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-sizing OF A BATTERY ENERGY-STORAGE SYSTEM FOR THE FACULTY OF TECHNICAL SCIENCES – BITOLA

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ABSTRACT

Renewable energy sources are the key to reducing carbon emissions and achieving more energy independency. Up to 2018 the Faculty of Technical Sciences Bitola used only electrical energy from the grid. In 2019, the faculty installed its first 20 kW of photovoltaic panels. The number of panels has doubled and as of 2023, the installed power is 40 kW. As a prosumer, the faculty uses the grid energy for covering the energy needs when the generation from the PVs is insufficient. When the generated energy from PVs is high, it is used by the faculty building and in cases when generated energy exceeds the faculty's load, the energy is exported to the grid. The positive thing is that the faculty's work time is synchronised with the generation of the photovoltaic panels (08:00-16:00). During periods of low PV energy production (such as cloudy weather), a battery storage system can offset energy shortfalls. The critical question is determining the optimal battery capacity that achieves maximum financial benefit by minimising investment costs and maximising returns from selling surplus energy back to the grid. The main goal of this paper is to calculate optimal capacity of battery energy storage for achieving minimum dependency from grid power and to reduce faculty costs for electricity from the grid.

Keywords: battery energy storage system, rooftop PV plant, linear programming.

INTRODUCTION

Solar energy is available for production from a PV plant only during daylight hours and weather conditions affect the amount of solar energy that will be delivered to the Earth's surface. Additionally, power supply interruptions can occur due to faults in the utility grid. These two factors (insufficient solar radiation and power outages) represent a problem that has led electrical engineers to consider the storage of electrical energy. It is known that electrical energy is stored in batteries, but at a low voltage level (a few volts) suitable for electronic devices. The case of interest is energy storage for households, commercial buildings and industrial facilities, which have higher consumption and operate at a higher voltage level (distribution network voltage).

Currently (year 2024), a 40 kW photovoltaic system is installed on the roof of the Faculty of Technical Sciences in Bitola. The faculty building, as a consumer, is supplied with electrical energy from its own PV system and when that energy is insufficient, it purchases electricity from the utility grid. When there is an excess of electrical energy production from the PV system, the surplus energy is sold to the grid. Due to this operation, the faculty building is considered a prosumer. The two issues from the previous paragraph can also occur to the faculty. The batteries for energy storage (hereafter referred to as Battery Energy Storage System (BESS)) for such a consumer are still expensive and are subject to aging and the loss of physical and chemical properties.

This paper focuses on finding the optimal technical and economic solution for installing a BESS using a developed methodology and Python code. The question is raised: What capacity should the BESS have to meet the needs of the faculty in order to reduce the amount of purchased electricity from the utility grid and achieve a return on investment for the BESS? Practically the main contribution of the paper is to answer the raised question in the previous sentence. Linear programming technique is used for the optimization process, using the electricity hourly prices from power exchange, load profile of the faculty and PV hourly generation profile.

The paper is structured as follows. Chapter 2 covers the working principle of a grid-connected photovoltaic system, its components and advantages and disadvantages of prosumers. Chapter 3 describes the types of batteries/BESS. Chapter 4 is the main part of this paper, presenting the methodology and proposed algorithm, and the results from the calculations of the code for optimal charging and discharging of the BESS to achieve maximum profit. Chapter 5 is the conclusion - summarizing the theoretical part of the BESS and the results, which benefit the faculty as a prosumer.

PHOTOVOLTAIC SYSTEM CONNECTED TO THE POWER GRID

The integration of photovoltaic (PV) systems with the power grid marks a significant advancement in renewable energy technology. These systems harness sunlight to generate electricity, offering a clean, sustainable alternative to conventional power sources. By enabling direct energy generation and grid connectivity, grid-connected PV systems play a crucial role in addressing global energy demands while reducing environmental impacts.

Operating principle of a PV cell

The solar cell is a semiconductor diode with a large surface area. The photovoltaic effect occurs when the cell is exposed to solar radiation. Light quanta (photons) with sufficient energy create electron-hole pairs on both sides of the p-n junction.

If the pair forms far from the junction, it quickly recombines. However, if it forms in or near the junction, the internal electric field separates the electrons and holes. In this process, electrons move toward the n-side, while holes move toward the p-side. As a result of this movement, a potential difference (voltage) appears at the ends of the solar cell, and the contact potential of the p-n junction is reduced. This establishes a new equilibrium state for the p-n junction with a potential difference at its ends, which depends on the intensity of the solar radiation. If a load is connected to the ends (contacts) of the solar cell, current will flow through the circuit. The upper contact structure is transparent and made in the form of widely spaced metal strips to allow the unobstructed passage of solar radiation.

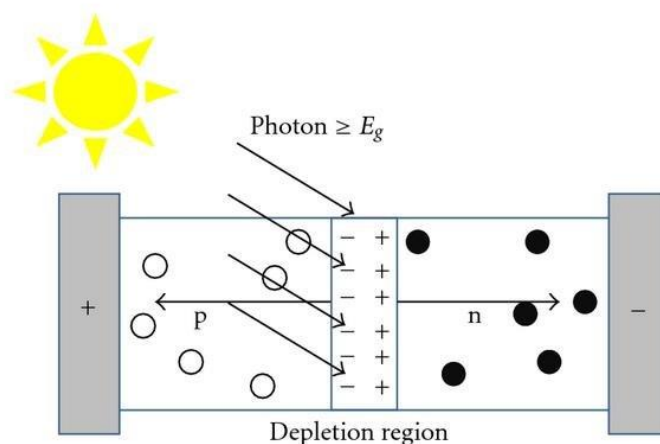


Figure 1 – p-n junction in a PV cell

Components of a PV plant

PV systems that operate on the utility grid are relatively simple. Beside the PV panels, they include an inverter in which a control device is integrated. Other components of a PV plant are the net metering and the utility grid itself.

There is a hierarchy for how the components of a PV array are combined: Many PV cells connected in series or in parallel form a PV module, PV modules connected in series or in parallel form a PV panel and PV panels connected in series or in parallel form a PV array. PV panels or arrays are placed on the ground or on rooftops under a certain angle for maximal solar energy usage. The series and parallel connections maximize the output current and voltage. The module consists of a harder glass on the front surface and of a shielded material on the back surface. The major purpose of the PV array is to convert the power of the sun rays into DC power.

The inverters are efficient, but costly. Their main task is the conversion of DC power into AC power, adjusting the frequency of the output AC power and controlling of the effective value of the output voltage. The significant characteristics of a PV inverter are its reliability and its efficiency. The inverters are manufactured to operate approximately at the maximum power point of the PV system. Generally, inverter efficiencies are varying from 90% to 96% at full load. When finalising a size to the inverters used in grid connected PV systems, the efficiency and ability to withstand in overload situation has to be considered. Inverters are placed in boxes referred to as power rooms together with transformers and relay protection/ power systems protection.

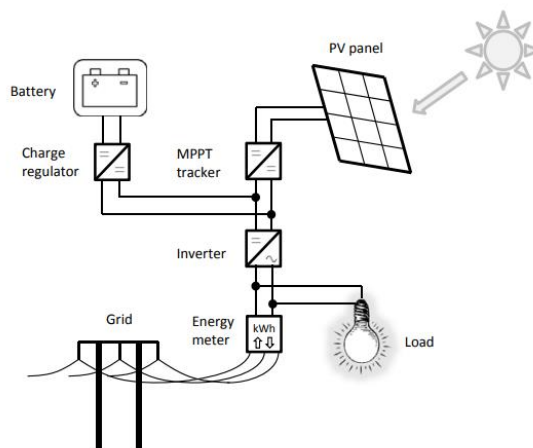


Figure 2 – Components of a PV plant

Prosumers. Advantages and disadvantages

The term ‘prosumer’ emerged in the early 1980s to refer to individual consumers who also produce goods and services. The types of industrial prosumers are numerous and may include, for example, agro-industrial operations such as pig, cattle, and poultry farms, mining operations, slaughterhouses, manufacturing plants, paper mills, solid waste management companies or forestry-related facilities.

An industry that produces and uses renewable energy sources such as solar, wind, and bioenergy, meets part or all of its energy needs on-site. In many cases, this involves selling excess energy or electricity to the national/local grid or to the surrounding community. Essentially, a prosumer represents an industry or building that is simultaneously a consumer but also produces its own energy. The Faculty of Technical Sciences in Bitola is a prosumer after the installation of the PV power plant on its roof.

The advantages of having prosumers are from (1) economic, (2) social, and (3) environmental perspectives: (1) price stability, reduced electricity costs, and greater independence from fossil fuels, stability of the electricity system, increased competition – better quality; an advantage might be the creation of new job opportunities, but since the faculty is a business-trading, not an industrial facility, this opportunity does not exist; (2) availability of electricity; (3) reduced negative environmental impacts by reducing carbon dioxide emissions required for electricity generation for the consumer (the faculty).

Barriers for prosumers are from social, financial, legal and technical perspectives, with issues such as: low awareness of renewable technologies, how they work and should be applied, lack of regulations for prosumers and high interest rates.

BATTERY ENERGY-STORAGE SYSTEMS

In recent years, the energy storage industry has evolved significantly, adapting to changing energy requirements and technological advancements. Energy storage systems provide a wide range of technical solutions for managing power supply, enabling a flexible energy infrastructure and cost savings for both grid operators and consumers. There are five methods for storing energy: electrochemical, electrical, chemical, mechanical and thermal.

Electrochemical energy storage is currently the most commonly used method across various applications. The two main types are batteries and fuel cells. These systems convert chemical energy into electrical energy. Batteries are further classified into two categories: rechargeable and non-rechargeable. Rechargeable batteries are particularly vital in renewable energy systems for storing surplus energy production.

When selecting batteries for the energy storage in a PV system, different aspects have to be taken into consideration. It is needed to be known whether the system is connected to the grid or operating as a standalone system. If it is not connected to the grid, the battery needs to have the capability to withstand any occasion, where the PV power is not available. In a grid connected PV system, the battery is used as backup when power outage has occurred in the utility grid. When the grid electricity price is high to purchase for the load, the battery power can be used to supply the load.

There are a few different battery technologies available on the market suitable for electricity storage in the form of electrochemical energy, for example lead-acid, lithium-ion (Li-ion), sodium sulphur (NaS), Nickel-cadmium (NiCd). Lead-acid is the most mature storage technique, but lithium-ion batteries have the greatest potential for future development and optimization due to high storage efficiency as well as high energy density. Their cost is however high and lead-acid batteries could have a negative impact on the environment.

Renewable energy systems typically utilize three primary types of lead-acid batteries, each offering distinct advantages: flooded, gelled electrolyte sealed, and Absorbed Glass Mat (AGM) batteries. Flooded batteries are the most cost-effective and widely used in PV systems, requiring regular maintenance and proper ventilation. They are particularly well-suited for renewable energy setups. On the other hand, gelled electrolyte and AGM batteries fall under the category of sealed batteries. These require no maintenance or venting, making them ideal for enclosed systems where regular upkeep is challenging.

Flooded Batteries: Flooded lead-acid batteries are the most common choice for PV applications due to their long lifespan and cost-effectiveness compared to other battery types. However, they require regular maintenance, which is a notable drawback. Often referred to as wet cells, these batteries come in two variants: serviceable and non-serviceable. Their durability and affordability make them a popular option in renewable energy systems.

Gelled Electrolyte Sealed Batteries: Gelled electrolyte batteries use silica gel to solidify the electrolyte, making them a type of valve-regulated lead-acid (VRLA) battery. Sometimes referred to as silicone batteries, they are well-suited for deep-cycle applications, such as marine trolling, sailboats, and electric vehicles. These batteries have a lower nominal charging voltage compared to other lead-acid batteries, as higher charging rates can create gas pockets and displace the electrolyte from the plates. Their design makes them reliable for applications requiring deep discharge and steady performance.

Sealed AGM Batteries: AGM batteries are another type of VRLA battery where the electrolyte is absorbed within fiberglass mats rather than being in liquid form. This design gives them a higher power density, resulting in greater ampere-hour capacity compared to flooded batteries. While AGM batteries offer enhanced performance and are commonly used in motorhomes, marine systems, and robotics, they are more expensive than other lead-acid

battery options. Despite the higher cost, their maintenance-free nature and robust performance make them a reliable choice for various specialized applications.

METHODOLOGY

BESS can be charged from surplus PV power P_{pv2b} , and cheap off-peak power imported from the utility grid P_{g2b} . Discharged power from the BESS can be used to, first, supply the faculty demand P_{b2L} , second, to export to the grid P_{b2g} only if it is profitable. Thus, battery power can be calculated as:

$$P_b[n] = (P_{pv2b}[n] + P_{g2b}[n]) \times \eta_c - \frac{(P_{b2L}[n] + P_{b2g}[n])}{\eta_d \times \eta_b}$$

where η_c , η_d , and η_b are BESS's charge, discharge, and roundtrip efficiency.

Further, battery SOC is estimated using ampere counting methods:

$$\text{soc}[n] = \text{soc}[0] + \frac{\sum_{\tau=1}^n P_b[\tau] \times \Delta t}{E_b} \times 100$$

and SOC is constrained to a minimum ($\text{soc}_{\min}$) and maximum ($\text{soc}_{\max}$).

$$\text{soc}_{\min} \leq \text{soc}[n] \leq \text{soc}_{\max}$$

Faculty load demand is firstly supplied by the solar power (P_{pv2L}), secondly by the BESS (P_{b2L}) and finally by the utility grid (P_{g2L}).

$$P_L[n] = P_{pv2L}[n] + P_{b2L}[n] + P_{g2L}[n]$$

The power generated by the solar array can be flown into the load (P_{pv2L}), BESS and grid (P_{pv2g}):

$$P_{pv}[n] = P_{pv2L}[n] + P_{pv2b}[n] + P_{pv2g}[n]$$

Power imported (P_{gim}) and exported (P_{gex}) from the utility grid can be expressed as

$$P_{gim}[n] = \frac{P_{g2L}[n] + P_{g2b}[n]}{\eta_{im}}$$

$$P_{gex}[n] = \eta_{ex} (P_{pv2g}[n] + P_{b2g}[n])$$

where η_{im} and η_{ex} are the efficiencies related to front-end converter when importing and exporting power, respectively. To restrict the simultaneous operation of export and import, an additional binary variable z_g is used.

$$z_g[n] = \begin{cases} 1, & P_{gim}[n] > 0 \\ 0, & P_{gex}[n] > 0 \end{cases}$$

The optimization problem is formulated as a mixed-integer linear problem.

$$\min C_{\text{daily}}(d) = \sum_{n=1}^N (P_{gim}[n] \times C_b[n] - P_{gex}[n] \times C_s[n]) \times \Delta t$$

where C_b is the price at which the power is bought from the grid and C_s is the price at which the power is sold to the grid. This problem is solved using linear programming techniques.

Battery parameters

Today, the cost of battery storage systems is high – from a few hundred up to more than a thousand US dollars per kWh of storage capacity. The following parameters beside rated capacity should be taken into consideration: voltage limitation, cycle life, calendar life, efficiency, state of charge, charging and discharging rate. Some of these terms are defined below.

Battery capacity: The amount of energy/charge that can be extracted from the battery bank from its fully charged state to the zero charged state is known as the battery capacity and usually, it is measured in ampere-hours (Ah). The capacity of the battery is not constant and it varies significantly depending on several factors such as the rate of discharge, age, temperature and the past history of the battery.

State of charge (SOC): The percentage amount of energy stored in the battery with respect to the nominal battery capacity, is known as the state of the charge of the battery. This is the main parameter that reveals about the current battery energy which stored in the battery. This is basically the opposite of the depth of discharge.

Charging and discharging rate: The amount of charge added/extracted from the battery per unit time is known as charging/discharging rate, which is measured in ampere-hours which is same as Coulombs/Sec. However, charging/ discharging rate is also defined in terms of the hours that takes to fully discharge the battery. For example, C20=500 means that the battery capacity is 500 Ah, when it is fully discharged in 20 hours.

Battery efficiency: The efficiency of the battery is described in two ways, that is coulomb efficiency and the voltage efficiency. Coulomb efficiency is the ratio of the amount of charge that enter the battery when it is charging for the amount of charge that can be extracted from the battery when it is discharging. The voltage efficiency is the ratio of the discharged average voltage to the charged average voltage. The round-trip efficiency is defined as the ratio of the energy extracted from the battery to the energy send into the device. Due to the battery is included energy losses these efficiencies are never equal to the 100 %.

RESULTS

The code is written in Python and operates based on linear programming. The following data is needed for the code to operate: (1) load profiles from three years; (2) electrical energy price according to HuPX; (3) energy production from the PV plant; (4) battery parameters for a CATL deep-cycle BEES. The only variable, that a user inputs, is the battery capacity (kWh). Output from the code is: savings in euros and payback period in years.

By entering capacities 10-300 [kWh] with a step of 10 kWh, we examine how the payback period and the savings behave. After conducting the study, we see that with increasing battery capacity, both the savings and the payback period increase constantly, but when there is a battery in the range of 170-180 [kWh], a value is evident where the payback period is shorter in comparison to some batteries with a smaller capacity, as presented on Figure 4 and Figure 5. Given this, the most optimal battery for the faculty building and its installed PV system is one with a capacity of **172 kWh**.

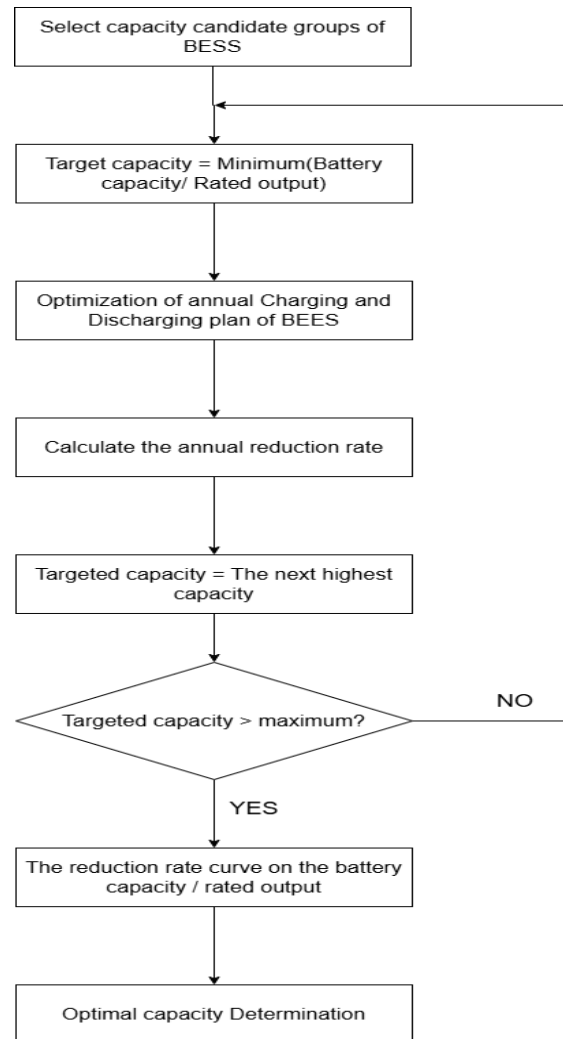


Figure 3 – Block diagram for the Python code

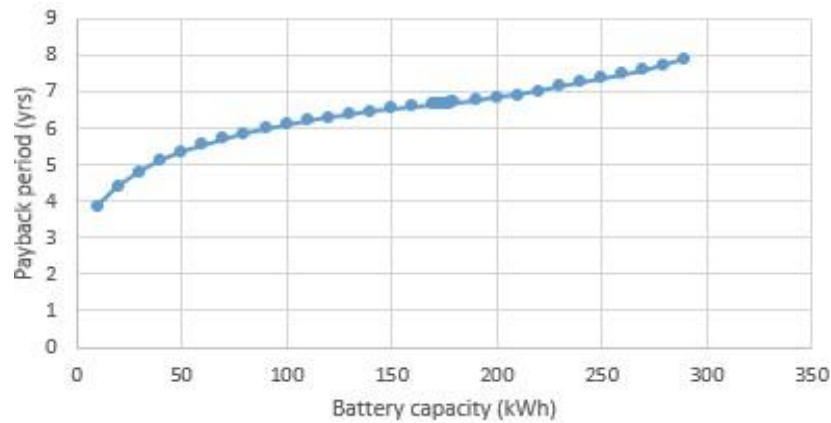


Figure 4a – Graphic of the payback period as a function of the battery capacity

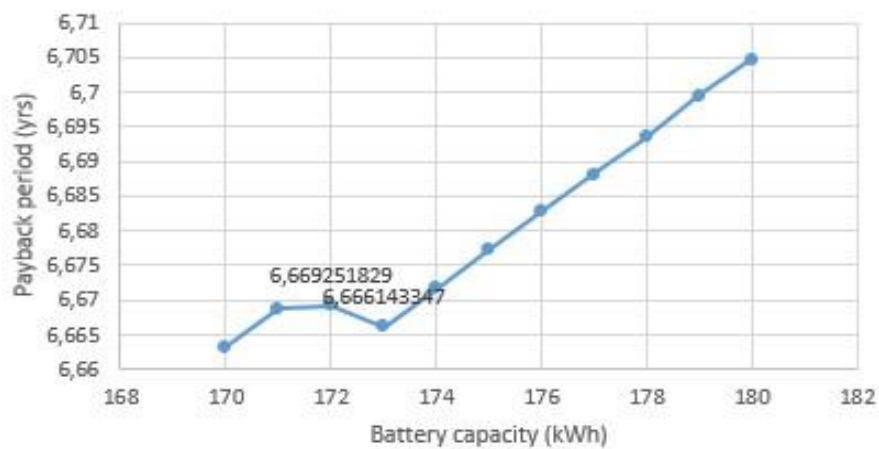


Figure 4b – Graphic of the payback period as a function of the battery capacity

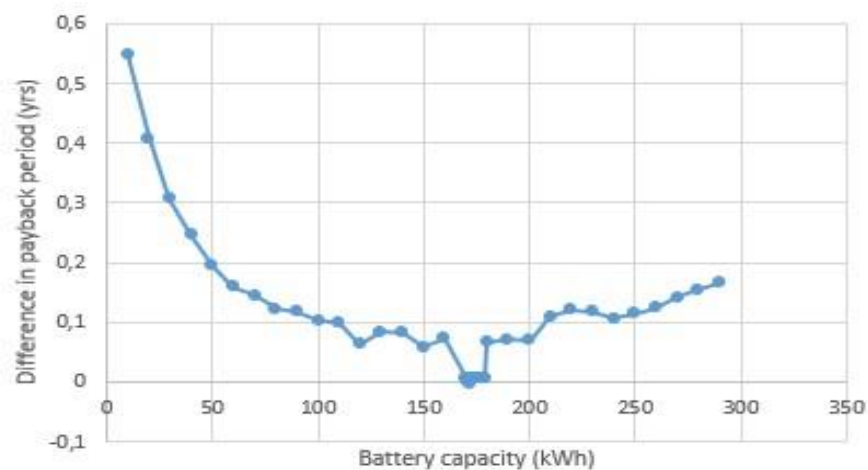


Figure 5a – Graphic of the difference in payback period as a function of the battery capacity

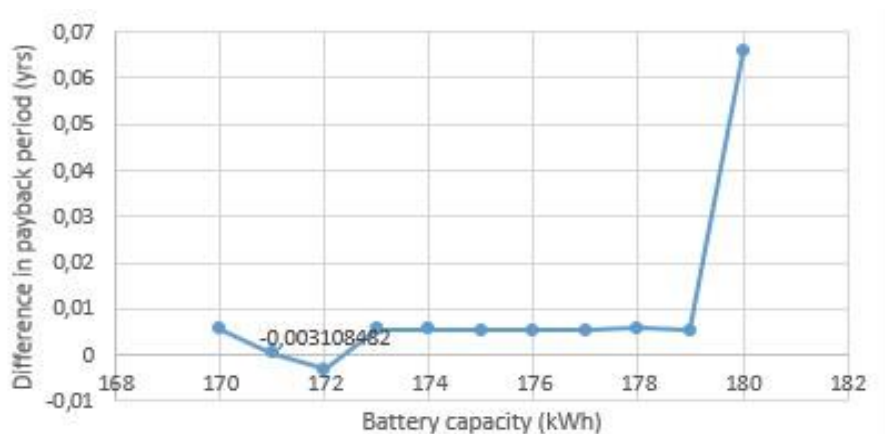


Figure 5b – Graphic of the difference in payback period as a function of the battery capacity

CONCLUSION

Insufficient solar radiation and power outages in the power systems are two reasons for installing a BESS to a PV plant. When there is an excess of electrical energy generated by the PV plant and stored in the BEES, it can be sold to the utility grid. In hours of low electrical energy price, electrical energy is bought to charge the BEES.

Since these BESS are expensive, it is important to size them properly. If the BEES is undersized, it will not be able to serve its purpose – supply the electrical energy needs of the consumer. If the BEES is oversized, more than what the consumer needs, the investment costs are high and likely not to be returned. With proper sizing of the battery energy-storage system, the consumer needs will be satisfied, buying electrical energy from the utility grid will be reduced or at least bought when prices are low in order to charge the battery and more energy independence will be achieved.

With a developed methodology and Python code, that uses the load profiles of the faculty building, the prices of electrical energy, battery parameters and data from the generation of electrical energy by the PV plant, it is shown that the 40 kW faculty PV plant needs a BESS with a battery capacity of 172 kWh. This battery capacity is most sufficient in terms of payback period and savings.

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