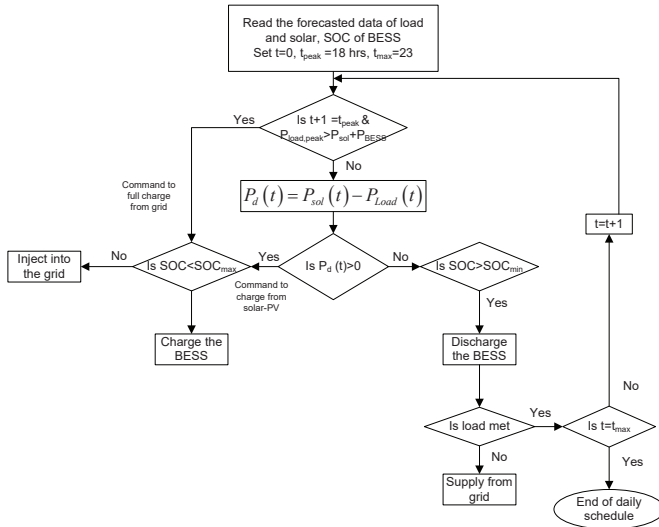
Fig. 4. Flow chart detailing the operation of BESS for load balance

- *Depth of discharge (DOD) is 80%.*
- *Battery charges, if,*
  - *PV power is available after meeting Marina load*
  - *SOC is less than $SOC_{max} - 90\%$.*
  - *Electricity cost during peak hours (18-22 hrs) is high. So charging command will be sent to BESS at 17.00 hrs depending upon the forecasted load of the peak hours.*
- *Battery discharges, if,*
  - *PV power is not sufficient to meet the Marina load*
  - *SOC is greater than $SOC_{min} - 10\%$.*

The detailed algorithm is illustrated with the help of a flow chart as shown in Fig. 4.

IV. SIMULATION RESULTS

The simulations are carried out in Matlab R2017a platform. The BESS is modeled with the basic equations that represents the charging/discharging characteristics of a Lithium-ion battery type with some model assumptions including the self-discharge of the battery is not represented and the internal resistance is assumed constant. There are three battery racks of each 80 Ah capacity, which are connected to 50 kW inverter. The minimum and maximum SOC limits are 10% and 90% of full BESS capacity. Inverter capacity defines the charging/discharging rates, it takes 4 hrs to completely charge the BESS and the actual discharge period will likely be longer when the solar-PV plant delivers energy along with the BESS. At the start of the simulations, the SOC of BESS is considered to be at SOC_{min}. Integer linear programming is used for solving the proposed methodology. For the Marina site, the buying price is 0.21 €/kWh and the selling price is 0.03 €/kWh and the electricity buying price during peak hours is considered to be 1.17 €/kWh. The costs and benefits are corresponding to the import and export of the energy, respectively with respect to the grid.
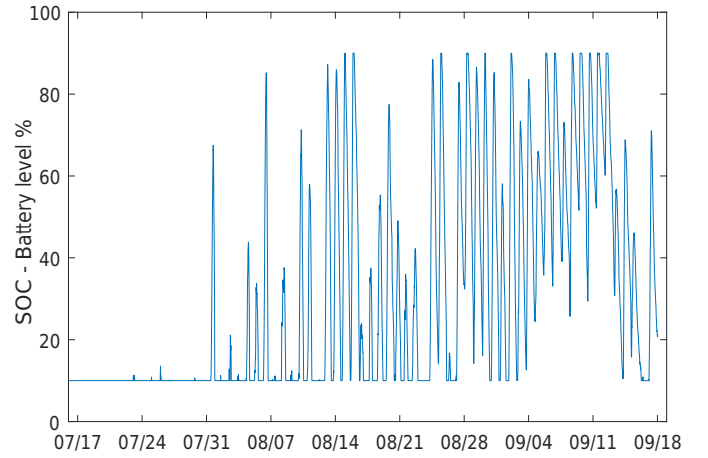

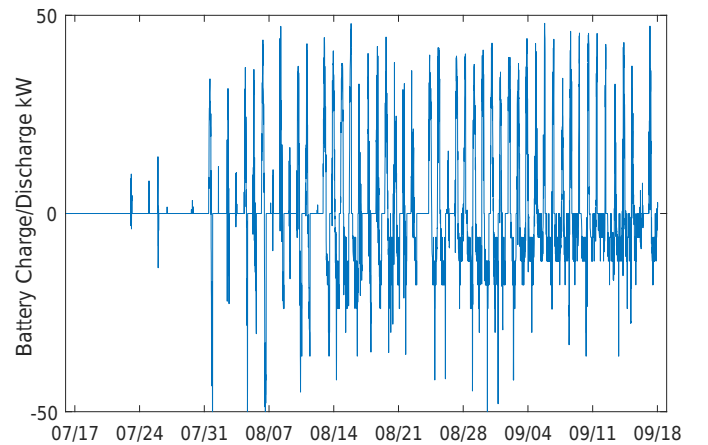Fig. 5. SOC of the 240 kWh BESS without charge from grid

Fig. 6. Proposed charging/discharging pattern of BESS without charge from grid

Figs. 5 & 6 show the SOC and charging/discharging profiles of BESS, relaxing the last constraint i.e., BESS charging from grid. As it can seen from Fig. 5, for the month of July, the BESS is always at its SOC_{min}, where there is no excess solar-PV production to charge the BESS. This is due to the fact that the Marina load is high and consuming total production from solar-PV during the July month and also the result is satisfying $SOC \geq SOC_{min}$ constraint.

Figs. 7 & 8 show the SOC and charging/discharging of BESS for Eq. (1). Almost whole month of July, as the available energy is less than the forecasted peak load, the full charge command is executed many times in the season, in order to satisfy the constraint of meeting peak load from PV-BESS system, thereby preventing the peak electricity prices.

Figs. 9 & 10 show the SOC and discharging profiles from a day operation of the BESS, respectively, considering all the constraints in the formulation that is given in Eq. (1). It can be observed from Fig. 9, at around 17 hrs before the peak hours, as the forecasted load (238 kWh) is higher than the available energy from both PV-BESS, which is only 48 kWh,
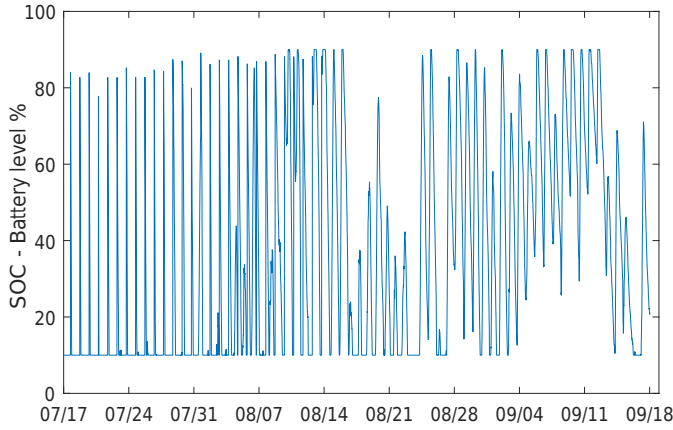
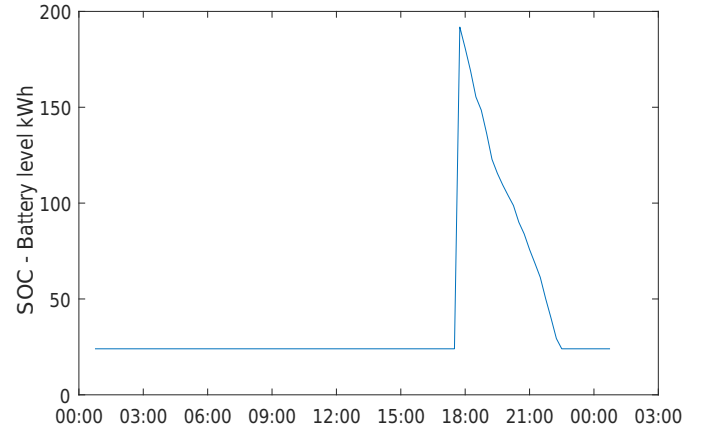Fig. 7. SOC of the BESS with charging from the grid

Fig. 9. SOC for a day in July with charge from grid
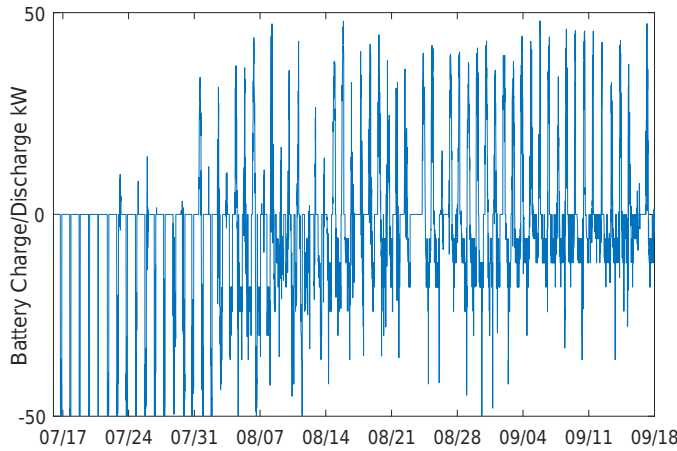

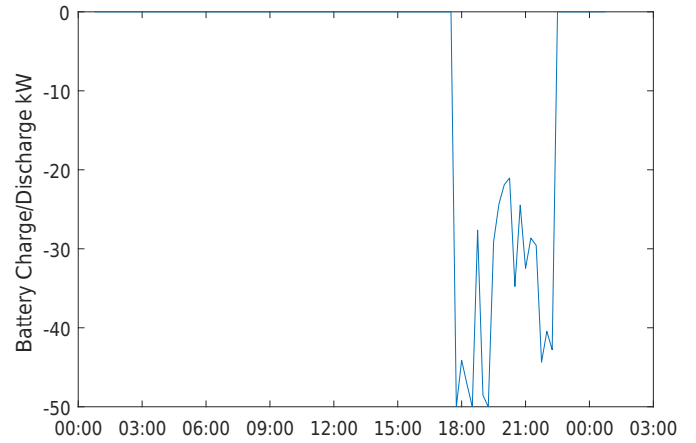Fig. 8. Charging/discharging pattern of BESS also charging from the grid

Fig. 10. Discharging pattern of BESS for a day in July with charge from grid

a command is given to BESS to full charge from the grid. During peak hours, BESS started discharging to meet the load minimizing import from the grid. As shown in Fig. 11, this is the amount of power import from the grid that is used for charging the battery and to meet the load.

The solar-PV power injected into the grid is shown in Fig. 12, which is represented by P_{inj} in the Eq. 1. As it can be observed that from the proposed optimal working BESS strategy, the export is as minimum $472.678 kWh$ for the considered summer period. The electricity price paid towards importing energy from the grid is calculated from the optimal power injection that is obtained from the proposed optimization algorithm is given in Table I.

V. Discussions

- The following are conclusions drawn from Table I, which gives the import along with export/injection of the power that is obtained from the proposed optimization algorithm.
- In the first case where there in no PV-BESS system, the total load is met by the grid, so there will be only
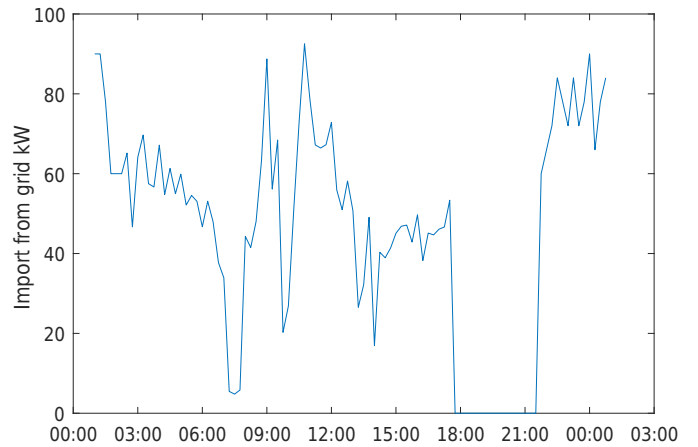

Fig. 11. Import from grid for a day in July with charge from grid

electricity import cost.

- The case with PV and without BESS, there will be periods where excess solar production is present and an amount of €426.93 is obtained by selling $6276.3 kWh$
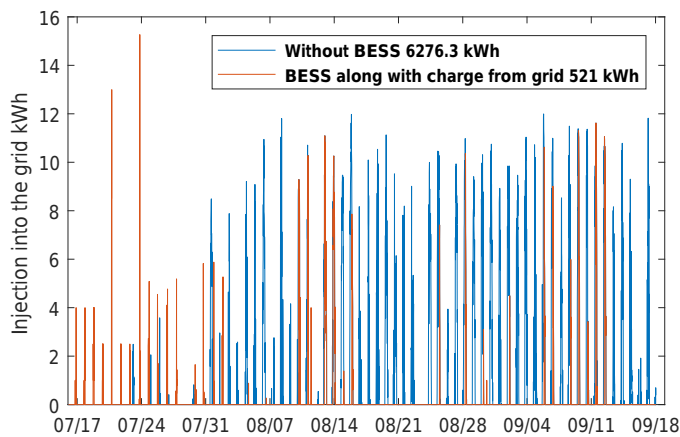
Fig. 12. Export/Injection into grid for the considered summer period

TABLE I
ENERGY IMPORT/EXPORT FOR THE CONSIDERED SUMMER PERIOD

Case	Import		Export(P_{inj})	
	kWh	€	kWh	€
W/O PV-BESS	41588	98501	-	-
W/O BESS	30991	14231	6276.3	426.93
With PV-BESS	24543	10915	682.36	20.470
With PV-BESS and charge before peak hours	25236	7918.8	521	15.63

into the grid.

- With BESS and condition of no possibility to charge from grid, unlike in the earlier cases, here excess solar-PV production is stored in the BESS for future use. It can be seen that in this case there is an export of $682.36kWh$.

- In the case where the PV-BESS charge from the grid in off-peak hours, the import form the grid is a little higher than in the case where there is no charing from the grid. This is due to the fact that the BESS is charging to its full capacity during off-peak hours. But, the price €7918.8 that is paid towards the energy import of $25236kWh$ mostly during off-peak, which is less expensive than the previous case cost €10915. But the injection into the grid in the last case is very minimal i.e., $521kWh$ compared to all other cases satisfying the constraints of the proposed optimization problem. When compared to earlier case, the export exists here because BESS is fully charged before peak hours and there are times where BESS is full and have no capacity to accommodate any excess solar-PV production leaving no option other than exporting this surplus from the solar-PV into the grid.

VI. CONCLUSIONS

An optimal strategy for maximizing the self-consumption of solar-PV for a commercial site in Samsø island is proposed in this paper. It can also be applied for domestic households.

The proposed BESS operation can increase the utilization of solar-PV production not only for summer season but also for all seasons. It is worth mentioning that here the summer case considered in this work, mostly peak demand is observed and the export will be as less as possible. The results show that there is considerable reduction of dependence on the main grid, making Samsø-Marina self-sustainable most of the time during a day. Also, it will be more interesting to incorporate demand response techniques on the flexible loads like heat pumps, boats etc that are present in the Marina site for obtaining more independence from the grid and also for managing the peak load, which will be our future work.

REFERENCES

[1] H2020-SMILE, "Specification and data report for the Samsø demonstrator," *Deliverable 3.1*, 2018.
[2] European-Commission, "Best practices on renewable energy self-consumption," *Technical report*, 2015.
[3] G. Litjens, W. V. Sark, and E. Worrell, "On the influence of electricity demand patterns, battery storage and PV system design on PV self-consumption and grid interaction," in *IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, Jun 2016, pp. 2021–2024.
[4] N. Liu, Q. Chen, X. Lu, J. Liu, and J. Zhang, "A charging strategy for PV-based battery switch stations considering service availability and self-consumption of PV energy," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 8, pp. 4878–4889, Aug 2015.
[5] K. Yuasa, T. Shimakage, N. Takeuchi, and Y. Sugiyama, "Optimized storage battery control in hybrid power distribution system for improving energy self-consumption," in *IEEE International Telecommunications Energy Conference (INTELEC)*, Oct 2016, pp. 1–6.
[6] F. J. Soares, J. P. Iria, J. C. Sousa, V. Mendes, and A. C. Nunes, "Impact of PV for self-consumption in the day-ahead spot prices," in *13th International Conference on the European Energy Market (EEM)*, Jun 2016, pp. 1–5.
[7] C. J. C. Williams, J. O. Binder, and T. Kelm, "Demand side management through heat pumps, thermal storage and battery storage to increase local self-consumption and grid compatibility of PV systems," in *3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, Oct 2012, pp. 1–6.
[8] R. Martins, P. Musilek, and H. C. Hesse, "Optimization of photovoltaic power self-consumption using linear programming," in *IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, Jun 2016, pp. 1–5.
[9] "Elafgiftsloven (electricity tax law)," https://www.skm.dk/skattetal/satser/satser-og-beloebsgraenser/elafgiftsloven, nr. 308, 24. marts 2017.