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The Roles of Battery Energy Storage System in Different Energy Communities

Filip Dimač, Ivan Rajšl, Sara Raos and Goran Ribić

Summary — This article analyses the concept of energy communities. Energy communities are basically divided into physical and virtual communities, and they are also differentiated according to business models. The development of these business models requires virtual connectivity enabled by digital platforms, smart grids and the Internet of Things. The advantages and disadvantages of energy communities are described, and the legal side is analysed. The role of battery storage in the energy community is described and the aim of this paper is to analyse the role of battery storage in different types of energy communities. A mathematical model has been described to analyse the viability of the battery in three energy communities with different consumption curves and the results obtained by simulation have been presented.

Keywords — energy communities, battery energy storage system, rooftop, PV solar system

I. Introduction

The energy transition process refers to changes in the way energy is produced and used, with the aim of reducing its price and its negative impact on the environment. The main reason for initiating the energy transition is climate change and the reduction of greenhouse gases. As a result of the energy transition, consumers are becoming active consumers – "prosumers" who not only draw energy from the grid but also make it available for others to use as needed. The development of information and communication technologies is making a significant contribution to the development of innovative management solutions [1]

Energy communities are proving to be one of the most suitable solutions for the integrating prosumers and their distributed sources. The application of this market-based mechanism can lead to a better local balance of supply and demand for electrical energy, reduce voltage deviations from nominal values and improve the welfare of the entire community. As part of the "Clean energy for all Europeans" package (2019), EU directives introduced new provisions for the organisation of the energy market and framework conditions for new energy initiatives. The framework for collective self-consumption is often defined separately from the provisions for energy communities due to its simplicity and significantly lower administrative and organisational requirements. [2] Three concepts are defined: collective self-consumption, renewable energy community and citizen energy community.

Energy communities can be implemented in different ways depending on various factors, but the simplest categorization is into physical and virtual energy communities. The main difference between the different types of energy communities lies in the way of using the power network and how the energy produced and consumed is billed and paid for. In the case of physical communities, a distinction can be made between collective self-consumption, i.e. consumers of their own renewable energy (private grid, e.g. neighborhood or residential building) and collective self-consumption (private and public grid). A virtual community is often defined as a regional community by its wider geographical context. [5]

Legislation can restrict the connection of members and thus the technical organisation of energy communities. An important aspect of energy communities is therefore to examine the legally permissible connections between participants before considering the technical aspects. In addition to the differences in the connection between participants, energy communities also differ in their business models. Research has identified and described six main archetypes and business models of energy communities. [4]

Battery energy storage systems (BESS) could solve many problems in electricity generation and distribution in the future. Generation from renewable energy sources (RES) is often dependent on weather conditions. Distributing the output of solar power plants (SPP) every hour or 15 minutes [12] is a challenge for the electricity system, which leads to an increased need for flexibility in the entire power system. In reference [9], the term flexibility of the electricity system was defined and the authors proved with their mathematical model that BESS have positive effects on systems with RES. Without RES, they reduce the need for peak load power plants, and with renewables they reduce the curtailment of renewable energy, but with BESS the flexibility of the electricity system was better. System flexibility was better with or without renewables when BESS was introduced.

The flexibility of power supply systems can be increased in many ways, including the intelligent use of electrical devices and the implementation of BESS. BESS are highly customisable and it is possible to choose the most suitable BESS solution for a specific purpose. Although BESS could be used to solve many problems related to energy systems, they are not yet widely used due to high costs and low profitability. Over the past decade, lithium-ion battery prices have fallen significantly and this trend is expected to continue. The decreasing cost of the battery makes it a more interesting solution and increases profitability.

In reference [3], the interaction of individual prosumers with the electricity grid was analysed and it was investigated how the

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organisation of prosumers in energy communities affects their interaction with the grid. Individual prosumers independently invest and manage their own photovoltaic (PV) and BESS sources and buy and sell energy directly from the grid, while in the prosumer community the capacity and operation of the PV and BESS are optimised at the level of the entire community. The electricity generated in the community can be freely used by all members to meet demand at any given time or to charge any battery. The community also has the possibility to trade (buy and sell) electricity with the grid.

The high integration of photovoltaic systems can cause the problem of overvoltage in the grid. This problem can be solved through the use of BESS, usually connected in parallel with the photovoltaic power plant, and a system that manages the battery at the local level (household or community), taking into account the technical conditions of the grid, i.e. the conditions for maintaining voltage quality. Economic strategies of system management, whose goal is to maximise profits, ignore these conditions, but by intelligently using the overall potential of BESS, participants have the opportunity to offer services to grid operators in this way as well. Research [6] has shown that if the battery degradation factor is ignored, the battery will actually cause voltage problems. Restricting the operation of the battery to reduce its degradation will result in lower voltage spikes. In other words, battery-friendly operation is also grid-friendly operation. The schematic of the energy community with PV generation and a BESS is shown in Figure 1.

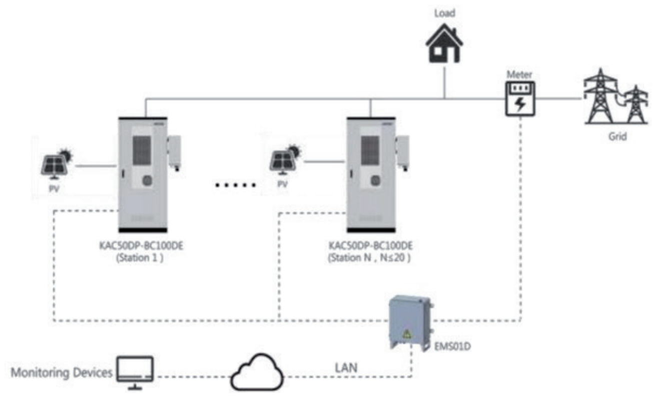

Fig. 1. BESS and PV integration scheme in the energy community [8]

The most common goal when installing BESS is to increase local self-consumption generated by photovoltaic systems. Although such systems reduce the amount of electricity exported to the grid from photovoltaic installations, there are many other benefits of the impact of batteries on the grid if they are properly managed. The BESS themselves have no influence on the production of photovoltaic power plants due to their temporal variability, but through their intelligent use it is possible to reduce peak consumption curves and thus relieve the grid and avoid grid congestion. This is possible by predicting generation from photovoltaic systems and consumption in households. Residential buildings are ideally suited to providing these services, as their consumption generally occurs at different times of day than the high output of the photovoltaic systems. This is in contrast to office buildings, where consumption is high during the day when generation from photovoltaic systems is also high. To maximise the economic benefit, the generation capacities and the battery must be correctly dimensioned based on the user's consumption. Generally, the production is dimensioned first and then the optimal battery capacity is determined.

This paper contributes to the evaluation of the role of battery systems in different energy communities. It also points out the advantages and disadvantages of the role of batteries in different energy communities. The rest of the paper is organised as follows: The evaluation approach and the applied software are presented in the Methodology chapter, while the Mathematical Model chapter presents the underlying mathematical expressions of the model. The results are presented and discussed in Chapter 4, Analysing battery storage in different types of energy communities, while Chapter 5 concludes the paper.

II. Methodology

The aim of this paper is to analyse the role of the BESS in different energy communities. For this purpose, three energy communities were designed and BESS was included in each of these three energy communities. The energy communities are differentiated by the seasonal electricity demand and the type of consumers that meet the needs of the communities themselves. Sometimes these communities may have a surplus of electricity. It is assumed that the surplus electricity generated can be sold at 80% of the current market price. The task is to perform a linear optimisation with a cost minimisation objective function that gives an optimal solution for each of the communities based on data on production, consumption, electricity prices, battery capacity, battery charging and discharging power and taking into account various constraints. Based on the optimisation solution, the municipalities can be compared and it can be shown in which type of municipality the use of BESS is most profitable. The Gurobi software package [13] was used to solve the optimisation problem. To perform the linear optimisation, data on annual electricity prices on the wholesale market on an hourly basis, data on annual consumption of electricity and thermal energy on an hourly basis and data on annual electricity generation from solar cells on an hourly basis are required. Data on electricity prices on the wholesale market in Croatia for the year 2023 on an hourly basis were used. [7]

To estimate electricity consumption, the nPRO software was used, which estimates heating, cooling and electricity requirements based on the geographical location, surface area and type of facility (kindergarten, school, hall, swimming pool, theatre, etc.). The facilities differ in terms of quantity and consumption curves. For more accurate modelling of heating, cooling and electricity demand for each type of facility, it is possible to manually enter data on specific annual consumption (kWh/m2/year) and total annual consumption (MWh). It is also possible to determine the start and end of the heating and cooling season, the percentage of heating for hot water production, the percentage of cooling for cooling the system and the percentage of heat recovery from heating losses. It is possible to make manual changes within the daily curve for each hour and each day of the week. Once all parameters have been set by pressing the "Calculate" button, the software outputs annual hourly consumption curves that can be created in an Excel document.

In order to cover the community's thermal energy requirements, it was assumed that the community uses heat pumps, as heat pumps use electricity to generate heat and therefore the entire energy requirement can be regarded as an electricity requirement, which greatly simplifies optimisation. The coefficient of performance (COP) indicates the ratio between the heat energy generated and the amount of electricity required by the heat pump for its work. In our case, we have assumed an efficiency of 3.

The SolarEdge [14] software was used to dimension the production capacity, which based on the geographical location, surface and slope of the roof, and on the basis of the type and slope of the photovoltaic panels, estimates how many photovoltaic panels can be installed on the roof, how many inverters are needed for the operation of the power plant and, ultimately, the production of the power plant. The software was used to

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estimate the roof and building areas, which is a necessary parameter for the nPro software that uses this data to estimate the consumption curves. The software was also used to estimate the number of photovoltaic panels that can be installed on the roofs, to estimate the maximum output of the photovoltaic power plant and to design a rooftop PV system. When dimensioning the production, the condition was taken into account that the production must not be higher than the peak consumption. When sizing all three communities, this was not the case at any time. Unfortunately, SolarEdge does not have the ability to generate Excel documents. For this reason, it was not used to obtain the annual hourly production curve required for further analysis.

Renewables.Ninja [15] [16] is a software that, based on the geographical location, the maximum DC or AC power of the photovoltaic power plant and the tilt of the panels, generates the annual hourly curves of the production of the photovoltaic power plant in the form of an Excel document.

The models of photovoltaic panels, inverters and battery storage in all communities are the same, but their sizing differs depending on the consumption of the communities themselves. The Trina Solar Vertex S TSM-DE09R.08 model was selected for the photovoltaic panel, 425 Wp efficiency 21.3%, dimensions 1762mm x 1134mm x 30mm and weight 21.8 kg. This photovoltaic panel was chosen for the reason that it has suitable dimensions and weight and is therefore easier to install, and the ratio of load on the roof and safety against strong winds and bad weather is optimal. In the first year, the panel loses 2% of its power, and then each time the power decreases by a maximum of 0.55%. The degradation factor must be taken into account when calculating the investment return.

The capacity of the battery storage is dimensioned based on the average electricity consumption during the night hours when there is no production in the community. The capacity to satisfy the eight-hour autonomy from 12 pm to 8 am was estimated.

The KSTAR 100kWh model was chosen for the battery storage. Battery storage always comes with its own converter.

Urban heat islands (UHI) represent increase of temperature inside of cities in regard to their rural environment, and with electricity production, photovoltaic panels have additional positive impact on thermal characteristics of the building on which they are installed by significantly lowering energy necessary for cooling inside the building. Panels block direct sun radiation which directly decreases roof temperature and wind drift between panels and roof additionally increases the positive effect by convection cooling. [10] Commonly, this important benefit is not taken into account when creating a mathematical model of a solar power plant, so we will not do it either, but it is important to point out that this positive effect will provide additional financial savings for all members of the energy community.

III. Mathematical Model

The goal of the model is to minimize the costs of the community that produces, consumes, stores, buys and sells energy in a period of one year.

The objective function of the optimization problem can be written as:

$$min \sum_{t=0}^{8760} price[t] * (B[t] - 0.8 * S[t]) \quad (1)$$

Where B is purchased energy, S is sold energy, *price*[*t*] is the price of electricity, and in the range of 0-8760 represents the number of hours in a year. The part of function price[t]∗(B[t]-0.8∗S[t]) represents expenses reduced for income.

The equation of balance between electricity consumption and production:

$$HH1ee[t] + HPe[t] == B[t] - S[t] + PV[t] + ch[t] - dch[t] \quad (2)$$

Variables:

B - purchased energy

S - sold energy

HP - thermal energy of the heat pump

HPe - heat pump electricity

ch - charging energy

dch - energy discharge

soe - battery charge status

x - charge discharge binary

XB - purchased energy binary

XS - sold energy binary

PV - production from photovoltaics

HH1ee - electricity consumption

HH1hd – heat demand

Constants:

$eff_{ch_{dch}} = 0.95$ =*charge/discharge efficien*

$COP = 3$ =*efficiency coefficient*

$Pmax$ =*battery discharge power*

$C =$ *battery capacity*

$HPmax =$ *maximum power of heat pumps*

In addition to consumption, production and price data, model constraints are also needed.

The constraints are:

1. State of charge of the batteries at the beginning and for all other hours:

$$soe[0] = 0 \quad (3)$$

$$soe[t] = soe[t-1] + ch[t] * eff_{ch_{dis}} - dch[t] * \left(\frac{1}{eff_{ch_{dis}}}\right) \quad (4)$$

2. The demand for thermal energy is met through heat pumps:

$$HPe[t] = HH1hd[t] * (1/COP) \quad (5)$$

3. Limitation of the maximum charging and discharging power and impossibility of charging and discharging at the same time:

$$ch[t] <= Pmax * X[t] \quad (6)$$

$$dh[t] <= Pmax * (1 - X[t]) \quad (7)$$

4.Limitationthatenergycannotbeboughtandsoldatthesametime:

$$B[t] <= M * XB[t] \quad (8)$$

$$S[t] <= M * XS[t] \quad (9)$$

$$XB[t] + XS[t] <= 1 \quad (10)$$

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Big number M (100,000) is used according to optimization practice in order to ensure that energy cannot be bought (charged) and sold (discharged) at the same time.

IV. Analysis of Battery Storage in Different Types of Energy Communities

A. Community 1

Community 1 consists of consumption, production and a BESS, and the community is located in the area of Zagreb. Consumers are: 40 apartments/apartments, a restaurant and a parking lot with a charging station for electric vehicles. The production is from photovoltaic panels that are placed on the roofs of all the mentioned buildings. Figure 2 shows the community 1 and layout of photovoltaic panels.

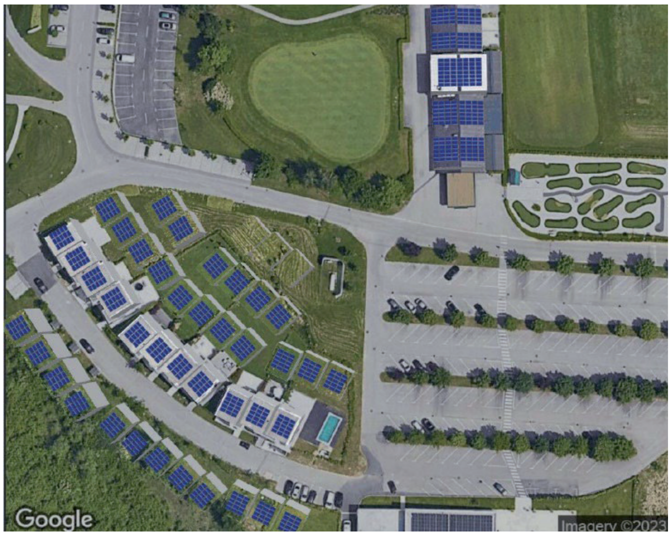

Fig. 2. Community 1

It is planned that each of the apartments consists of two bedrooms with one bathroom and a separate toilet and is 60m2 in size in order to meet the requirements of the 4-star tourist apartment categorization. The apartments and the restaurant are open all year. Restaurant and restaurant roof area data were estimated in Solar Edge software and shown in Table 1.

Table I

Areas of Buildings and Number of People in Community 1

Object	Surface area	Number of people
40 apartments/flats	2400 m²	160
Restaurant	680 m²	350
Total	3080 m²	510

There are two charging stations (Siemens VersiCharge 7.2 kW) in the parking lot, for which the estimated daily charging of two cars per charging station is 4 hours per charge. On a daily basis, the filling station consumes 115 kWh, while on an annual basis it consumes 42 MWh. The estimated annual consumption of electricity is 361.1 MWh.

Figure 3 shows energy consumption by month. The largest share of consumption for each month goes to heating and cooling.

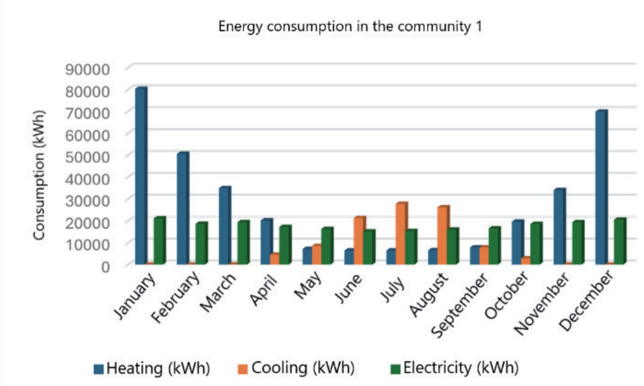

Fig. 3. Energy consumption in the community 1

The SolarEdge software tool was used to dimension production capacities. Estimated consumption and available roof area were taken into account. 209 photovoltaic panels were installed on the roof of the restaurant with an area of 680 m2, while 600 photovoltaic panels were installed on the roofs of the apartments with an area of 2,400 m^2, for a total of 809 photovoltaic panels. Solar Edge estimates production of 370 MWh annually. The simulated estimated annual output of Community 1 PV from Renewables ninja is 372 MWh which is slightly higher than consumption, but system operators have been more flexible in this regard over the years and the excess output should not cause problems. In the winter months consumption is significantly higher than production, while in the other months, except for the summer months, production is approximately equal to consumption or slightly higher. In the summer months, production is significantly higher than consumption, which is shown in Figure 4.

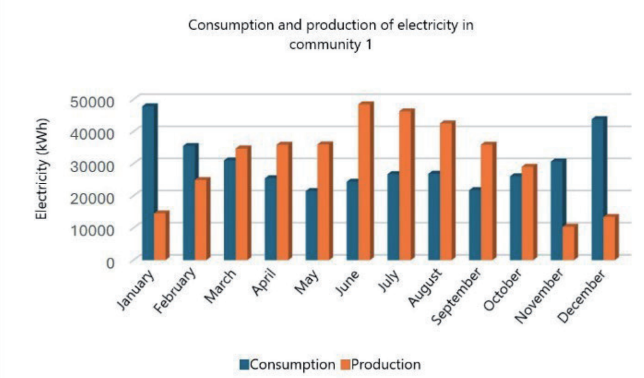

Fig. 4. Consumption and production of electricity in community 1

The average electricity consumption of the community at night is 22 kWh/hour, which for a period of 8 hours amounts to 176 kWh. The battery capacity that would enable autonomy at night is 200 kWh.

Figure 5 shows how many times per year the battery of community 1 is charged or discharged at maximum power (0.5C). In community 1, that number is 175.

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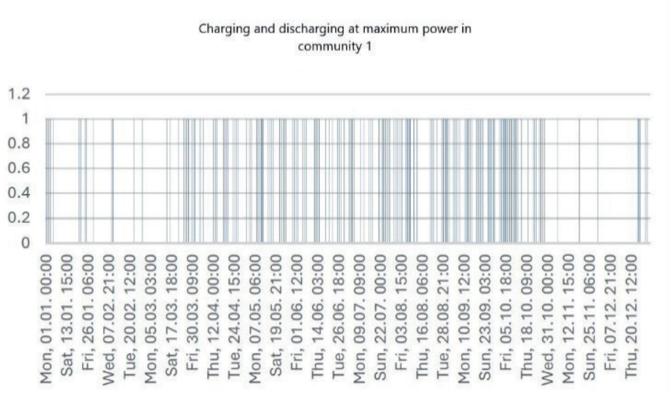

Fig. 5. Charging and discharging at maximum power in community 1

Figure 6 shows the battery activity on January 7. If you look at the activity every day of the year, by adding up the energies that entered the battery and left the battery, you can see how active the battery was. The total annual discharged energy is 78.101,97 kWh and charged energy is 78.222 kWh. If these numbers are divided by the battery capacity, it can be concluded that the battery was "discharged" 390.5 times and the battery was "charged" 391 times, which is a total of 390.5 cycles.

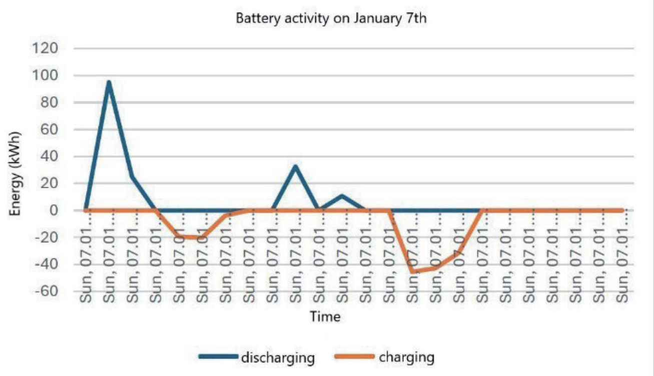

Fig. 6. Battery activity on January 7th

Fig. 7. – Community 2

TABLE II
HOTEL OCCUPANCY CAPACITY BY MONTH

Month	Hotel occupancy rate [%]
January	0
February	0
March	30
April	50
May	70
June	90
July	100
August	100
September	90
October	70
November	50
December	30

B. Community 2

Community 2 consists of consumption, production and BESS, and the community is located on the island of Lošinj. Consumers are: a boutique hotel and an electric vehicle charging station. Production is from photovoltaic panels that are placed on the covered parking lot and on the roof of the hotel. Figure 7 shows community 2 and the layout of the photovoltaic panels.

Although nPro software has a lot of possibilities for the purpose of precise modeling of the consumption of individual objects, there is one drawback. The consumption of community 2 differs from the others because it is seasonal in nature. It is possible to change the hourly percentages for days of the week, weekends and holidays, but it is not possible to change these data by month, that is, in the case of community 2, to model seasonal consumption, but the hotel is viewed as if it works at full capacity all year round, which is not true. For the purpose of more precise modeling of community 2, the assumption of hotel capacity occupancy is given in Table 2.

In January and February, even though the hotel is not working, there is a minimum consumption of the cold operation, which is 10% of the consumption that would be in those months. Electricity consumption in the other months is scaled depending on the occupancy capacity of the hotel.

The highest turnover of the hotel, and therefore consumption, is in the summer months. The estimated annual consumption of electricity for community 2 is 422.9 MWh, which is the highest consumption of all communities. This information is not surprising considering the nature of the facility and the content it offers. Figure 8 shows the consumption of electricity by month. The largest share of consumption goes to cooling.

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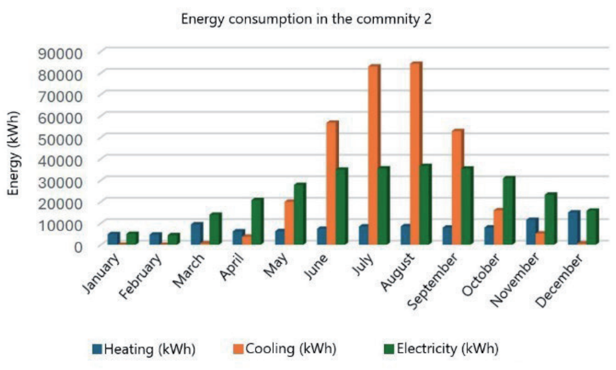

Fig. 8. Energy consumption in the community 2

The production capacities are dimensioned in such a way that the annual production is approximately equal to the annual consumption. For this purpose, 459 photovoltaic panels were installed on the roof of the covered parking lot and the hotel, facing east, west and south. The estimated annual production from the community's photovoltaic panels is 255.9 MWh. Production is significantly lower than consumption due to the lack of roof space. Electricity production in the community is highest in the summer months, and it exceeds consumption in January, February and March, while in April it is approximately equal to consumption. Display in Figure 9.

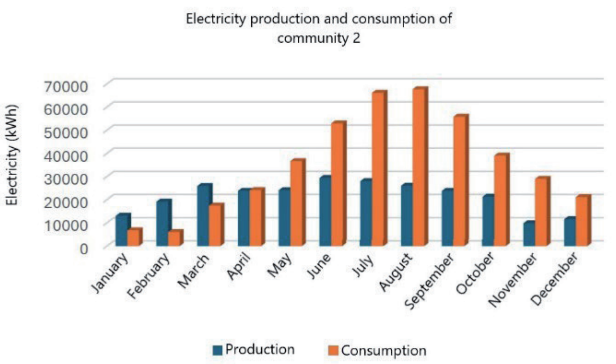

Fig. 9. Electricity production and consumption of community 2

Data on the surface of roofs and the surface of buildings were evaluated in the SolarEdge software. The hotel accommodates 160 people and employs 100 workers. Data on the area of the hotel and the number of people using the community are given in Table 3.

Table III

Areas of Buildings and Number of People in The Community 2

Object	Surface area	Number of people
Hotel	3,500 m²	260

As in Community 1, there are two charging stations for electric vehicles in the parking lot (Siemens VersiCharge 7.2 kW) which consume 42 MWh of electricity annually.

The average electricity consumption of the community at night is 32 kWh/hour, which for a period of 8 hours amounts to 256 kWh. The battery capacity that would enable autonomy at night is 300 kWh.

Figure 10 shows how many times per year the battery of community 2 is charged or discharged at maximum power (0.5C). In community 2, that number is 199. It is noticeable charging and discharging frequency 0.5C in months where production is greater or approximately equal to production.

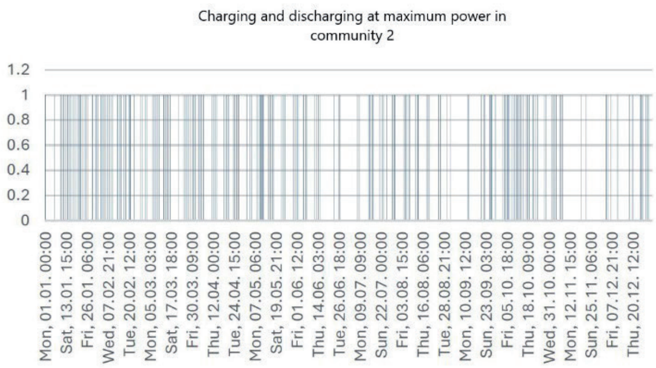

Fig. 10. Charging and discharging at maximum power in community 2

Figure 11 shows the battery activity on January 7. The total annual discharged energy is 111.647 kWh and charged energy is 111.827 kWh, which means that the battery was "discharged" 372 times while the battery was "charged" 372 times, which is a total of 372 cycles.

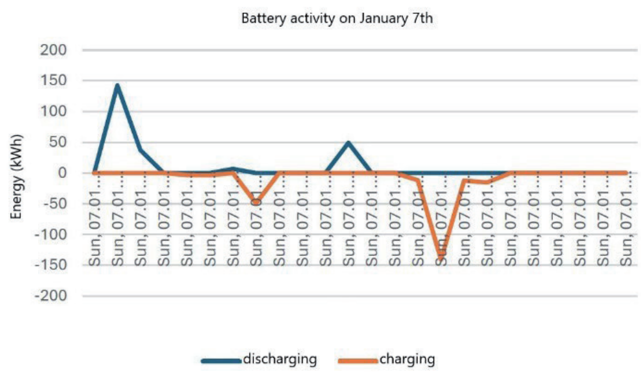

Fig. 11. Battery activity on January 7th

C. Community 3

Community 3 includes a school, gymnasium, and kindergarten. The BESS shows significant benefits due to consistent consumption patterns. Production is from photovoltaic panels that are placed on the roof of the sports hall and elementary school. Figure 12 shows community 3.

Data on the surface of roofs and the surface of buildings were evaluated in the SolarEdge software. If an eight-year primary school has 4 classes per year and an average of 30 students per class, that amounts to 960 students. Taking into account the teachers and all other employees of the school, it was estimated that 1,000 people attend the school every day. In the kindergarten, there are 8 educational groups of 20 children per group and two kindergarten teachers per group. In addition to other employees of the kindergarten, the estimated number of people in the kindergarten every day is 190. The area of the primary school, kindergarten and sports hall and the number of people per community facility are shown in Table 4.

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Fig. 12. Community 3

Table IV

Areas of Buildings and Number of People in The Community 3

Object	Surface area	Number of people
Primary school	4,200 m²	1000
Kindergarten	1,250 m²	190
Sports hall	970 m²	-

The estimated annual electricity consumption for community 3 is 417 MWh.

Figure 13 shows energy consumption by month. As in every community, until now the largest share of consumption goes to heating and cooling, but in community 3 that share is significantly higher. The table shows that the highest consumption is in January, June and December. Considering the school summer holidays, it is expected that July and August are the months with the lowest consumption, along with April and September, when the needs for heating and cooling are much lower than in the summer and winter months.

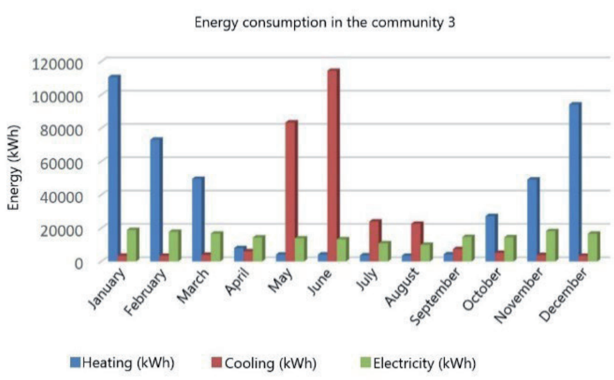

Fig. 13. – Energy consumption in the community 3

The production capacities are dimensioned in such a way that the annual production is approximately equal to the annual consumption. For this purpose, 882 photovoltaic panels were placed on the roofs of elementary schools and sports halls, facing east, west and south. According to the simulation results of SolarEdge, 392.49 kWp of DC power was installed, while the maximum achieved AC power of the power plant is 309 kW. According to the simulation, the power plant produces 443 MWh annually, Renewables.ninja-e production is somewhat different from the power plant's product 413.4 MWh. Production and consumption of the community are shown in Figure 14.

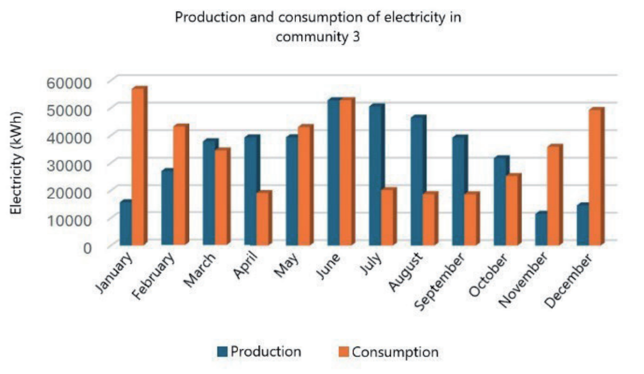

Fig. 14. Production and consumption of electricity in community 3

The average electricity consumption of the community at night is 30.4 kWh/hour, which for a period of 8 hours amounts to 243.2 kWh. Battery capacity that would enable autonomy at night is 250 kWh.

Figure 15 shows how many times per year the battery of community 3 is charged or discharged at maximum power. In community 3, that number is 171. It is noticed that the battery charges or discharges 0.5 C less often in months when consumption is higher than production.

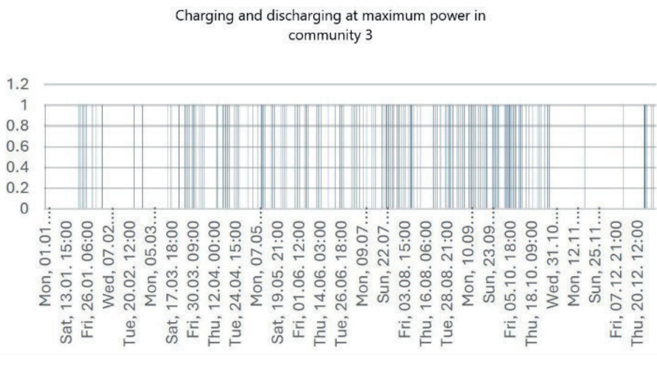

Fig. 15. Charging and discharging at maximum power in community 3

Figure 16 shows the activity of the battery on January 7. The total annual discharge energy is 96.386 kWh and charge energy is 96.536 kWh, which means that the battery "discharged" 385 times, while the battery was "charged" 386 times, which is a total of 385.5 cycles.

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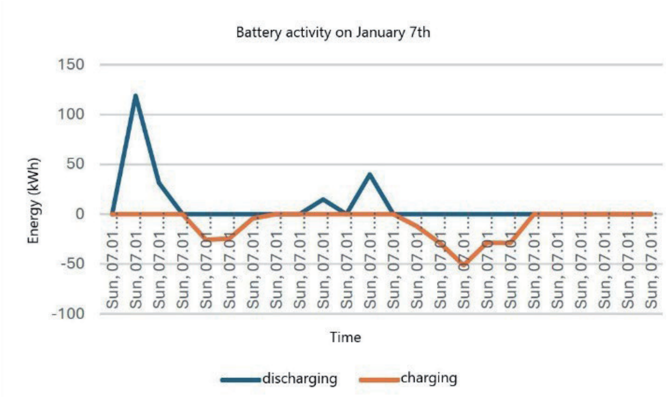

Fig. 16. Battery activity on January 7[th]

Figure 17 shows the battery activity for one summer day. Lower electricity prices are observed at night, but this still does not prevent the battery from doing arbitrage on the price difference and bringing profit to the community. Charging of the battery in periods of lower prices and discharge in periods of higher prices is observed.

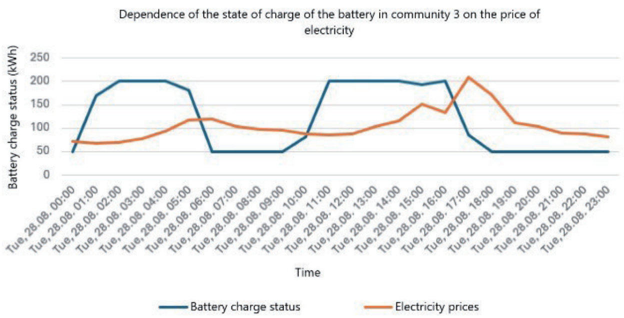

Fig. 17. Dependence of the state of charge of the battery in community 3 on the price of electricity on the date of August 28th

Figure 18 shows the activity of the battery for one winter day. There is one increase in prices per day during the period of peak consumption when citizens return home from work. During this period, the battery is discharged.

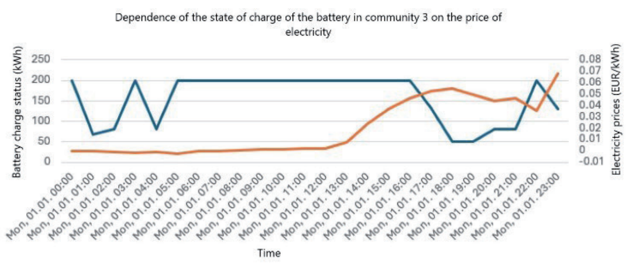

Fig. 18. - Dependence of the state of charge of the battery in community 3 on the price of electricity on the date of January 1st

D. Comparison

Tables 5, 7, 9 show investment data for each community. The investment is roughly estimated based on the costs for the solar panels and the battery, and other costs are ignored.

Tables 6, 8, 9 show annual costs and electricity savings for all communities in 4 cases. Each row in those tables is one scenario: 'Only consumption', Photovoltaic power plant, 'PV battery system with unlimited battery charging/discharging' and 'PV battery system with the condition of battery state of charge between 20% and 80%', so those tables have 4 rows with data.

The first case is when the community would be exclusively a consumer without of any production of energy or BESS. The cost of electricity for community without photovoltaic panels is calculated by adding up for each hour the hourly consumption multiple by electricity prices in that hour.

The second case is when the community would be with production from photovoltaic panels, but still without a BESS.

The third and fourth cases are for communities with the photovoltaic panels and with BESS.

In our scenario, we created 4 cases in such a way that we distinguished the differences regarding the existence or non-existence of a solar power plant and BESS, but it is possible to extend the analysis to cases in which the difference regarding the consumer itself is considered. In reference [11] authors explored such a form of scenario, but such an analysis would be useful if we wanted to elaborate in more detail on one of our 3 communities and then we would also deal with the Performance Ratio (PR) of the power plant itself, but all this represents the potential for future work and future articles.

By installing the photovoltaic panels and by installing BESS, savings are expected considering that the community is not only a consumer but also a producer who can sell their surplus energy and use the stored energy later with the BESS. Optimizing with the goal of minimal electricity costs, results were obtained in cases where the community uses a BESS.

Two cases were considered, when the full battery capacity is used and when the battery state of charge is limited between 20% and 80% of the battery capacity.

Community 1 electricity cost in case of battery charging and discharging restrictions is not significantly higher (1,300 euros per year) than the case when the battery does not have such limitations but the life of the battery is significantly extended by avoiding excessive charging and deep discharge, i.e. by maintaining a moderate level of charge, which is not a negligible factor for batteries of this capacity and their prices so it is more profitable to extend the life of the battery than to save a few thousand euros per year. The cost difference of these two cases in Community 2 is slightly higher (approximately 3,000 euros per year), but still extending battery life is more profitable. The same conclusion was reached in community 3.

Table V

Investments in the Community 1

Community 1	Number	Price per panel [EUR]	Total price [EUR]
Panels	809	200	161,800
	Capacity (kWh)	Price for 100 kWh [EUR]	
Battery	200	50,000	100,000

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Table VI

Savings in the Community 1

Community 1	Costs [EUR]	Saving [EUR]	Saving [EUR] per capita
Only consumption	40,340	-	-
Photovoltaic power plant	11,273	29,067	56.99
PV battery system with unlimited battery charging/discharging	4,264	36,076	70.74
PV battery system with the condition of battery state of charge between 20% and 80%	6,578	33,762	66.2

For community 1, the investment in the form of photovoltaic panels amounts to 161,800 euros and an additional 100,000 euros for the BESS. If the community 1 had only production without the possibility of storing electricity, the return on the investment is in 5.566 years (not taking into account panel degradation, inflation, accompanying costs, e.g. installation, etc.).

The return on investment for the photovoltaic panels and BESS with unlimited charge/discharge of the battery is 7.257 years (not considering battery degradation, etc.). The return on investment for the photovoltaic panels and BESS with the battery charge condition between 20% and 80% is 7.754 years.

Table VII

Investments in the Community 2

Community 2	Number	Price per panel [EUR]	Total price [EUR]
Panels	459	200	91,800
	Capacity (kWh)	Price for 100 kWh [EUR]	
Battery	300	50,000	150,000

Table VIII

Savings in the Community

Community 2	Costs [EUR]	Saving [EUR]	Saving [EUR] per capita
Only consumption	41,776	-	-
Photovoltaic power plant	20,585	21,191	81.5
PV battery system with unlimited battery charging/ discharging	11,365	30,411	116.97
PV battery system with the condition of battery state of charge between 20% and 80%	14,314	27,462	105.62

For community 2, the investment in the form of photovoltaic panels amounts to 91,800 euros and an additional 150,000 euros for the BESS. If the community 2 had only production without the possibility of storing electricity, the return on the investment is in 4.33 years (not taking into account panel degradation, inflation, accompanying costs, e.g. installation, etc.).

The return on investment for the photovoltaic panels and battery container with unlimited charge/discharge of the battery is 7,951 years (not considering battery degradation, etc.). The return on investment for the photovoltaic panels and BESS with the battery charge condition between 20% and 80% is 8,805 years.

TableIX

Investments in the Community 3

Community 3	Number	Price per panel [EUR]	Total price [EUR]
Panels	882	200	176,400
	Capacity (kWh)	Price for 100 kWh [EUR]	
Battery	250	50,000	125,000

Table X

Savings in the Community 3

Community 3	Costs [EUR]	Saving [EUR]	Saving [EUR] per capita
Only consumption	45,215	-	-
Photovoltaic power plant	12,222	32,993	27.73
PV battery system with unlimited battery charging/discharging	4,138	41,077	34.52
PV battery system with the condition of battery state of charge between 20% and 80%	6,742	38,473	32.33

For community 3, the investment in the form of photovoltaic panels amounts to 176,400 euros and an additional 125,000 euros for the BESS. If the community 3 had only production without the possibility of storing electricity, the return on the investment is in 5,347 years (not taking into account panel degradation, inflation, accompanying costs, e.g. installation, etc.).

The return on investment for the photovoltaic panels and battery container with unlimited battery charging/discharging is 7,337 years (not considering battery degradation, etc.). The return on investment for the photovoltaic panels and BESS with the battery charge condition between 20% and 80% is 7,834 years.

Table 11 shows the investment return times for all cases in all communities. The investment payback times are approximately the same for communities 1 and 3, while the investment payback time is slightly longer for community 2. Given the fact that the annual savings in community 2 are the least and that the investment payback time is the highest, i.e. less in other communities, it can be concluded that in communities 1 and 3 batteries will pay off more.

Table XI

Investment Return Time in Communities

Investment return time [year]	Community 1	Community 2	Community 3
Photovoltaic power plant	5.666	4.33	5.347
PV battery system with unlimited battery charging/discharging	7.257	7.951	7.337
PV battery system with the condition of battery state of charge between 20% and 80%	7.754	8.805	7.834

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If, in addition to this data, the data on the activity of the battery and the way it is used are taken into account, a conclusion can be reached in which community is most profitable to install a BESS.

Table 12 shows how many times a year the battery was charged and discharged and how many times the battery was charged or discharged at 0.5 C. The number of charges and discharges at 0.5 C is observed for the reason that it is the most unfavorable way of charging and discharging the battery and thus the battery is consumed the most. Given that both numbers are smaller for community 3 than community 1, it can be concluded that battery 3 has the highest chance of having the longest life and therefore the most worthwhile.

Table XII

Number of Battery Charging and Discharging AND Number of 0.5C Charging and Discharging by Communities

	Community 1	Community 2	Community 3
Number of chargers and discharges (cycles) per year	390.5	372	385.5
Number of chargers and discharges at 0.5C	175	199	171
Ratio	0.2238	0.2675	0.2218

V. Conclusion

Energy communities offer innovative and sustainable approaches for the transformation of energy systems towards decentralisation, participation and environmental responsibility. Investments in BESS are still costly, but feasible with subsidies. Further research and technological advances are needed to make these concepts financially sustainable in the near future.

This concept promotes the local balancing of energy supply and demand, reduces greenhouse gas emissions and promotes sustainability. With the rapid development of renewable energy sources and energy storage technologies, energy communities are becoming important players in achieving energy independence and reducing dependence on traditional energy sources. The development of information and communication technologies also supports innovative management solutions in the transition from the traditional inelastic to the modern energy system.

In order to realise all the benefits of this model, it is necessary to promote it through further legal frameworks, technological innovation and education to ensure fairness, transparency and efficiency in the work of energy communities. By involving citizens in the decision-making process, creating favourable conditions for local initiatives and supporting the development of smart technologies, energy communities have the potential to become a key factor in the transition to a sustainable energy system.

Analysing the concepts of different types of energy communities explained in this paper, it can be concluded that investments in BESS are still extremely expensive, but feasible with the help of subsidies from the European Union. With further research and technological advances, these concepts will be financially feasible in the near future.

As mentioned in the introductory chapter, the high integration of photovoltaic power plants can cause the problem of overvoltage in the grid. This problem can be solved by using BESS, which are usually connected in parallel to the photovoltaic power plant. This issue is targeted as an extension and goal for future work. In addition, more attention will be focussed on virtual energy communities.

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