Using of Battery Storage to Match the Supply and Demand of Electricity in Smart Grids

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Abstract. *Distributed electricity generation from renewable energy sources is in the increase in distribution grids. This gives opportunity to local generation and consumption of electricity. To match the supply and demand of electricity, battery storage (BS) is required. It is required to measure different parameters like electricity consumption, photovoltaic (PV) generation, battery state of charge, and temperature and exchange them in real-time with the utility grid. This is the concept of smart grids where different sensors are used for real-time measures and fast communication is required to ensure a fast response to unpredictable changes in PV generation and electricity consumption. In this paper, the application of BS in smart grids is presented. According to results, 21.42 % less electricity from the utility grid is required with BS which reduces electricity cost by 25.66 %. The amount of electricity exported to the utility grid is reduced by 89.83 % which increases the share of PV generation used for supplying own electricity consumption by 26.92 %.*

Keywords. Renewable energy sources, smart grid, battery storage, electricity demand

1 Introduction

The share of generation from renewable energy sources is on the rise and the main focus is on wind and solar. Wind power plants are connected to transmission grids while PV power plants can be connected to different grid levels depending on the installed power. PV power plants are very common in distribution grids where the main idea is to generate free electricity and use it at the same location which has a significant contribution to improving energy efficiency and sustainability.

Electricity generation from PV is variable, intermittent, and unpredictable which makes it a challenge to match local consumption with generation. Production from PV is high over the day when people are usually at work and electricity demand is low. During this period, there is an excess of PV generation which is exported to the utility grid. In the evening people are at home and load demand increases. In the evenings, the PV generation is no longer available and electricity for supplying demand is imported from the utility grid (Radhakrishnan & Selvan, 2015).

One possible solution is shifting electricity consumption from periods without PV generation to periods when the PV generation is available. There are time-shiftable devices in households (Pawar, Sampath, Ghosh, & Vittal, 2018) that can be used in any part of the day. As periods with a lot of sun are over days when people are at work, home energy management systems are required to send signals to devices when to turn on.

Another solution to match the supply and demand of electricity is the implementation of BS (Reka & Ramesh, 2015). The idea is to store PV generation excess in periods with more generation than consumption of electricity and then to use stored electricity in periods with lower generation than consumption of electricity (Tutkun, Burgio, Jasinski, Leonowic, & Jasinska, 2021). To decide when to use BS, real-time measurements of the generation and consumption of electricity are required. Different parameters like temperature, humidity, and electricity price should also be measured to control electricity demand and improve electricity use. There is a requirement for fast communication between sensors, control units, and the system operator to enable the real-time match of supply and demand of electricity.

Smart grids use digital modern technologies, including sensors and software to match electricity supply with electricity demand in real-time. The concept of the smart grid is presented in Fig. 1. In the smart grid in addition to energy flow are data flows. Energy flows are one-way energy flows from renewable energy sources to the smart grid and from the smart grid to consumers and two-way energy flows between battery storage and the utility grid. Data flows are two-way between the smart grid and consumers, renewable energy sources, battery storage, and utility grid. Data flows enable the exchange of real-time consumption data, generation data, electricity price, temperature, and other information important for the operation of the smart grid.

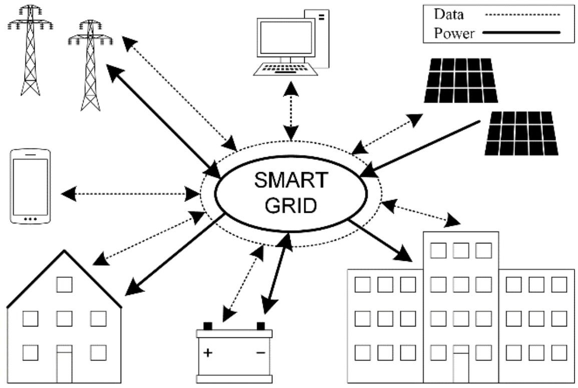

Figure 1. Smart grid concept

In this paper, a smart grid with electricity generation from the PV power plant, electricity consumption of the residential building, and BS is simulated. Simulations are done without and with BS to see the influence of using BS to help match electricity demand with electricity generation.

This paper is organized as follows. The first chapter is an introduction to smart grids and the importance of BS systems. In Chapter 2, the methodology of this work is explained with emphasis on the used algorithm and input data. In Chapter 3 results are presented and discussed. The last chapter is the conclusion.

2 Methodology

In this chapter, the algorithm for battery storage and required input data is explained.

2.1 Battery storage algorithm

The algorithm for deciding when to charge and discharge BS is explained. The algorithm requires the amount of electricity generation and electricity demand in each hour to decide how to use battery storage. The flow chart diagram of the used battery storage algorithm is presented in Fig. 2.

2.1.1 BS charging

When the amount of PV generation is higher than the electricity demand in the observed hour, there is an excess of electricity that can be stored in the BS. Battery charging is possible if battery storage is not full. If battery charging is not possible, electricity excess needs to be exported to the utility grid.

2.1.2 BS discharging

When the amount of PV generation is lower than the electricity demand in the observed hour, there is a lack of energy that can be delivered from BS if there is enough stored electricity. If there is not enough electricity in battery storage, the required electricity is imported from the utility grid.

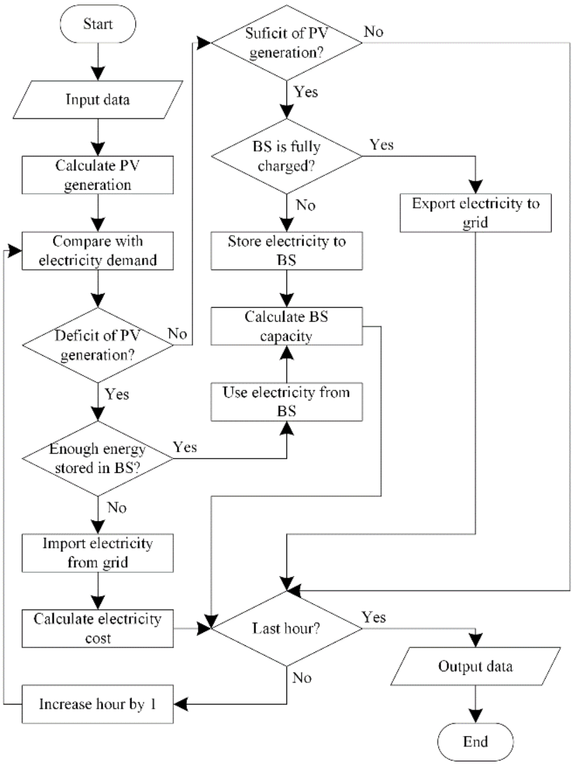

Figure 2. Flow chart diagram of BS algorithm

2.2 Electricity generation from PV power plant

Electricity generation from the PV power plant is modeled according to the solar irradiation data available from PV GIS (European Commission, 2022) for the selected location with hourly resolution. The amount of PV generation in each hour is calculated according to eq. 1.

$$P_{pv}(t) = G(t) \cdot n_m \cdot A_m \cdot \eta_m \cdot \eta_{inv} \qquad (1)$$

Where:

- $P_{pv}(t)[W]$ – output power of a PV power plant in each hour *t*;
- $G(t)[W/m^2]$ – solar irradiation in each hour *t*;
- n_m – number of PV modules;
- $A_m[m^2]$ – the square area of a PV module;
- η_m – efficiency of a PV module;
- η_{inv} – efficiency of the PV inverter.

The PV module used in this model is a module with a rated power equal to 500 kW and an efficiency in the amount of 21.3 % (Bluesun Solar, 2022). Dimensions of a PV module are 2.056 m in length and 1.140 m in width which results in a square area equal to 2.34 m^2.

The installed power of a PV power plant is 20 kW which means that there are 40 PV modules. The efficiency of the PV inverter is 98 % and the PV output power is calculated. The PV generation during one month is presented in Fig. 3.

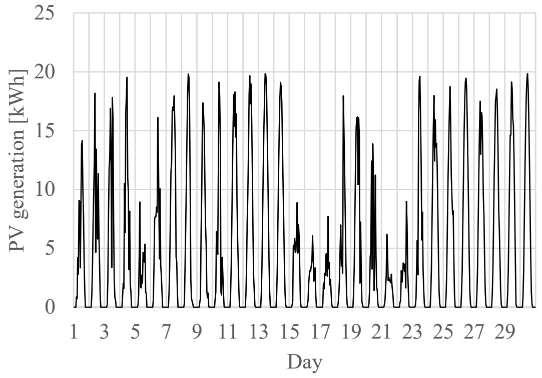

Figure 3. The PV generation

2.3 Electricity demand

Electricity demand is modeled according to the measured consumption data. Electricity consumption data is measured for one week with a 10-minute time interval and averaged to electricity consumption data with an hourly time interval.

The electricity consumption data is then scaled to building size. Electricity consumption data during one month is presented in Fig. 4.

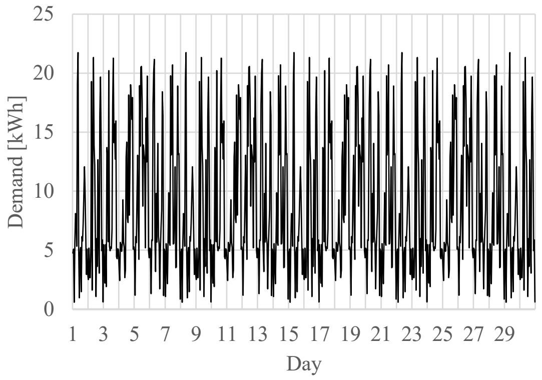

Figure 4. Electricity demand

2.4 Electricity price

The electricity pricing model used in this work is a tariff billing model for electricity buyers from the household category in Croatia. The electricity billing items for electricity buyers from the household category are presented in Table 1.

VAT for electricity in Croatia is 13 %. The high tariff is from 08:00 to 22:00 and the low tariff is from 22:00 to 08:00 during summer. During winter, the high tariff is from 07:00 to 21:00 and the low tariff is from 21:00 to 07:00 (HEP Elektra, 2023), (HEP ODS, 2022). The assumption is that the smart grid is simulated for one month in summer.

Table 1. Billing items for buyers from the household category in Croatia

Billing item	EUR/kWh
Electricity - high tariff	0.074789
Electricity - low tariff	0.036697
Grid using fee - high tariff	0.051762
Grid using fee - low tariff	0.022563
RES incentive fee	0.013239

2.5 Battery storage model

Battery storage in smart grids is required to help match the supply and demand of electricity. Absorbing electricity excess from PV generation helps to increase the share of local electricity generation used to cover local electricity consumption. Using stored energy in periods without available PV generation and charging BS with electricity from the utility grid at a low price helps to reduce electricity costs.

During charging and discharging of battery storage, the state of charge needs to be monitored. The SoC in each hour is calculated according to eq. 2.

$$SoC(t) = SoC(t-1) + P_c(t) \cdot \eta_c - P_d(t)/\eta_d \qquad (2)$$

Where:

- $SoC(t)$– battery SoC in hour t;
- $SoC(t-1)$ – battery SoC in previous hour $t-1$;
- $P_c(t)[W]$ – battery charging power in hour t;
- η_c– battery charging efficiency;
- $P_d(t)[W]$ – battery charging power in hour t;
- η_d– battery discharging efficiency.

Battery storage used in this work has a battery capacity of 60 kWh and the rated power is 20 kW which is equal to the installed power of a PV power plant. The battery storage technology is assumed to be Lithium iron phosphate ($LiFePO_4$) with cycle efficiency equal to 92 % and maximum depth of discharge (DoD) equal to 80 %.

3 Results

In this chapter results of using BS in a smart grid through simulation are presented. Simulation is done in a Python environment. Results for two different cases are presented. The first case is a simulation without BS and the second case is a simulation with BS. Two different days are observed, a sunny day with a lot of available PV generation and a cloudy day, without enough PV generation. The PV generation and electricity demand during a sunny day are presented in Fig. 5 and during a cloudy day in Fig. 6.

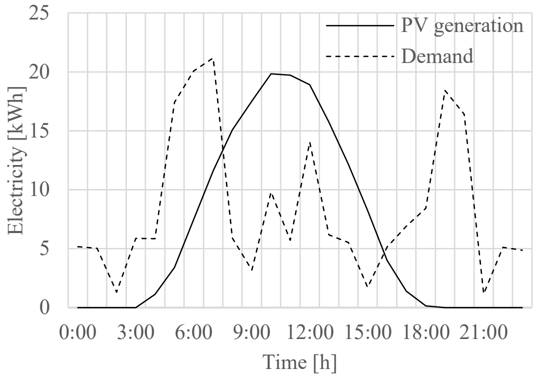

Figure 5. PV generation and electricity demand during a sunny day

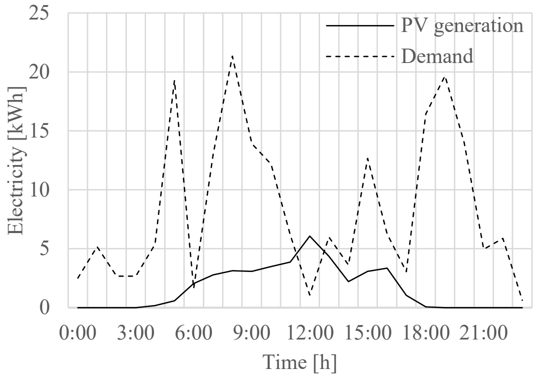

Figure 6. PV generation and electricity demand during a cloudy day

3.1 Daily results without BS in smart grid

When BS is not available in the smart grid, the entire PV generation excess occurs in hours in which the amount of electricity from the PV power plant is higher than the electricity demand is exported to the utility grid. The high electricity demand, which occurs in periods without enough electricity generation from the PV power plant, is covered with electricity imported from the utility grid, as shown in Fig. 7 for a sunny day.

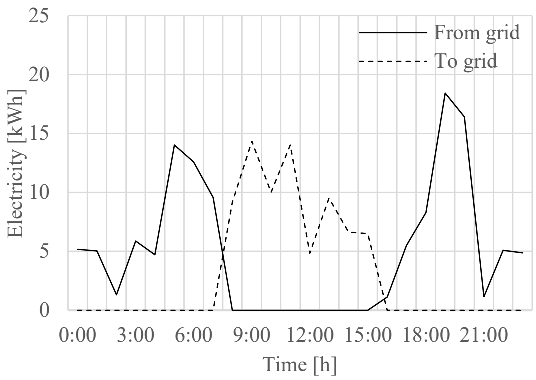

Figure 7. The exchange of electricity with the utility grid during a sunny day without BS

During a cloudy day, only a small amount of electricity is exported to the utility grid. Most of the time, the electricity required to supply electricity demand is imported from the utility grid as shown in Fig. 8.

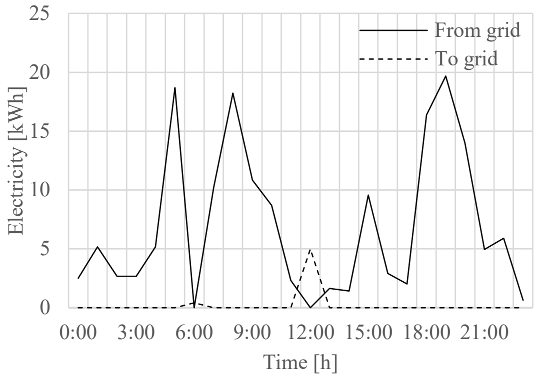

Figure 8. The exchange of electricity with the utility grid during a cloudy day without BS

3.2 Daily results with BS in smart grid

Using the BS in the smart grid enables to storage excess of PV generation for later use instead of exporting it to the utility grid. BS is charged from 8:00 to 11:00 hours when the PV generation is available during a sunny day and discharged from 16:00 to 22:00 when the amount of PV generation is not enough to supply the entire electricity demand, which can be seen from Fig. 9.

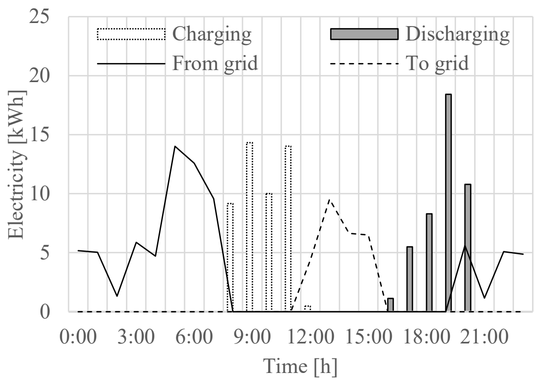

Figure 9. The exchange of electricity with the utility grid and the BS during a sunny day

The BS is not charged from 12:00 to 15:00 because the BS is full, which can be seen from Fig. 10 which represents the battery state of charge (SoC). During this period the PV generation excess is exported to the utility grid.

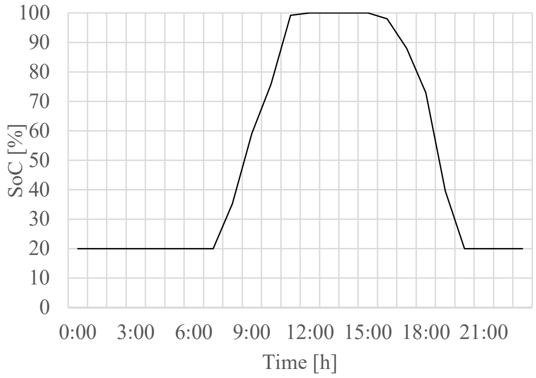

Figure 10. The battery SoC during a sunny day

A small excess of PV generation during a cloudy day is now stored to BS, as it is shown in Fig. 11 but this energy is not significant and electricity demand is supplied from the utility grid. The battery SoC is at the minimum level due to low PV generation, as it is shown in Fig. 12.

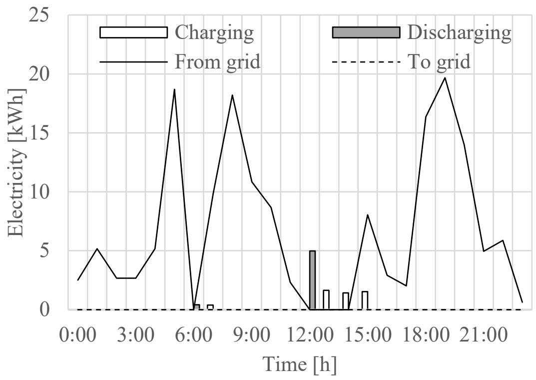

Figure 11. The exchange of electricity with the utility grid and the BS during a cloudy day

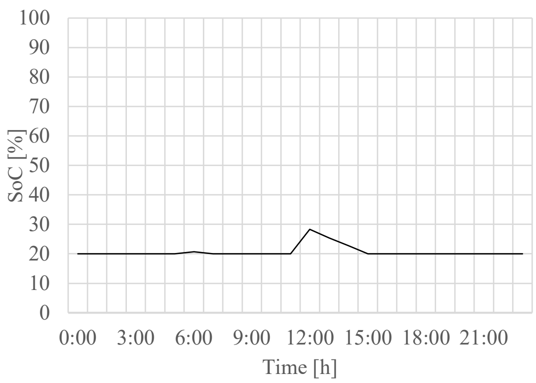

Figure 12. The battery SoC during a cloudy day

3.3 Monthly results

Total monthly simulation results are presented in Table 2. Electricity demand in the observed month is 6259.66 kWh while estimated PV generation is 3241.72 kWh. The amount of electricity imported from the utility grid is 4073.70 kWh without BS, while the amount of electricity imported with BS is 3201.14 kWh which is a decrease of 872.56 kWh or 21.42 %. The amount of electricity exported to the utility grid without BS is 1055.76 kWh and 107.32 kWh with BS which is the decrease in the amount of 948.44 kWh or 89.83 %.

Table 2. Monthly results

	Without BS	With BS
Demand [kWh]	6259.66	
PV generation [kWh]	3241.72	
Import from grid [kWh]	4073.70	3201.14
Export to grid [kWh]	1055.76	107.32
Stored to BS [kWh]	-	948.44
Used from BS [kWh]	-	872.56
Electricity cost [EUR]	532.97	396.18
PV share [%]	67.43	94.35

The amount of PV generation stored in BS is 948.44 kWh and the amount of 872.56 kWh is used from BS to match electricity demand. The amount of usable electricity is lower due to battery cycle efficiency in the amount of 92 %. Without BS, the electricity cost is 532.97 EUR and with BS, the electricity cost is 396.18 EUR. The electricity cost decrease is 136.79 EUR or 25.66 %. The share of PV generation used for supplying electricity demand has increased from 67.43 % without BS to 94.35 % with BS which is an increase of 26.92 %.

4 Conclusion

In this work, the importance of using BS to match the supply and demand of electricity in smart grids is explained and confirmed with an example. Without BS, it is not always possible to match the supply of electricity from intermittent and variable renewable RES like PV power plants with the electricity demand. One solution is shifting electricity consumption from periods without PV generation to periods when the supply of electricity from the PV power plant is available. There are time-shiftable devices in households that can be used in any part of the day. As periods with a lot of sun are over days when people are at work, home energy management systems are required to send signals to devices when to turn on.

When BS is available in the smart grid, the free electricity from the PV power plant can be stored in BS in periods with a lot of sun and with low electricity demand and used in periods without sun and with high electricity demand.

According to the results, 21.42 % less electricity is imported from the utility grid with BS than without BS. This leads to a reduction of electricity cost by

136.79 EUR of 25.66 % for one observed month. The amount of electricity exported to the utility grid is reduced by 89.83 % because this difference is stored in BS and used later in periods without enough PV generation. This leads to the increase of the share of PV generation used for supplying the own electricity consumptions for 26.92 %.

In future work, the BS algorithm can be improved to find the optimal time for charging and discharging. In addition to charging BS when there is available PV generation, BS can be charged with electricity from the utility grid when the electricity price is low.

Acknowledgments

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