Energy Storage and Conversion 2024, 2(4), 1546.
https://doi.org/10.59400/esc1546

Article

Holistic approach to energy storage management aspects in sustainable community

Grzegorz Augustyn*, **Jerzy Mikulik**

AGH University of Krakow, 30-059 Kraków, Poland
*** Corresponding author:** Grzegorz Augustyn, augustyngrzegorz@agh.edu.pl

CITATION

Augustyn G, Mikulik J. Holistic approach to energy storage management aspects in sustainable community. Energy Storage and Conversion. 2024; 2(4): 1546. https://doi.org/10.59400/esc1546

ARTICLE INFO

Received: 19 July 2024
Accepted: 15 October 2024
Available online: 28 November 2024

Abstract: Energy management is nowadays key topic for synchronic operation of renewable sources of energy and their recipients. Contemporary national electrical power grid systems more often cannot supply efficiently electrical energy and cannot receive energy produced by renewable sources. The common approach to the problem is to meet energy demands supplying from electrical grid and renewable power sources with energy storage feature. From the other side, off-grid solutions based on the co-generation biogas plants are commonly aimed on small local communities as power supply supported by renewable energy systems like photovoltaic (PV) systems, wind power plants or small water plants with energy storage to support self-consumption of electrical energy. Integration of intermittent renewable power sources, such as solar, wind and biogas plant, increases the difficulty of managing the electricity grid and maintaining the balance of electricity supply and demand, especially in small communities. The holistic approach to the energy storage management takes all above aspects and presents the concept where municipal waste is used to produce energy in biogas plant supported by PV systems and community shared electrical energy storage to provide uninterrupted power supply. The study also presents how energy storage management can be used in whole process to adjust the size and manage energy supply and demand within the community based on energy self-consumption optimization. It is also shown that by utilizing municipal waste produced by the community we can meet the goals of circular economy and sustainable development of local communities as the waste will be used in full without necessity of recycling it outside the community. The novelty of the study is the foundation for energy storage capacity and renewable energy sources size evaluation to balance energy management process without the need of on-grid power supply and with use only municipal biodegradable waste for biogas fuel supply and solar energy for energy production.

Keywords: energy storage; circular economy; energy management; sustainable community; circular economy

1. Introduction

The development of energy and the continuous development of urban areas have caused a real threat of rapid depletion of fossil fuels such as coal, crude oil, natural gas and progressive environmental pollution resulting from their combustion. This resulted in an increase in the content of carbon dioxide and other greenhouse gases and dust in the atmosphere. The increase in them and other greenhouse gases may affect global warming and the related weather anomalies [1]. Therefore, alternative ways of generating electricity from renewable energy sources (RES) have begun to develop [2].

Investing in RES has a more practical dimension and brings financial benefits. In addition to climate change, we experience constantly rising energy prices. Higher bills result from political conflicts and inflation, but mainly from the fact that we heat our homes and generate electricity using resource deficits [3]. RES are sources that use wind, solar, water, geothermal and biomass energy in the processing process. They use natural processes to produce electricity and heat and do not emit substances harmful to the environment. They are therefore clean, safe and planet-friendly energy [4]. There are many benefits to using RES. This is primarily related to ecology, because it does not contribute to the depletion of natural resources and pollution of the natural environment. Generating energy in this way means security and energy independence, as well as economic benefits [5,6].

The global energy industry is moving towards energy storage systems and renewable energy installations located close to end users and small local municipality. Such an approach fosters greater independence from imported energy sources and diversification of energy sources [7,8]. In times of crisis and political conflicts, these activities help to improve energy security and become more independent from countries exporting energy fuels. The research presents an idea for energy management concept which bonds together possible sources of energy and the ways of its production and storage to secure the local community power demands in the off-grid circular energy flow with ability to return the surplus energy to the power grid by using the ecological electrical energy production methods (PV and biogas plant) and utilizing the municipal waste produced by the local community towards self-sufficient energy management system [8].

This process allows to reduce greenhouse gas emissions, which is to improve air quality and stop climate warming [9] as well the use of the municipal waste which helps to minimize the amount of waste required utilization [10,11]. The other important aim is to provide the secure electrical energy supplies and electrical security for its local receivers by using their waste to fulfill power demands as well as commercial and industrial units [12].

As mentioned above biogas plant is the one of the key power sources in our concept of sustainable community energy production and management because for the production of biogas can be used biodegradable municipal waste (kitchen waste and green waste). Such waste is an important substrate. Biogas produced from waste in rural areas around cities has great potential to meet the energy needs of cities [13,14]. It can be also used for smaller communities especially if supported by PV systems which are commonly used in more number of households due to various government supporting programs [15–17].

The other direction is implementation of energy storage systems which increase the auto-consumption of electrical energy however it is very often part of the PV system to store the unused energy surplus for PV system for future use during the PV decreased efficiency during the day or season [18].

All these component systems are usually bonded together to create hybrid or off-grid micro-networks to better use the energy produced by biogas plants, PV and energy storage and to overcome the disadvantages and fluctuations of energy production in case of more or less predictable energy demands by the community of its recipients (householders) [19].

There is also important consideration in the terms of carbon emission policies which affects the urbanization process and from the other side urbanization itself has substantial influence on the carbonization and CO_2 global emission. Smaller community with less urbanization and population density can be also the solution for negative correlation between population density and per capita CO_2 emissions, which we can see especially for developing countries. With exception of China, CO_2 emissions trends are generally larger large cities or higher urbanization areas than the national averages. As the urbanization seems to be playing an increasing role in driving national emissions we can observe the importance of mitigation policies for cities [20]. Smaller communities which are using the hybrid renewable energy systems (HRES) or RES micro-networks as described above can be affected by these policies, however they can play an important role in whole process and strategy showing that smaller communities can provide solutions and contributions to this process. Urbanized areas consist of small communities of various size of population. The same approach in global strategy of decarbonization and lowering CO_2 emissions can be applied to local communities, especially when we consider divided areas around citied and suburban areas. Large urbanized areas consist of smaller areas and all actions taken at the lower level influences the result in more global scale. However, the policy for smaller communities and solutions developed to limit CO_2 emissions, even if appropriate to the national policy, can suffer from the same lack of over-national policies and face the same problems as described and suggested in [21]. We need to then consider that this is one of the ways to comply the general process and provide micro-scale solutions which might work in global-national, over-national or global scale.

2. Renewable energy solutions (RES) in on-grid and off-grid micro networks considerations

The main disadvantage of renewable energy is its unreliability and the inability to work efficiently due to the intermittent and fluctuating nature of the work, which usually leads to system oversizing, thus increasing the investment cost. For this reason, hybrid renewable energy systems (HRES—Hybrid Renewable Energy Systems) are built. Their popularity is due to the effectiveness of eliminating the disadvantages of RES systems based on a single source. A hybrid system consists of at least two power systems of different origins (renewable and fossil fuels), energy storage and electronic devices controlling them. The main advantages of HRES are: greater reliability, better efficiency, increased energy storage capacity, lower energy costs throughout the life cycle, minimization of greenhouse gas production [22]. Hybrid systems for the production of electricity can be a microgrid. It is a locally controlled energy system that uses:

1) different types of renewable energy sources: sun, wind, biomass or water,
2) energy generators (diesel, gasoline, biogas, biodiesel),
3) energy storage systems (batteries, hydrogen, heat),
4) loads (residential, commercial, industrial),
5) control devices (inverters and converters) [23].

There are two types of microgrid, a type of on-grid and off-grid. The former are connected to the national power grid, the latter are autonomous and operate outside the national power grid. The combination of photovoltaic technology and other RES with a biogas generator can be a profitable solution that will power even the most remote and sparsely populated rural areas. Such a hybrid system is optimal and less expensive than traditional. In off-grid networks, energy is generated by photovoltaic panels and a biogas generator, and stored in a battery bank. The batteries should have the capacity to power buildings for a certain number of days without sun, wind or biogas [23,24].

Building microgrids in which renewable energy is used brings environmental benefits such as reducing overall energy consumption, improving energy efficiency, reliability of energy supply, reducing transmission losses, voltage control and security of energy supply. HRES supports the implementation of sustainable development with the use of renewable energy [25]. The climatic risk is the occurrence of long interruptions in the supply of electricity from the national grid, caused by its damage due to weather factors, e.g. strong wind, snowfall or freezing rain [26]. Its occurrence and ailments are reduced by HRES microsystems independent of the national network, which are also an energy reserve for this network [27].

In rural and sparsely populated areas, terrain and economic considerations play an important role in planning the power grid. They make the importance energy produced from renewable sources, which are easy to install, have a higher rate of energy use, lower transmission losses and lower operating costs [24,25]. In addition, the use of environmentally friendly renewable energy sources in rural areas can reduce environmental pollution also in surrounding towns. The use of alternative energy sources makes communication more accessible and reduces dependence on fossil fuels, which reduces the negative impact on the environment [27].

Example of such approach is the designed by Habiba et al., who used kitchen waste from dormitories and hostels located on the university campus for the production of biogas. PV panels were installed on the roofs of these buildings [28]. More broadly, in cities and surrounding areas, a large amount of biodegradable municipal waste is generated from preparing meals (fruit and vegetable leftovers, groats, pasta, egg shells, coffee and tea grounds) and from home gardens (wood, leaves, flowers, small branches) [29]. It is estimated that an average household generates 60–80 kg/person/year of kitchen waste and 1.5–2 kg/m^2/year of green waste. [30]. On the island of Java there was proposed hybrid system consisting of a PV plant and a biogas plant. Electricity is produced by PV panels in the dry season (April–August) with a high intensity of sunlight (123–1075 W/m^2). The energy generated in this way can be stored in batteries, so it can be used by the inhabitants of the island at times when energy is not produced by PV panels. The strategy of the hybrid system work is that the PV panels produce electricity during the day, and the biogas plant generates electricity at night. Due to the climate on the island of Java, during the rainy season, the photovoltaic efficiency drops by 50%–70%. As a result, both RES systems can complement each other, constituting the optimal hybrid power system on this island [31]. The solution is also to create a system of effective distribution of energy generated from renewable energy. It is possible to build hybrid energy grids parallel to the commercial grid. This solution can make electricity successfully distributed to rural and urban areas, which will solve the electricity problem [23,31]. This example also shows that for the local community we can provide the same strategy and by using the proper energy management inside the system by calculating the energy flow and routing between all its components can increase its efficiency in electrical energy production and consumption and what is more we could consider the prosumer mode when it is connected to the power grid network [32].

Some solutions for large scale storage for on-grid power networks for midsize or large communities shows the direction for electrical storage application based on packaged electrical energy system storage (EESS) [33]. Such applications allow for profile shifting and grid-demand support to better optimize energy consumption and storage balance, where battery balances and optimizes storage between on-grid power supply and PV installation or wind turbines. This direction for energy distribution and storage model does not assume self-sufficiency, however this solution gave the foundation for application storage for hybrid power systems [34] as well as shared community storage, where all participants can share common storage to optimize electrical energy distribution [35,36] by use of lithium-ion batteries or flow batteries. Further study on the optimization of storage, but from the cost point of view for various types of storage is shown in [37,38] where calculation method for energy storage was developed.

3. The concept of holistic approach to energy storage management

Energy systems are more commonly powered by renewable energy sources such as wind, solar and biogas. The main disadvantage of renewable energy is its unreliability and the inability to work efficiently due to the intermittent and fluctuating nature of the work, which usually leads to system oversizing, thus increasing the investment cost. Hybridization of energy sources increases the reliability of the energy system as a combination of two or more sources of electrical energy to provide reliable and uninterrupted power supply according to the local community needs. Implementing community shared electrical energy storage solution to the hybrid energy network solutions can create the opportunity to increase energy self-consumption and better energy management for long term perspective without on-grid power source.

In off-grid networks common approach, electrical energy is generated by photovoltaic panels supported by energy storage and a biogas plant. The batteries should have the capacity to power buildings for a certain number of days without sun, wind or biogas [23,24]. However, when we consider the small community there are still problems with adjusting the size of electrical energy storage and renewable energy sources especially if we consider that biogas energy production is based only on municipal biodegradable waste produced by the local community and we would like to stay with off-grid system to limit green gas emissions and use all municipal waste produced by the community.

The concept of holistic approach to electrical energy storage management combines the biogas plant and renewable energy sources, as well as community shared electrical energy storage to achieve fully closed-circuit electrical energy flow for the small community. Such micro-network uses biodegradable waste for supply biogas plant electrical power production and use no other fuels or energy sources helps to increase sustainability in the waste management aspect. In this way we can advance process towards self-sufficient solution of electrical energy management with all advantages taken from other types of micro-networks adjusted to the small community scale. We would like to show that this approach allows for design of appropriate size of community shared energy storage size to ensure that energy management process can fully secure power demands, optimize the size of renewable power sources and helps to increase sustainability by municipal waste usage for electrical energy production in biogas plant.

Below on **Figure 1** there is a scheme presenting the concept of the holistic approach to energy storage management. As biogas plant can produce heat and electricity we will take into consideration only electricity production for further energy management consideration.

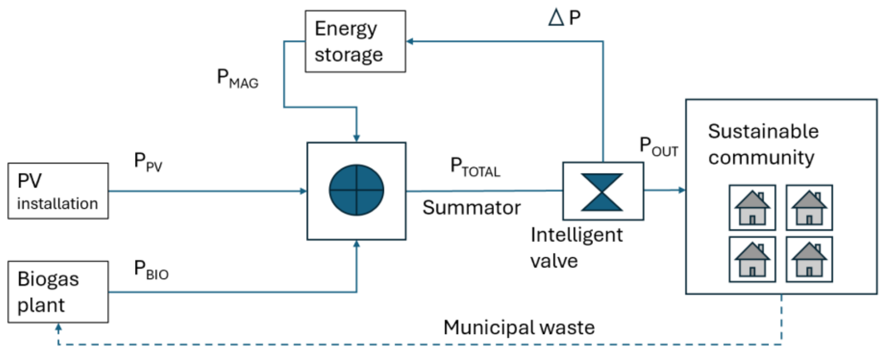

Figure 1. Diagram of energy flow where PPV—photovoltaic energy input, PBIO—biogas energy input, PMAG—energy storage input/output, ΔP—energy difference between demand and supply, POUT—energy demand directed to their recipients.

As the result we should improve energy efficiency, reliability and security of energy supply, eliminate waste utilization cost by using it as the fuel for biogas plant. We are not considering the cost or technical aspects of the set up or power grid details as our goal is to show how we can design he process to achieve uninterruptible power supply for households based on their own waste and renewable electrical energy production.

The resented idea is to connect all components: biogas plant, renewable energy source, electrical energy storage in the common circuit to manage electrical power production and storage in the way which allows for off-grid functionality with system size optimization by energy management algorithms. Main change is that energy storage is not attached to the specific power source, but it is common shared by the community.

It means that electrical energy storage which is not dedicated to PV installations but it is community shared electrical energy storage for all power sources as well as storage for excess electrical energy which is not used in the time instance by recipients (individual households). This should allow for smaller installation size and better energy management with increased level of self-consumption as well as increased sustainability because biodegradable municipal waste will be used in full to produce electrical energy by biogas plant.

The key role in this concept plays the energy management algorithm which is applied to the distribution valve as the part of automation system, which manages the amount of energy which is routed to the common shared energy storage, which can be biogas plant, PV circuits or energy storage. The valve is responsible for adjusting the excess energy flow or making the decisions about energy storage during its energy production period or discharging the storage when the power demand excess energy production capabilities of the system.

In this model our system moving towards keeping the state of homeostasis where ΔP is the electrical energy balance as the measure of the process and shows the amount of excess electrical power produced by the system or demand for additional power by bonding together three input electrical power values P_{IN}, P_{OUT}, P_{MAG}.

P_{IN} is the summary of power sources like PV and biogas plant which are working with the certain production profile depending on the sun operation and community waste delivery and it is changing over the time period. P_{OUT} is the energy demand from the local recipients which is also expressed by the certain individual energy usage profile of individual household. Only the third variable—P_{MAG} is the variable which can be used as the source or load to the system and can be used to balance all three electrical power inputs with ΔP as the measure of the process. This concept is expressed in below Equation (1).

$$P_{PV}(t) + P_{BIO}(t) + P_{MAG}(t) - P_{OUT}(t) = \Delta P(t) \tag{1}$$

where:

P_{PV}—electrical power produced by the PV installation from all households

P_{BIO}—electrical power produced by the biogas plant by utilization of community municipal waste

P_{MAG}—discharging power of the community shared energy storage

P_{OUT}—power demand of households in the community

ΔP—power balance (excessive power produced or the difference between produced power by the biogas plant, PV installation and power demand of households)

Above equation gives foundation for the valve algorithm (**Figure 2**) which decides if the electrical energy is routed to charge the energy storage or discharge it to support power production from other sources biogas plant and PV installation as presented in [39].

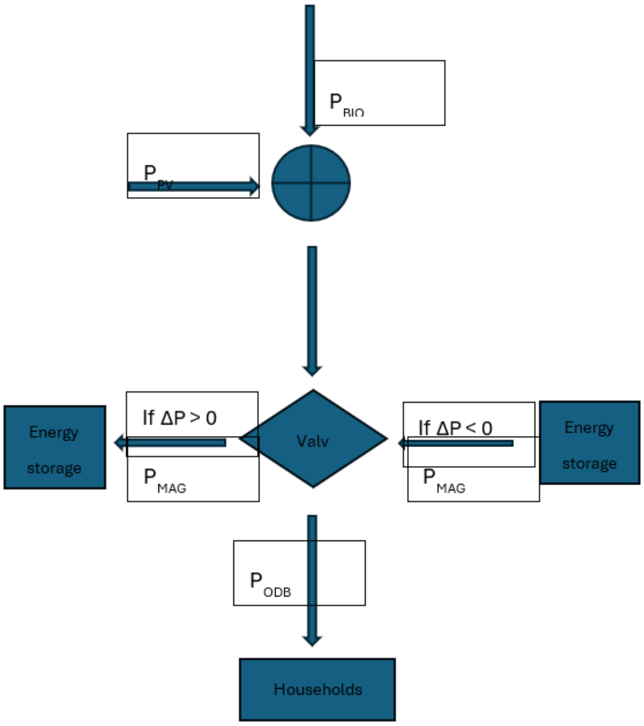

Figure 2. Valve algorithm where: PPV—photovoltaic energy input, PBIO—biogas energy input, PMAG—energy storage input/output, ΔP—energy difference between demand and supply, POUT—energy demand directed to their recipients.

The valve is responsible for routing the energy to the energy storage or supplying it back to the system when it is needed and individual recipients demand is more than PV installation and biogas plant can produce as presented in [39].

Based on Equation (1) when energy production by PV installation and biogas plant exceeds the P_{ODB} the energy surplus is routed to charge the energy storage. In this situation the valve acts as the exceed valve controlled by the proper calculation of C_n coefficient ($C_n > 0$), which is calculated by the measuring the energy demand in reference to the overall energy production by the PV installation and biogas. If the households are demanding more electrical energy than PV installation and biogas plant can produce ΔP is below zero, and C_n coefficient ($C_n < 0$ in this case) is calculated to evaluate the amount electrical energy from storage to be discharged as the additional electrical energy to the circuit to satisfy the current electrical power demand of the community.

Following above can calculate the size of common shared energy storage based on the maximum values of energy consumption for the community and maximum energy production from the power sources like biogas plant and PV installation. The energy storage size is the buffer which allows for balancing between the size of the PV installation having certain biogas electrical productions value and the individual household energy demand. We can also apply this to the predefined size of the community where each household has certain profile and produces adequate amount of municipal waste.

This model also allows for evaluation the power of the PV installation, when we consider biogas plant working on the certain municipal waste production profile and determined size of the energy storage to keep the system balanced. In this scenario, energy storage should recover to its constant starting value at certain periods and system is able to provide energy to all its recipients.

4. Simulation

Simulations were taken based on following assumptions:

1) Local community with 10 average households (individual buildings)
2) Small biogas plant as one of the sources of electrical energy with municipal waste usage from 10 individual buildings in the same local community (av. 150 m^2, 4 persons),
3) 10 individual buildings in the same local community (av. 150 m^2, 4 persons) as the electrical energy recipients in the energy management process with average monthly energy consumption 3.5 kW,
4) Community shared generic energy storage based on lithium-ion battery system, minimum state of discharge 20%, daily discharge no more than 0.1%, which size will be determined as the result of simulation,
5) photovoltaic installation working at its average profile as the multiplication of 10 KWP standard size installation located at the South of Poland (Wieliczka county) installed at the roof with 27–32 degrees angle of each household,
6) 60 months simulation period, based on 12 months energy usage and production profiles

Based on the above assumption we were able to generate input data to the algorithm which allows to create two simulation scenarios:

(1) how energy storage charging and discharging process works in terms of various electrical energy production scenarios with various size of PV installation in this set up.
(2) What is the optimal size of the PV installation with certain electrical energy storage capacity to keep all energy management process self-sufficient

Following to above we need to define the energy requirement profile for the recipients during 12 months. Our recipients are 10 individual houses as the passive energy recipients and generating municipal waste to produce substrate for biogas plant.

The municipal waste amount produced over the year by the 10 households is shown in the **Table 1**. This data is used to calculate biogas annual electrical power production [39].

Table 1. Biodegradable municipal waste amount produced by 10 individual households and electrical produced by biogas plant over 12 months.

	Months											
	I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
Municipal waste amount [kg]	50.0	52.5	87.5	215.0	390.0	422.5	390.0	372.5	360.0	415.0	450.0	120.0
Electricity [kW]	97.7	102.8	170.8	420	761.6	825.1	761.7	727.5	703.1	810.5	878.9	234.4

Power production profiles and power demands of individual households are taken form the literature [12] and available sources and calculations are based on the regular average profile during the year. These data series are shown on the **Figure 3** when we can see the separate electrical energy profiles for the biogas plant electrical energy production from municipal waste supplied by 10 individual households, 10 KWP PV installation and average energy consumption of individual household over the year. The community itself and its contribution to the process is expressed by the electrical energy produces by PV installation and amount of municipal waste used for producing substrate to supply biogas plant.

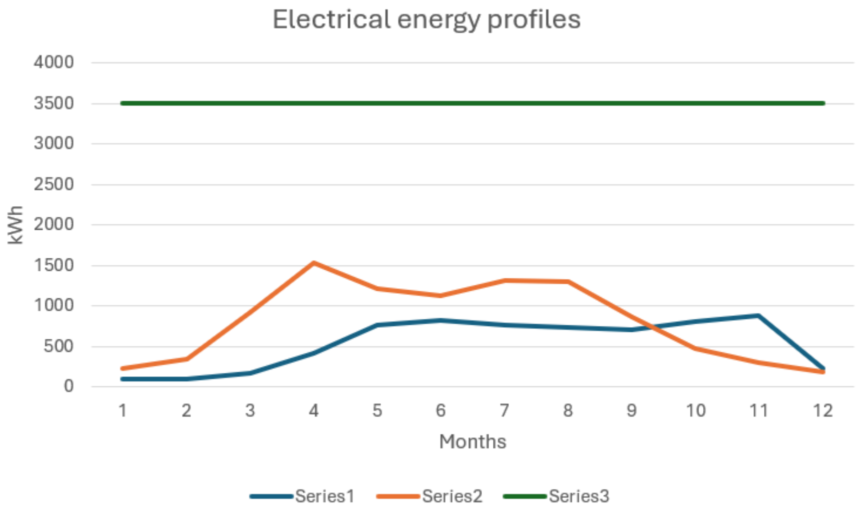

Figure 3. Electrical energy production profiles from installation components during the 12 months period, source [39].

We have defined now all necessary inputs for our simulations to calculate the amount of electrical energy which will be needed to charge the energy storage and which will be needed to cover the energy demands in the moments where its production is not able to fulfill recipients demands [2]. To properly calculate the value of the electrical energy which will be loading or discharging the energy storage we will need to take into account the loading process of the energy storage.

Our simulation assumes that excess electrical energy production from the previous period will be used to charge the energy storage. In this way we will be able to recharge and prepare the storage for the high energy usage when no energy will be produced by biogas plant or photovoltaic installation (e.g., during the night).

This can be expressed in the formula as below:

$$C_n = \frac{P_{MAG_{init}}}{P_{MAG_{init}} + \sum_{n=1}^{60} (P_{MAG_{init}} + \cdots + P_{MAG_{n-1}})} \quad (2)$$

where: $P_{MAG_{init}}$—initial value of electrical energy stored in the energy storage, n—time instance during a year calculated for every month in the 12 months period, where n = {1, 2, …, 12}, C_n—energy storage coefficient for the calculated time instance.

Our simulation for these assumptions and calculations is shown on **Figure 4** below where we present C_n coefficient values for certain biogas plant electrical power production profile and various energy storage initial value. We can see that charging and discharging profile repeats in every 12 months as it is also reflects annual profiles for power production by the biogas plant and PV installation. We can see that excessive electrical power production is in the months where PV installation works at its best and community waste amount is higher than in the autumn and winter months. During these periods energy storage is mostly discharging to provide extra power to satisfy power demands of households. This shows what capacity should be considered as commune share energy storage to store enough electrical energy for the autumn and winter periods and keep electrical energy supplies uninterruptible for longer periods.

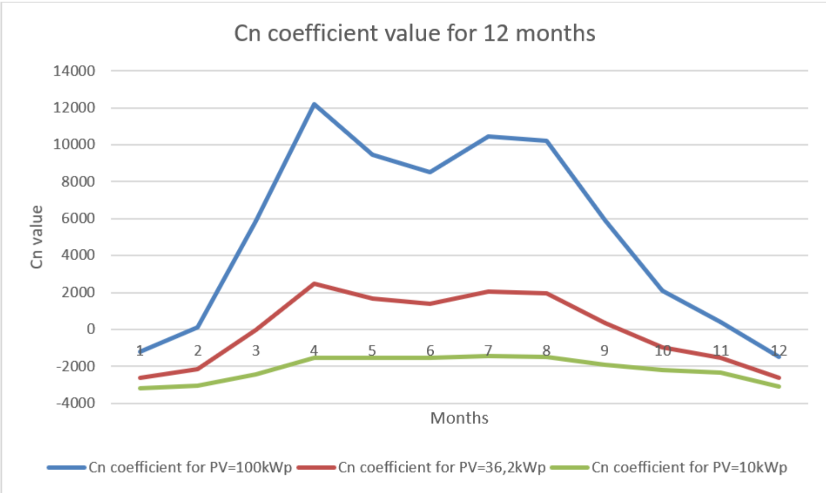

Figure 4. Cn coefficient values simulation for all elements of the circuits including energy storage management for three various sizes of PV installation over 12 months.

Above implicates that all electrical energy from biogas plant and photovoltaic installation is managed by the valve in the way that there is no necessity to connect to the electrical power grid and there is no electrical energy returned to the power grid as well.

We can also determine the size of the common share energy storage needed to sustain the process of the energy management in our micro network. The size can be determined by the analysis of coefficient profile. We cannot allow for constant discharging or charging profile. In the first case (PV = 10 KWP) constant discharging means that C_n is most of the time below zero which means that we need to supply additional power form external sources (such as national power grid). The second case (PV = 100 KWP) shows that we need to store excess energy every year without using it for the community demands. If we do not have connection to the national power grid we cannot consider sales of electrical energy surplus. That is why we need to adjust the size of the PV installation to keep C_n average profile close to zero value over the considered period. This case in our micro network is possible when PV installation is at 36.2 KWP. This is shown on the **Figure 5** where we simulate energy storage capacity for all three above sizes of PV installation.

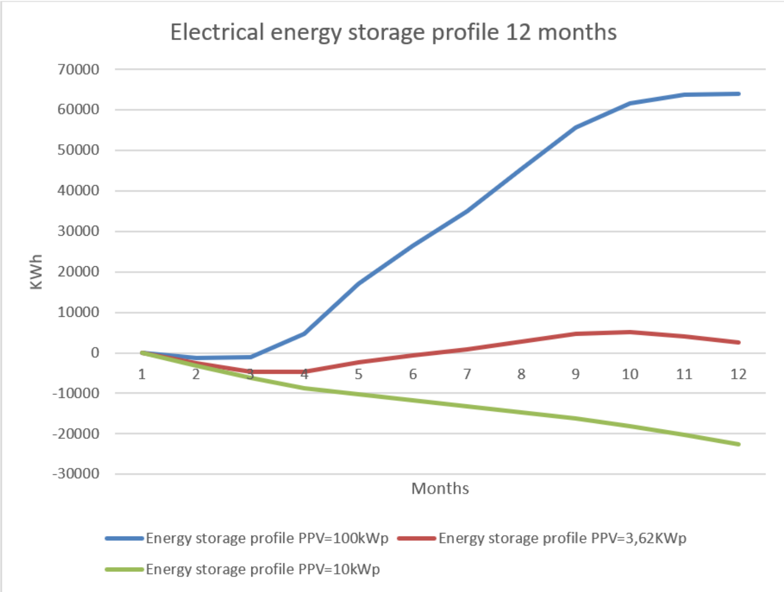

Figure 5. 12 months simulation of energy storage load/charging prediction based on the various scenarios of the PV size installation.

The result as of the simulations depicted on **Figure 5** show that for certain value of PPV installation size 36.2 KWP and energy storage capacity of 5100 kW, community energy demand and biogas plant size system is stable and keeps energy storage restored year by year in terms of charging-discharging profile for. For the other sizes of PPV the system stores too much energy or installation is not able to handle the energy demands of the community.

We can also observe similar patterns on all three cases. In the first quarter of the year electrical energy produced by the biogas and PV installation is not sufficient to supply the community. In this period storage is discharging and diminishing its initial stored energy amount (we can see also on **Figure 4** that C_n coefficient is below 0). Further on during the year community produces more waste (especially green waste) and sun operates longer during the day. Energy storage is recovering as the more excess electrical energy is produced. C_n coefficient is positive and more energy is stored in the battery. In the third and fourth quarter of the year the energy demand of the community raises (we can see it also thorough electrical energy profiles) and stored energy is used to support insufficient electrical energy production by the biogas plant and PV installation by discharging the storage.

We can see patterns as well in the C_n coefficient and energy storage profiles, but they are same shape but stretched or diminished depending on the amount of energy in the system. The coefficient is the base for the energy distribution process in the system, so it reflects in another patterns we can observe with every size of the PV installation, however when the installation is 100 KWP electrical energy produced by the installation is so excessive that at the end of the year we can see its cumulation over the community needs which shown as increasing energy amount over the year. If the PV installation is small (10 KWP) the system cannot cumulate enough energy and energy storage at the end of the year is discharged below its initial value. Only 36.2 KWP installation allows for restoring initial amount energy stored in the battery and provide stable cycle over the year. If we apply this to the longer time period (more than one year) the process will repeat itself with end-of-year-initial values.

5. Discussion

The aim of this discussion is to evaluate if the concept of electrical energy storage management with common shared energy storage can be applied in sustainable community and under what conditions such approach can be realized.

First of all, we can see from above simulations that common shared electrical energy storage concept where it is dedicated to all power sources, not only for PV installation or biogas plant itself, reflects its bigger size as it has to store excess energy for a longer period of time. This solution is closer to the large scale storage where on-grid power plays significant role for the community.

In our concept small local community produces biodegradable waste to power up the biogas plant, which is one of the goals of the sustainability, despite the fact that biogas itself is considered as the low emission source of power. Biogas plant produces electrical energy, but its amount during 12 months is not enough to provide uninterruptible electrical power supply. From the other side considered community uses renewable energy source like PV installation to generate additional electric power to satisfy community electrical energy demands. This is also not sufficient to provide long term energy management. Both ways of electrical energy generation can use or dedicated storage or individual household storage. It is also worth of mention that individual household cannot produce electrical energy from PV installation even if supported by small individual electrical storage, to meet the energy demand of the single household and thus we need to consider on-grid connection. Introducing common shared electrical energy storage for the community makes possible to consider biogas plant supplied by the substrate from biodegradable community waste. Another source of electrical power is PV installation which usually is installed for each individual household with 10 KWP. Considering community of 10 households we can see certain electrical energy production and average electrical energy consumption profiles which can be balanced by common shared electrical energy storage if the storage will cover summary profile of electrical energy production. This allows for longer time storage of excess electrical energy in the periods where biogas plant and PV installation production exceeds individual households demands.

We can also observe from above simulations that biogas plant is dependent on the waste production amount in the annual period and electrical energy produced by PV installation is dependent on the average solar conditions. Both sources working together are very effective in the middle half of the year, however it exceeds individual households demands, but for the rest of the year they are not able to produce enough electrical energy to satisfy the needs of community. Common shared electrical storage with the proper management of electrical energy flow allows for electrical energy distribution between sources and its recipients allows for the longer period assuring the self-consumption without the need of on-grid connection.

Proposed algorithm for the valve, which is responsible for proper electrical energy routing backed up with common shared energy storage gives the opportunity to balance all the process and leads to the introduction of global electrical energy management process for the community. The algorithm routes the excess electrical energy in the way as the excess valve works to the battery of common shared storage and discharge it when community demand exceeds the capabilities of current electrical energy production from biogas plant and PV installation. The formula for charging and discharging coefficient allows for estimation of storage size, which keeps the process balanced. It returns substantially large capacity, so it should be also considered further in terms of economical investment.

Energy storage management algorithm allows also for evaluation of the size of storage which is needed to balance all process through the year and provide uninterruptible electrical energy supply throughout considered period. However, we can observe that for the 10 KWP PV installation for the individual household we cannot charge the storage enough to avoid insufficient electrical energy supply. From the other side if we consider 100 KWP PV installation which means that every household has been equipped with 10 KWP installation, the excess energy charges the storage battery infinitely increasing year by year. Simulations shows that for certain parameter of the PV installation (36.2 KWP), at the constant biogas profile which is dependent on community waste production, we can achieve balance between charging and discharging the storage over the year without the need of on-grid connection and without exceed charging of the storage.

This also implicates that through this approach for the management of electrical energy in the community there is also possible to diminish and determine the correct PV installation size, which also can prevent such community against oversizing of the sources and storage. The other advantage in terms of sustainability is also the fact that we use all biodegradable community waste produced by households, so there is no need to external recycling and utilization.

Nevertheless, the results obtained in this research should be interpreted carefully as they are based on a simple case study. We still need to consider that electrical storage size and its evaluation can suffer from real world problems, charging and discharging effectivity, electrical energy losses, battery lifetime capacity loss and changes in annual community waste production and solar energy due to the weather changes. Also, we do not consider in detail technical aspects of electrical network which is needed for energy distribution like inverters, routers etc., however proposed algorithm can be used as the foundation for further, more detailed research for various starting conditions and disturbance which can influence the process. There is also a good starting point for artificial intelligence to evaluate and predict the process in more efficient way and in other scenarios or input conditions.

6. Conclusions

This research presented a novel holistic approach to the electrical storage energy management in the small local sustainable community where municipal waste is used for energy production in the local biogas plant supported by PV installation without on-grid power network connection. Such solution is possible because electrical energy storage is used as the common shared global storage for all power sources and recipients. Community also uses available resources (municipal waste and solar energy) to produce electrical energy full filing the goals and direction for achieving better sustainability.

This research provides a method to optimally improve electrical energy storage management. The results are meant to demonstrate the capabilities of the electrical energy distribution circuit by using the method for calculating required storage size and renewable energy system. Presented algorithm for energy management and distribution using the valve shows that not only storage size might be determined, but also implicates certain size of PV installation preventing the system against oversizing.

Future research should investigate the impact of different conditions and distortions, changes in energy profiles that are used as the inputs for the energy management algorithm. These potential future investigations could also consider various emerging electrical energy storage technology that were not considered in this research to optimize the size and cost of the investment when considering application to the specific community. The other direction for further research is the possibility to include more advanced formulas or calculations methods for improving parameters calculations and algorithm adjustment for more precise and real-time management or fine tuning of the process, where local conditions vary in smaller periods of time (e.g., daily basis) and the electrical energy production profile have fluctuations or distortions in reference to the assumed electrical energy profiles. This should lead to size adjustment of the PV installation and electrical energy storage parameters selection to better reflects the action of the circuits and more efficient in cost and electrical energy security of the process in the smaller periods of time.

Finally, this approach indicates that common shared electrical energy storage used for energy management could be essential for the transition to a green economy and improve the sustainability and self-sufficiency for the small communities which can better manage their waste and resources.

Author contributions: Conceptualization, GA and JM; methodology, GA and JM; software, GA; validation, GA; formal analysis, GA and JM, investigation, JM; resources, GA; data curation, JM; writing—original draft preparation, GA and JM; writing—review and editing, JM; visualization, GA; supervision, JM; project administration, JM; and funding acquisition, JM. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by AGH University of Krakow, Agreement DS No 16.16.200.396 B410 from AGH maintaining and development of research potential programmer.

Data availability statement: Data are contained within the article.

Conflicts of interest: The authors declare no conflict of interest.

References

1. Borowski PF. Biomass as a response to increased energy security and climate change (Polish). Przegląd Organizacji. 2008; 28-32. doi: 10.33141/po.2008.78.07

2. Chmielewski A, Gumiński R, Mączak J, et al. Aspects of balanced development of RES and distributed micro-cogeneration use in Poland: Case study of a μCHP with Stirling engine. Renewable and Sustainable Energy Reviews. 2016; 60: 930-952. doi: 10.1016/j.rser.2016.01.131
3. Cucchiella F, D'Adamo I, Gastaldi M. Financial analysis for investment and policy decisions in the renewable energy sector. Clean Technologies and Environmental Policy. 2014; 17(4): 887-904. doi: 10.1007/s10098-014-0839-z
4. Stanek W, Czarnowska L, Gazda W, et al. Thermo-ecological cost of electricity from renewable energy sources. Renewable Energy. 2018; 115: 87-96. doi: 10.1016/j.renene.2017.07.074
5. Ortega-Izquierdo M, del Río P. Benefits and costs of renewable electricity in Europe. Renewable and Sustainable Energy Reviews. 2016; 61: 372-383. doi: 10.1016/j.rser.2016.03.044
6. Burgos-Payán M, Roldán-Fernández JM, Trigo-García ÁL, et al. Costs and benefits of the renewable production of electricity in Spain. Energy Policy. 2013; 56: 259-270. doi: 10.1016/j.enpol.2012.12.047
7. Igliński B, Piechota G, Iwański P, et al. 15 Years of the Polish agricultural biogas plants: their history, current status, biogas potential and perspectives. Clean Technologies and Environmental Policy. 2020; 22(2): 281-307. doi: 10.1007/s10098-020-01812-3
8. Theuerl S, Kohrs F, Benndorf D, et al. Community shifts in a well-operating agricultural biogas plant: how process variations are handled by the microbiome. Applied Microbiology and Biotechnology. 2015; 99(18): 7791-7803. doi: 10.1007/s00253-015-6627-9
9. Bischoff A. Insights to the internal sphere of influence of peasant family farms in using biogas plants as part of sustainable development in rural areas of Germany. Energy, Sustainability and Society. 2012; 2(1). doi: 10.1186/2192-0567-2-9
10. Piskowska-Wasiak J. Obtaining and processing biogas from controlled fermentation of biodegradable fractions of municipal waste (Polish). Nafta-Gaz. 2015; 71(7): 510-519.
11. Kłos L. Municipal waste management a challenge of the 21st century (Polish). Studia i Prace Wydziału Nauk Ekonomicznych i Zarządzania. 2012; 28: 131-143.
12. Szyba M, Mikulik J. Analysis of Feasibility of Producing and Using Biogas in Large Cities, Based on the Example of Krakow and Its Surrounding Municipalities. Energies. 2023; 16(22): 7588. doi: 10.3390/en16227588
13. Tagne RFT, Dong X, Anagho SG, et al. Technologies, challenges and perspectives of biogas production within an agricultural context. The case of China and Africa. Environment, Development and Sustainability. 2021; 23(10): 14799-14826. doi: 10.1007/s10668-021-01272-9
14. Pathak H, Jain N, Bhatia A, et al. Global warming mitigation potential of biogas plants in India. Environmental Monitoring and Assessment. 2008; 157(1-4): 407-418. doi: 10.1007/s10661-008-0545-6
15. Szyba M. Spatial planning and the development of renewable energy sources in Poland. Acta Innovations. 2021; (39): 5-14. doi: 10.32933/actainnovations.39.1
16. Certificates of origin of electricity. Available online: https://www.biznes.gov.pl/pl/opisy-procedur/-/proc/207 (accessed on 3 April 2024).
17. Reference prices, Energy Regulatory Office. Available online: https://www.ure.gov.pl/pl/oze/aukcje-oze/ceny-referencyjne/6539,Ceny-referencyjne.html (accessed on 3 April 2024).
18. Yang Y, Bremner S, Menictas C, et al. Battery energy storage system size determination in renewable energy systems: A review. Renewable and Sustainable Energy Reviews. 2018; 91: 109-125. doi: 10.1016/j.rser.2018.03.047
19. Popczyk J. What does intelligent infrastructure mean in the civilization transformation of energy and where is its place (Polish). Warszawa, Poland; 2018. pp. 6-27.
20. Labzovskii LD, Mak HWL, Takele Kenea S, et al. What can we learn about effectiveness of carbon reduction policies from interannual variability of fossil fuel CO_2 emissions in East Asia? Environmental Science & Policy. 2019; 96: 132-140. doi: 10.1016/j.envsci.2019.03.011
21. Luqman M, Rayner PJ, Gurney KR. On the impact of urbanization on CO_2 emissions. npj Urban Sustainability. 2023; 3(1). doi: 10.1038/s42949-023-00084-2
22. Document of the Council of Ministers, Directions of development of agricultural biogas plants in Poland in 2010-2020 (Polish). Available online: https://www.pigeor.pl/media/js/kcfinder/upload/files/Kierunki-Rozwoju-Biogazowni-Rolniczych-w-Polsce-na-lata-2010--2020.pdf (accessed on 21 March 2024).

23. Yimen N, Hamandjoda O, Meva'a L, et al. Analyzing of a Photovoltaic/Wind/Biogas/Pumped-Hydro Off-Grid Hybrid System for Rural Electrification in Sub-Saharan Africa—Case Study of Djoundé in Northern Cameroon. Energies. 2018; 11(10): 2644. doi: 10.3390/en11102644
24. Chowdhury N, Akram Hossain C, Longo M, et al. Feasibility and Cost Analysis of Photovoltaic-Biomass Hybrid Energy System in Off-Grid Areas of Bangladesh. Sustainability. 2020; 12(4): 1568. doi: 10.3390/su12041568
25. Tiwari Y, Prashansa P, Chaudhary SK. A study of solar and biogas hybrid power generation system with max power tracking by solar panel. Int. J. Electr. Electron. Eng. 2015; 7: 257-266.
26. Juhola S, Laurila A, Groundstroem F, et al. Climate risks to the renewable energy sector: Assessment and adaptation within energy companies. Business Strategy and the Environment. 2023; 33(3): 1906-1919. doi: 10.1002/bse.3580
27. Jumare IA, Bhandari R, Zerga A. Assessment of a decentralized grid-connected photovoltaic (PV) / wind / biogas hybrid power system in northern Nigeria. Energy, Sustainability and Society. 2020; 10(1). doi: 10.1186/s13705-020-00260-7
28. Habiba U, Talukdar SK, & Islam MR. Designing Solar and Biogas based Renewable Energy System on University Campus and its Impacts on Energy Cost after Renewable Energy Interconnection to the University Grid Network. Global Journal of Research in Engineering. 2013; 13(13): 1-11.
29. MPO Krakow. Available online: https://mpo.krakow.pl/pl/mieszkancy/selekcja/zasady (accessed on 14 May 2024).
30. Estimation of the composting level of bio-waste (Polish). Available online: https://odpady.net.pl/wp-content/uploads/2021/05/Zalacznik-3-18.5-1.pdf (accessed on 19 May 2024).
31. Mudgal V, Reddy KS, Mallick TK. Techno-Economic Analysis of Standalone Solar Photovoltaic-Wind-Biogas Hybrid Renewable Energy System for Community Energy Requirement. Future Cities and Environment. 2019; 5(1). doi: 10.5334/fce.72
32. The Polish Chamber of Commerce for Renewable and Distributed Energy (PIGEOR). Biogas. Available online: https://www.pigeor.pl/biogaz (accessed on 28 March 2024).
33. Sepulveda NA, Jenkins JD, Edington A, et al. The design space for long-duration energy storage in decarbonized power systems. Nature Energy. 2021; 6(5): 506-516. doi: 10.1038/s41560-021-00796-8
34. Wang X, Shen Y, Su C. Exploring the willingness and evolutionary process of public participation in community shared energy storage projects: Evidence from four first-tier cities in China. Journal of Cleaner Production. 2024; 472: 143462. doi: 10.1016/j.jclepro.2024.143462
35. Farah S, Andresen GB. Investment-based optimisation of energy storage design parameters in a grid-connected hybrid renewable energy system. Applied Energy. 2024; 355: 122384. doi: 10.1016/j.apenergy.2023.122384
36. Kenyon G. Electrical Energy Storage: An introduction, The Institution of Engineering and Technology. London, United Kingdom The Institution of Engineering and Technology; 2016
37. Shekhar R, Kumar P. Hybrid Energy Storage System using Wind power system, Journal of Power Technologies. 2024; 104(3): 181-188
38. Stenclik D, Denholm P, Chalamala B. Maintaining Balance: The Increasing Role of Energy Storage for Renewable Integration. IEEE Power and Energy Magazine. 2017; 15(6): 31-39. doi: 10.1109/mpe.2017.2729098
39. Augustyn G, Mikulik J, Rumin R, et al. Energy Self-Sufficient Livestock Farm as the Example of Agricultural Hybrid Off-Grid System. Energies. 2021; 14(21): 7041. doi: 10.3390/en14217041