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Techno-economic assessment of university energy communities with on/off microgrid

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ABSTRACT

The integration of small-scale renewable energy sources, in particular in areas with favorable meteorological conditions and medium size power request, supported by governmental incentives and other regulatory facilities determined their aggregation towards local energy communities. In addition, the new technological developments like smart grids, smart measuring and blockchain for locally managing energy flows and monetary transactions determined the diffusion of the energy communities towards educational facilities, in particular university campuses. These campuses benefit for large open spaces, important rooftops areas and various energy consumption installations. The paper deals with the analysis of a real case study of an energy community university campus in the seaside area of Romania. A planning investment process was carried on accommodating the smart grid facilities to cover load demand minimizing energy costs, concomitant with the up-scaling design for ensuring decarbonation of the university campus. An optimization problem is formulated based on the existing renewable energy sources and storage systems such that to maximize the profit obtained by the university campus in exchanging energy flows with the upstream grid, and considering the benefits of load consumption considering the university character of the facility. The simulation results are based on the real measurements.

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1. Introduction

The technological advances, the reduction of investment costs in renewable energy sources, the governmental incentives, the increased requirement of consumers to become prosumers or to aggregate into energy communities determined the continuous increase of renewable energy sources integrated at various power system voltage levels [1].

The Green Deal package elaborated by the European Union established targets to be fulfilled by the member states of EU for reduction of greenhouse gas emissions such that to be CO_2 neutral by 2050 [2]. Hence, the use of renewable energy sources concomitant with reduction of power plants production is strongly encouraged and incentivized [3].

As part of the regulatory package "Clean Energy Package", the European Union directive 944/2019 established the premises for creating electricity markets focused on the end-user and consolidation of the concept of energy community. The energy community gives the members the possibility to autonomously manage the internal smart grids that supplies their customers and new suppliers can appear to serve these entities. The citizen energy community represents a legal entity that "[…] has for its primary purpose to provide environmental, economic or social community benefits to its members or shareholders or to the local areas […] and may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, […] or provide other energy services to its members […]" [4].

A possible definition for the energy community is *the energy community refers to residents collaborating to efficiently energy use and to increase local distributed energy resources generation for providing better energy services and for achieving socio-economic-*

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environmental benefits.

A comprehensive analysis of energy community concept is conducted in Ref. [5]. A review of social implications, technical designs and impact of energy communities considering various actors participating and interacting is carried on in Ref. [6]. The social involvement of the local community and the local constraints (architectural and environmental) represent a key point in planning and developing energy communities in islands [7]. The key characteristics of energy communities for boosting the local sustainable development and social innovation in European cities are identified and analyzed in Ref. [8].

The most used renewable energy sources, like wind turbines and photovoltaic installations, are characterized by high production volatility function of meteorological conditions [9]. Thus, for the safe operation of power systems balancing measures are required. In the last decade, with technological advances, energy storage systems are more and more diffused in distribution systems, at prosumer and energy community levels [10]. New market models are in place at low voltage level and distribution level such that to obtain most benefits from the integration of prosumers and energy communities in electrical networks.

A system dynamics-based project evaluation model for community developers to evaluate the success of proposed design or the renewable energy system supplying the community under variation of current conditions is formulated in Ref. [11]. The integration of multi-energy system and storage units to manage renewable energy sources in energy communities for minimizing the total costs in a residential district in Italy is investigated in Ref. [12]. A literature review of thermal energy communities considering solar and bio energy, as well as ambient conditions and air quality, is carried on in Ref. [13]. A multi-objective optimization model minimizing life cycle costs and environmental impact, maximizing use of renewable energy sources and social benefits for a residential community in Netherlands to facilitate transitions from low carbon buildings to positive energy ones is formulated and analyzed in Ref. [14]. An energy management system for a neighborhood community with hybrid energy storages, renewable energy sources, and demand-side controls to increase local renewable energy sources diffusion and mains supply independence in Hong Kong was proposed in Ref. [15]. The energy management strategy and profit allocation for an energy community in France for electricity bills reduction and economic benefits are proposed in Ref. [16]. An optimization model for determining the economic profitability and for sizing a photovoltaic installation for energy communities in Austria, as well as for upscaling the system to large scale energy community, is proposed in Ref. [17]. An optimization model for using the energy of a battery system in a cooperative environment to minimize energy costs while accounting for electricity prices is proposed in Ref. [18]. A photovoltaic and wind based hybrid system with various storage technologies for supplying a remote community in Australia are modeled and simulated under different configurations in Ref. [19]. Cost-effective combinations of wind energy systems and dispatchable load for improving the energy security in a rural community in Alaska are simulated and analyzed in Ref. [20]. An optimization model for designing and sizing a hybrid renewable energy system for supplying a desalination plant for supplying water to a small community in Saudi Arabia was elaborated and solved in Ref. [21]. Techno-economic analysis of a hybrid renewable energy system with storage installations supplying community loads and commercial loads under different sensitivity analyses was carried on in Ref. [22]. A peer-to-peer energy sharing framework consisting of hybrid renewable energy systems and grid connected consumers, with and without storage systems, is proposed in Ref. [23] demonstrating the energy savings and electricity bill reduction. An optimum capacity management framework generating profiles for the controllable generators and devices for clearing the electricity market in a local energy community is proposed and tested on a pilot site in Ref. [24]. The optimization of a hybrid system that contains a photovoltaic installation and generating units using biomass to supply a university campus was implemented in Ref. [25]. The sizing of a hybrid system consisting of photovoltaic panels, wind generators, batteries, fuel cells to supply critical and non-critical loads in a smart grid was analyzed in Ref. [26].

The integration and performance analysis of a 100% renewable energy system at community level is carried on in 30 cities in China in Ref. [27]. An optimization framework is formulated to obtain the optimal design of the full renewable energy sources supplied system.

The analysis of a sustainable energy investment for a residential aged care community in Australia, considering photovoltaic and battery storage installations under energy or demand tariffs, for typical days within a year was conducted in Ref. [28]. A modeling framework for optimally managing community microgrids with an internal market given the social-environmental-economic benefits is proposed and tested on a real case study in Ref. [29].

An innovative power sharing model of the energy produced from common sources for different residents of buildings and energy communities, where the N-1 users are passive towards the distributor and 1 user is acting as slack bus, is proposed in Ref. [30]. A stochastic optimization model to cope the uncertainties of renewable energy sources for day-ahead trading combined with an intra-day model for a local energy community is formulated and analyzed in Ref. [31]. A survey of energy communities characteristics and impact on power systems operation in Italy, like the interaction between communities and electricity markets and the need for blockchain technology for local markets, is conducted in Ref. [32]. A cooperative game for peer-to-peer trading to overcome volatility of renewable energy sources in local energy communities is proposed in Ref. [33]. Optimal business models for sustainable peer-to-peer energy trading for almost 1600 households in Germany, in particular cost-savings and financial benefits., are proposed in Ref. [34]. The important roles of the microgrids and blockchain technologies in energy communities' operation and trading considering the cybersecurity, the power system reliability and safe operation, the energy flexibility and cooperative market are highlighted and discussed in Ref. [35].

The energy management of a university campus in Romania under various electricity market strategies was investigated in Ref. [36]. A hybrid energy system proposed for a college in India considering the on-grid and off-grid operation was modeled and simulated in Ref. [37]. A renewable energy hybrid system operation at a university facility in Moroccan climate for different scenarios of hybrid system operation is conducted in Ref. [38]. The simulation of a distributed generation based smart grid at a university facility in India considering the integration of storage systems is conducted in Ref. [39]. The network data acquisition in a university campus containing a photovoltaic system, a storage system and different types of consumers, to reduce energy consumption and the transition to a smart grid is presented in Ref. [40].

This paper deals with an energy community project implemented in a real smart grid supplying a university campus. The university energy community has administrative buildings with accommodation facilities and lecture rooms electrically supplied by renewable energy sources (photovoltaic and wind energy installations), storage systems, Diesel generator, and interconnected with the upstream mains supply. The university energy community is operating for an entire university year. Modeling and simulation analyses were carried on for designing the elements suitable for

supplying the energy community and minimizing the costs. In addition, an upscaling of the production installations was carried for ensuring the possible islanding operation of the energy community. The optimization model is solved for minimizing the operating costs of the university energy community, but also to ensure supply security and power quality within the facility. The analysis is conducted considering the on-grid operation and off-grid operation during outages of the mains supply. Different case studies were simulated and validated with real-practice measurements. In addition, a real-practice installation was locally implemented and is supplying the community. A stochastic mathematical model was proposed, based on the real practice grid data, to maximize the benefits of the energy community participating in the electricity market considering the volatility of the electricity prices and the large increment occurring in Europe since the end of 2020. Five price scenarios, considering possible future increase of the energy price over the current value in Romania considering the political influences, were analyzed starting from the values registered on Romania electricity market. The paper addresses the current concerns of university campuses to find the most suitable solutions for the operation of small energy communities, at a minimum cost with a high level of power quality concomitant with the reduction of pollutant emissions.

1.1. Modeling and simulation of energy community within the university campus

The real-practice energy community at the university campus located in south-eastern part of Romania (Constanta) is schematically illustrated in Fig. 1. The top-view geographical image of the facility is illustrated in Fig. 2. The facility is composed of an accommodation building and a building with rooms for university teaching activities like course lectures and laboratories. The accommodation building has 24 rooms dedicated to student dormitories and 16 rooms for teachers hosting. The building dedicated to teaching activities has 17 rooms dedicated to courses and laboratories, accommodating more than 500 students.

The electrical layout illustrated in Fig. 1 is composed of a 5.1 kWp photovoltaic installation (21 panels supplying 3-phase inverters equipped with maximum power point tracking algorithms), a wind turbine designed for operating with low values of wind speeds, Diesel generator for supplying the critical loads during interruptions of the mains supply, an electrochemical storage system

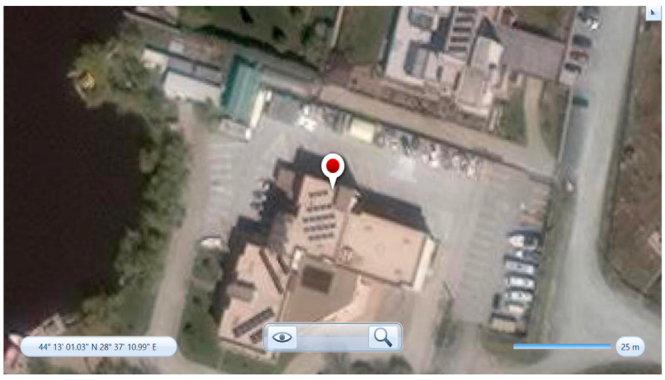

Fig. 2. Geographical top-view image of the energy community.

for storing the energy excess generated by the renewable energy in periods with low consumption, an automation electric panel equipped with programmable logic controllers for acquiring the main electrical parameters of the energy community supply system, as well as an interface with the mains supply registering the bidirectional power flows and allowing the islanding operation of the entire facility.

As illustrated in Fig. 2, photovoltaic installations are currently placed on the rooftop of the university budlings. Further developments will be carried on covering the entire roof surface with photovoltaic installations. Also, the location nearby the lake makes possible installing wind turbines [41,42].

1.2. Photovoltaic system

The photovoltaic (PV) installation is composed of 21 polycrystalline photovoltaic panels of 245Wp. The PV installation is equipped with 3-phase inverters to ensure three balanced, sinusoidal currents are injected in the internal network of the energy community within the university campus. The inverters are equipped with maximum power tracking algorithms and have the possibility for on/off grid operation of the panels. An islanding inverter is operating as “master” and controls all inverters used in the facility. Fig. 3 shows the average of solar radiation at the point of monitoring at the university energy community.

The modeling expression of the photovoltaic system:

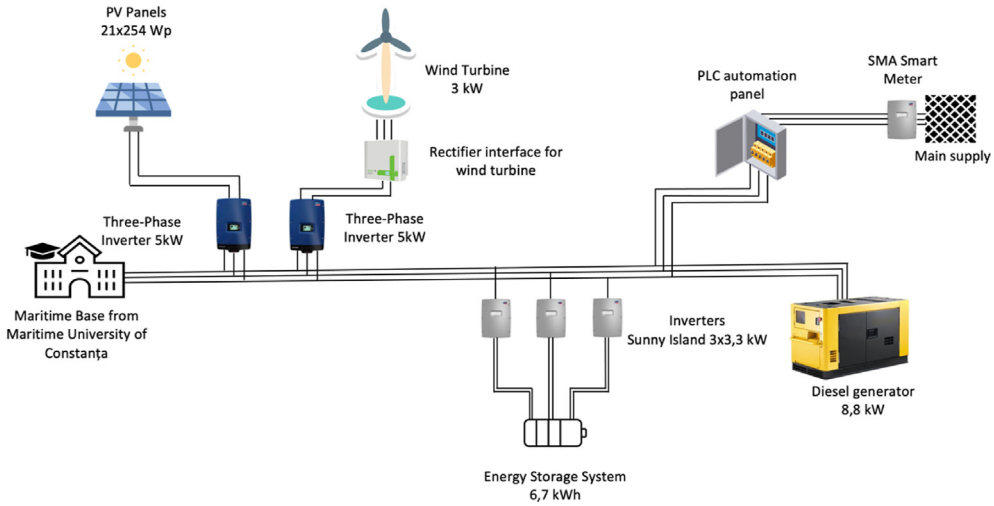

Fig. 1. Layout of the energy community at university campus in Constanta.

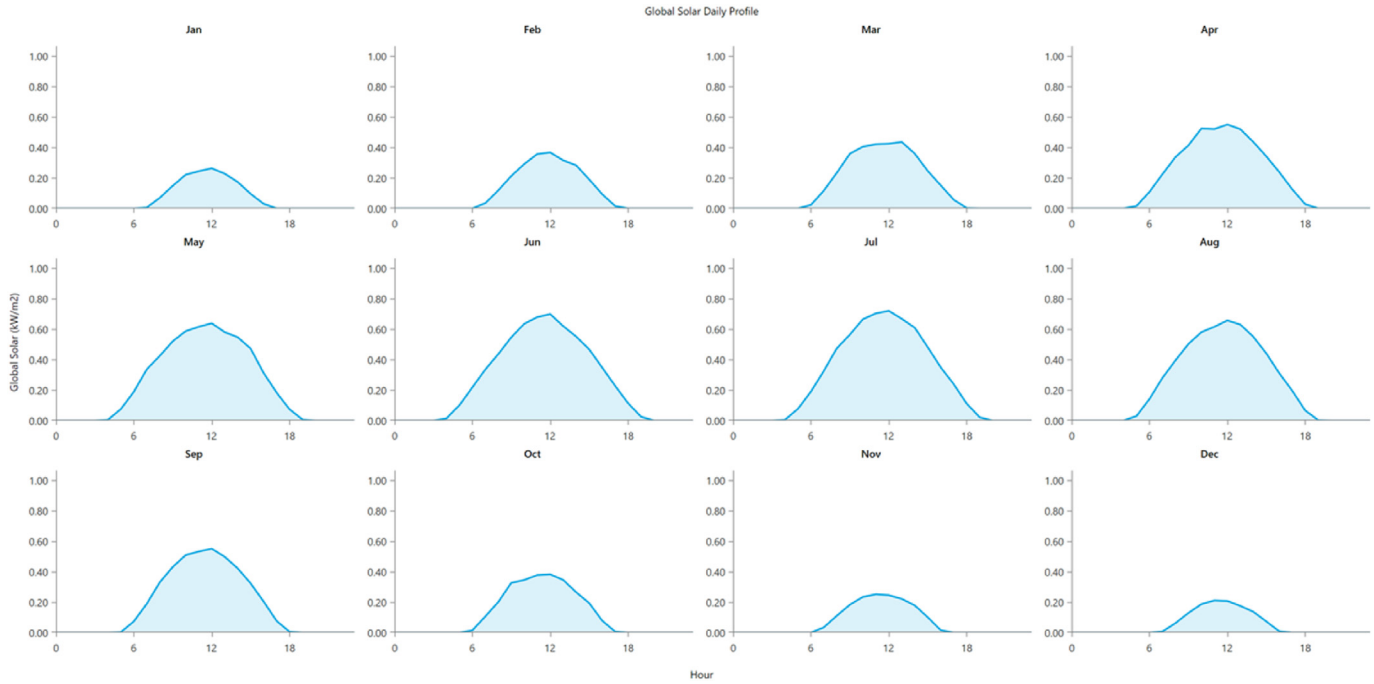

Fig. 3. Solar radiation for the university energy community.

$$P_{PV} = P_{DC,STC} \cdot DF_{PV} \cdot \left(\frac{G_T}{G_{T,STC}}\right) \cdot [1 + \alpha_p (T_{PV} - T_{PV,STC})] \quad (1)$$

where $P_{dc,STC}$ [kW] represents the DC power of the array calculated by adding each module ratings under standard test conditions; DF_{PV} [%] accounts for inverter efficiency, dirty collectors, mismatched modules, and differences in ambient conditions, losses in DC and AC wiring, impact of partial shading; G_T [kW/m^2] is the global solar radiation incident on the surface of the PV array; $G_{T,STC}$ [kW/m^2] is the solar radiation incident under STC conditions [1 kW/m^2]. The coefficient α_p [%/°C] indicates the relationship between the power produced by the PV system and the temperature on the surface of the PV panel. This coefficient has a negative value because the power produced by the PV system decreases with increase of cell temperature. During the night, the temperature of the PV cell is the same as the ambient temperature, but in daylight, the cell temperature can exceed the ambient temperature by 30 °C or more. The temperature of the PV system in the current time step is T_{PV} and $T_{PV,STC}$ represents the temperature of the PV system in standard test conditions [25 °C].

The real production of PV panels is recorded and continuously stored with a sampling of 1 min. For simulation processes, the recorded measurements are aggregated each interval of 15 min.

1.3. Wind system

The wind system is composed of a single wind turbine of 3 kW supplied with 230 V. Currently a single wind turbine is placed to evaluate the potential of using wind turbines with PV panels. Fig. 4 illustrates the variation of yearly production with the wind speed. As it can be seen in Fig. 5, the turbine reaches the maximum power generated for the wind speed of about 12 m/s. The wind turbine is mounted on a support pole at a height of 13 m. The value of the wind speed and direction is measured by a meteorological station for the analysis of the wind turbine efficiency. Fig. 6 shows the

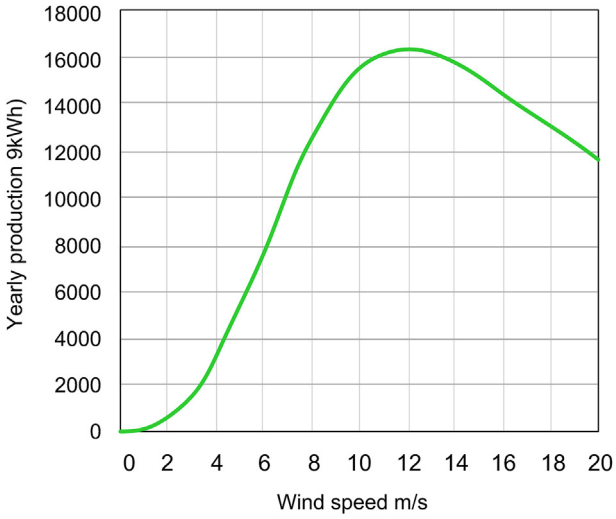

Fig. 4. Diagram for the estimated amount of energy produced by the wind turbine.

variation of the average monthly wind speed, measured at 10 m height above ground level.

The wind speed at the hub height is:

$$v_{hub} = v_{anem} \cdot \left(\frac{H_{hub}}{H_{anem}}\right)^{\alpha} \quad (2)$$

where v_{hub} [m/s] is the wind speed at the hub height, v_{anem} [m/s] is the wind speed at the height of the anemometer, H_{hub} [m] represents the hub-height of the wind turbine, H_{anem} [m] is the anemometer height, and α is the power law exponent (equal to 1/7) [43]. The height of the anemometer is the height at which the wind speed data is measured. The wind speed tends to increase with the increasing of the height from the ground, so if the height of the hub

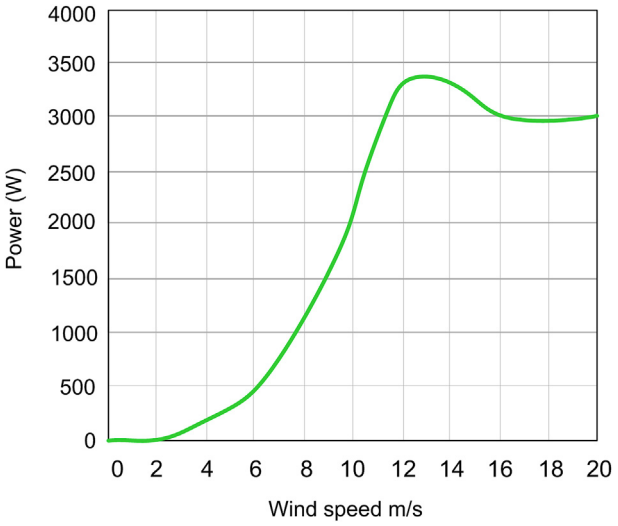

Fig. 5. Wind turbine performance diagram.

is not the same as the height of the anemometer the wind speed data is adjusted.

After determining the wind speed at the hub height, the estimated power of the wind turbine at the estimated wind speed under standard conditions of temperature and pressure is calculated. The power generated by the wind turbine for the actual meteorological conditions is expressed as:

$$P_{WT} = P_{WTG,STP} \cdot \left(\frac{\rho}{\rho_0}\right) \tag{3}$$

where P_{WT} [kW] is the power produced by the wind turbine, $P_{WT,STC}$ [kW] is the power produced by the wind turbine under standard temperature and pressure conditions, ρ [kg/m^3] is the current air density, and ρ_0 [kg/m^3] is the air density under standard temperature and pressure conditions.

1.4. Diesel generator

The back-up generator is water-cooled and fueled with diesel, delivering the electrical energy through a three-phase connection for supplying critical loads during outages in the mains supply. The variation of fuel consumption with produced power can be usually modeled with a first order or a second order expression. In this paper, a first order expression is used.

The fuel consumption of the generator in units/h depending on the power produced is:

$$B = b_0 \cdot P_{nom} + b_1 \cdot P_{gen} \tag{4}$$

where b_0 [monetary units/kWh] is the no-load fuel consumption, b_1 [monetary units/kWh] the first-order fuel-power variation coefficient, P_{nom} [kW] is the rated capacity of the generator, and P_{gen} [kW] is the power output of the generator. The analysis is conducted considering the 1 h time step of operation of the generator, as it considered to operate in critical cases.

The efficiency of the generator, η_{gen}, is defined as the electrical energy produced divided by the chemical energy of the fuel used:

$$\eta_{gen} = \frac{3.6 \cdot P_{gen}}{\dot{m}_{fuel} \cdot LHV_{diesel}} \tag{5}$$

where $\dot{m}_{fuel}$ [kg/h] is the fuel mass flow rate, LHV_{diesel} [MJ/kg] represents the lower heating value of diesel fuel.

1.5. Energy storage system

The energy storage system is based on Li-Ion technology. The battery is used in the energy community of the university campus for absorbing renewable energy sources eventual production

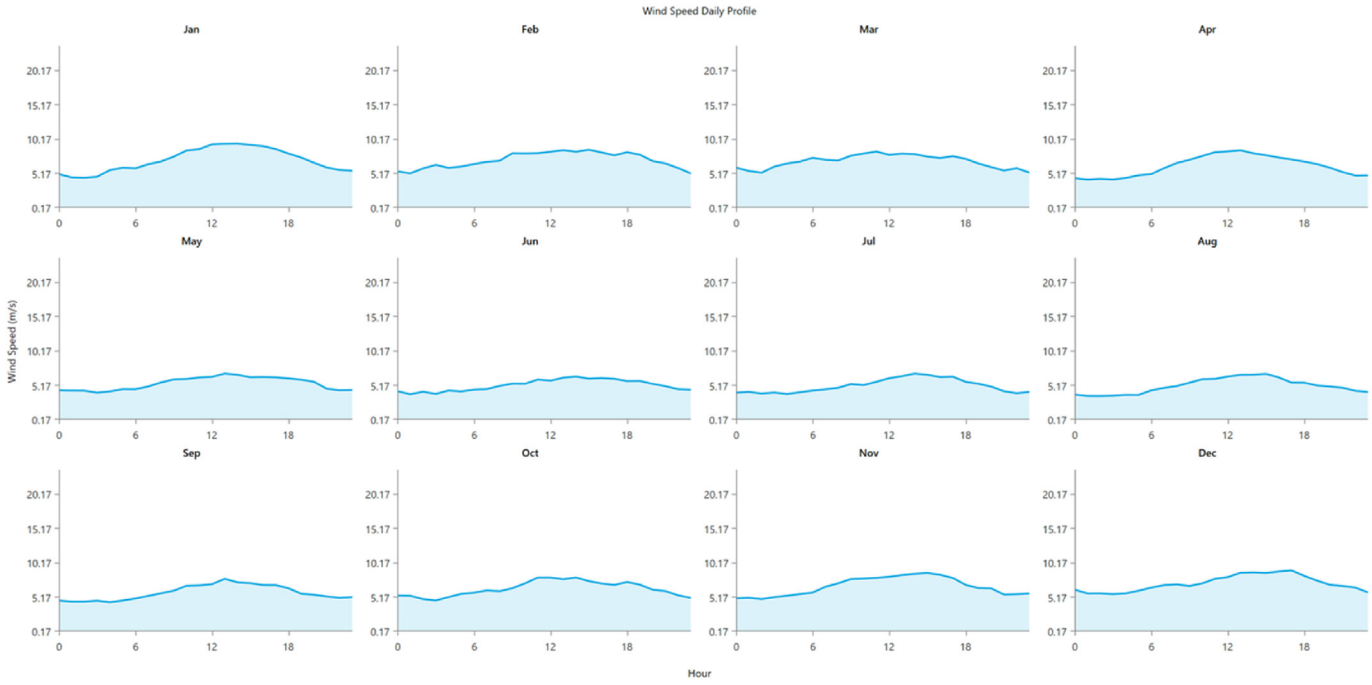

Fig. 6. Wind speed variation at the monitoring point at university energy community.

surplus, for discharging during short-interruptions and voltage sags occurring in the internal network, for balancing the fluctuations of renewable energy sources production fluctuations.

The maximum battery charging power is expressed as:

$$P_{bat,ch,\,max} = \frac{k \cdot E_0 \cdot e^{-k \cdot \Delta t} + E \cdot k \cdot c \cdot \left(1 - e^{-k \cdot \Delta t}\right)}{1 - e^{-k \cdot \Delta t} + c \cdot \left(k \cdot \Delta t - 1 + e^{-k \cdot \Delta t}\right)} \quad (6)$$

where E_0 [kWh] is the battery available energy at the beginning of the time step, E [kWh] is the total energy of the battery at the beginning of the time step, c is the ratio of the storage capacity, k [h^{-1}] is the storage rate constant, and Δt is the time step.

The maximum charging rate of the battery is expressed as:

$$P_{bat,ch_{rate},\,max} = \frac{\left(1 - e^{-\alpha_c \cdot \Delta t}\right)(E_{max} - E)}{\Delta t} \quad (7)$$

where α_c [A/Ah] is the maximum charging rate of the storage system, and E_{max} [kWh] is the battery total storage capacity.

The maximum battery discharging power is expressed as:

$$P_{bat,disch,\,max} = \frac{-k \cdot c \cdot E_{max} + k \cdot E_0 \cdot e^{-k \cdot \Delta t} + E \cdot k \cdot c\left(1 - e^{-k \cdot \Delta t}\right)}{1 - e^{-k \cdot \Delta t} + c\left(k \cdot \Delta t - 1 + e^{-k \cdot \Delta t}\right)} \quad (8)$$

The maximum charging and discharging rates of the battery are considered equal. The charging and discharging powers of the battery are adjusted with battery efficiency.

1.6. University community demand

The consumption of the University Maritima of Constanta (UMC) integrates the consumption of the university community, together with the student accommodation and administrative activity of the university. The university community is an energy community because it has the possibility to inject the surplus electrical energy generated from renewable energy sources into the main grid [44,45].

The energy consumption in November 2020 was 4392 kWh resulting in an average of 147 kWh/day, a low consumption according to the current pandemic period. This period is chosen as a full university month period, with low temperatures in the seaside region of Romania, but with sunny days. The teaching processes in the university during the pandemic period in the Romanian universities were done remotely on-line, the students possibly being in the accommodation facilities.

Fig. 7 shows the demand profile of the university community for a representative day in each month. As it can be seen, the maximum consumption is during the evening, when master students have the classes or returned to the accommodation.

1.7. Mains supply interface

A bidirectional smart meter is equipping the interface unit between the university community and the distribution system operator. The meter recorda the exchanged flows among these entities. In addition, the logic controller records parameters of the university community internal network (both production and consumption). Also, it can determine the islanding operation of the university community. Secure operation and electromagnetic compatibility analyses are required for safe operation of this ensemble.

2. Optimization model for the university energy community

The university energy community can use the electrical internal network equipped with renewable energy sources and storage systems to maximize the benefits of energy utilization. The exchange flows within the grid and with the external mains can be optimized such that to fulfill securing the energy supply for the entire community and to obtain the financial benefits in using the electrical energy within the community.

A mixed-integer linear programming model is formulated for maximizing the benefits of using and exchanged energy with the mains. The optimization model is solved for a real energy community within a university campus. The university campus is located on the seaside area of Romania in vicinity of a lake, where the wind conditions are favorable for the wind energy production and photovoltaic installations can be placed on the rooftops of the university buildings. The uncertainties in the production from renewable energy sources were investigated in Ref. [46], where different scenarios of the production of renewable energy source (photovoltaic installation) were considered. Thus, considering the large variations of the electricity prices in Europe occurring in the last years, a stochastic optimization model for accounting the variations, through statistical scenarios with certain probability, of the electricity prices which highly impact the administrative operation of a university campus was proposed and implemented.

2.1. Renewable energy sources

The energy production of the renewable energy sources is depending on the meteorological conditions, respectively solar irradiation and wind speed. Their production is registered through whole year and represents an input of the mathematical model.

2.2. Diesel generator

The integration of the diesel generator operation in the optimization model is based on minimizing the fuel consumption function of output power (expression 4) and of the fact that can be in operation or not during a certain period. The output power state being modeled with a binary variable $u(t)$:

$$u(t) \cdot P_{gen}^{min} \le P_{gen}(t) \le u(t) \cdot P_{gen}^{max} \quad (9)$$

where P_{gen}^{min}, P_{gen}^{max} are the minimum, respectively the maximum, output powers of the diesel generator. The transition between the possible states of the diesel engine determines costs associated to startup C^{SU} and shutdown C^{SD} cases:

$$\begin{aligned} &C^{SU}(t) \ge S^U \cdot (u(t) - u(t-1)),\ C^{SU}(t) \ge 0 \\ &C^{SD}(t) \ge S^D \cdot (u(t-1) - u(t)),\ C^{SD}(t) \ge 0 \end{aligned} \quad (10)$$

where S^U and S^D are the involved costs associated with the startup and shutdown processes.

2.3. Energy storage system

The integration of the energy storage system into the optimization model is based on the energy available in the battery to be delivered within the energy community to support its operation, as well as for minimizing system operation costs and maximizing the benefits of the energy community. The state-transition expression for the energy level $E_{bat}(t)$ is:

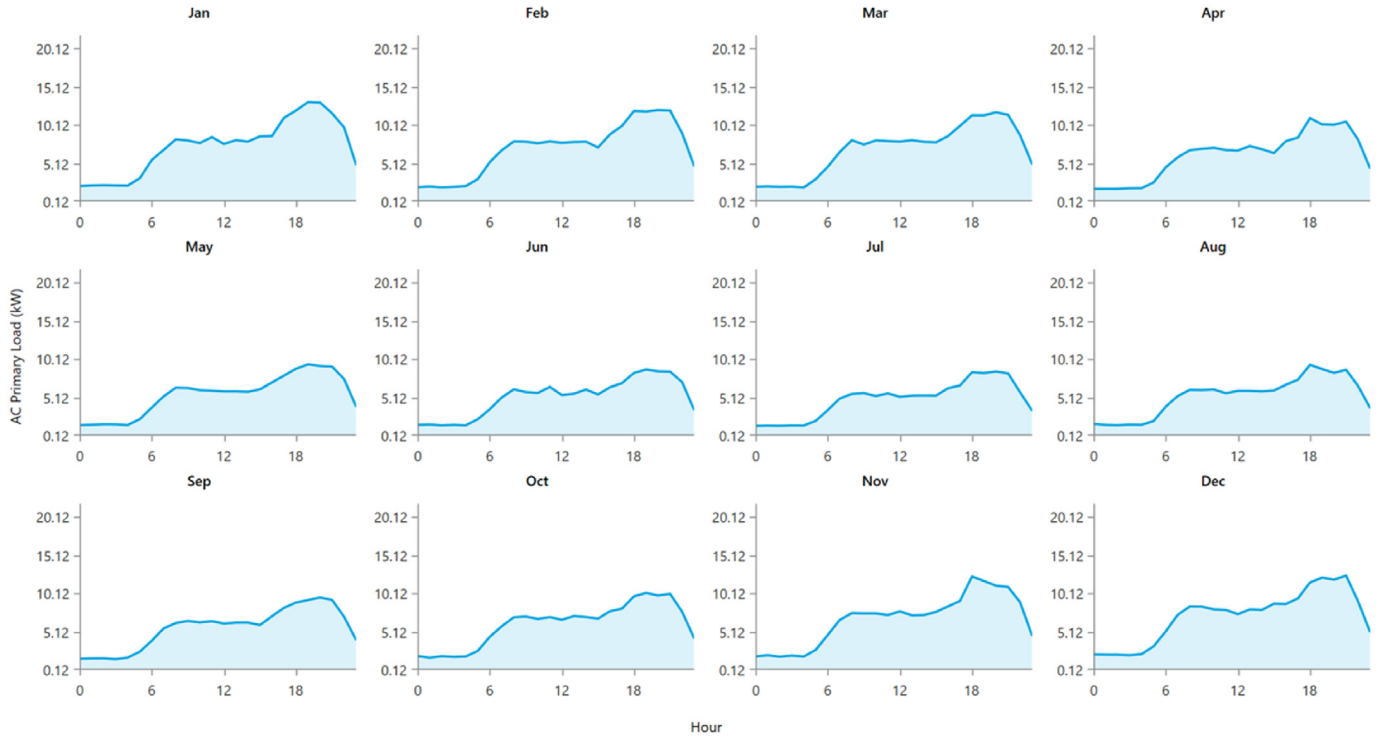

Fig. 7. Load profile of the university community.

$$E_{bat}(t) = E_{bat}(t-1) + P_{bat,ch}(t) \cdot \eta - \frac{P_{bat,disch}(t)}{\eta} \tag{11}$$

The conversion efficiency η is lower than 1. The charging and discharging power are limited by their maximum values.

2.4. Loads

In the energy community, the loads are electrically supplied from the mains grid as well from the internal smart grid equipped with renewable energy sources. The use of electrical energy is a requirement for the excellent functioning of the university facility to reach the objective of high-level education and training of future engineers. The daily energy consumption should be adjustable function of daylight, external temperature, internal temperature air conditioning set-point, as well as function of university holidays and national days. Thus, there is a percentage of consumption that can be adjusted and optimized for reducing the operation costs and for maximizing the profits. Based on recorded energy consumption values, it is considered that maximum 40% of the load can be adjusted and daily optimized to lead to maximizing the economic benefit of the facility.

The power demand $P_{load}\ (t)$ of the load is limited by the minimum and maximum values

$$P_{load}^{min}(t) \le P_{load}(t) \le P_{load}^{max}(t) \tag{12}$$

and the daily consumption $E_{load}(t)$ should be bounded by minimum and maximum values:

$$E_{load}^{min}(t) \le E_{load}(t) \le E_{load}^{max}(t) \tag{13}$$

The modeling of the load is based on the registered consumption during the same characteristic day in 2019. The consumption daily profile is illustrated in Fig. 7.

2.5. Equilibrium expression

During the 8760 h within a year, the equilibrium between production and consumption must hold, considering also the possible exchanged energy with the mains supply:

$$\begin{aligned}&\left(P_{gen}(t) + P_{PV}(t) + P_{Wind}(t) + P_{bat,disch}(t)\right) \cdot 1 \\ &= \left(P_{load}(t) + P_{mains}(t) P_{bat,ch}(t)\right) \cdot 1\end{aligned} \tag{14}$$

2.6. Objective function

The objective function is maximizing the profit associated with the operation during one year, considering the electricity price of the exchanged energy with the mains supply and the benefit of using energy for teaching rooms and laboratories. In the last year, large scale variation of the electrical energy price occurred, and compensation measures are in place today for overcoming the electricity costs impact on rural areas.

The stochastic modeling of the entire operation was considered and the objective function of the stochastic problem was expressed as:

$$\begin{aligned}[\mathrm{MAX}]\, f = \sum_{t=1}^{N} \sum_{sc=1}^{5} p_{sc} \cdot \{&\pi(t,sc) \cdot P_{mains}(t) - B(t,sc) + \pi(t,sc) \\ &\cdot P_L(t,sc) - SU(t,sc)\}\end{aligned} \tag{15}$$

where p_{sc} are the different probabilities associated with stochastic evolution of electricity price and $\pi(t,sc)$ is the electrical energy price.

3. Results and discussion

The generators and equipments within the university community were acquired in an university research project for smart energy and sustainable development. The modeled and simulated network is illustrated in Fig. 8. The data regarding solar radiation and meteorological parameters measured for the analyzed area are collected from the local meteorological stations and from the NASA Prediction of Worldwide Energy Resource. After implementing the smart grid, the optimal solution for system costs, operation and sizing is determined. The layout of the energy community is presented in Fig. 8.

The objective for analyzing the university community is:

1. Minimizing the net present costs considering the lifetime period of the generators and the fact the facility has an approximately regular consumption during this period, being used for students teaching and accommodation.
2. Maximizing the benefits of energy community under a stochastic optimization model.

Simulations were carried on for on-grid and islanding operation, minimizing the costs and supplying the loads such that the classical generators are economically dispatched and renewable energy sources are delivering energy to the storage system and towards the mains. The wind speed within the university community is varying through the year between 5 and 10 m/s, with a yearly average value of 7 m/s. The solar power production has a typical hill-shape characteristic, with a maximum during summer periods.

The multistep procedure illustrated in Fig. 9 was elaborated to assess the performance of the university community in various operating conditions. The procedure contains two phases: the first one starts from consumption data and meteorological parameters and establishes the optimal solution minimizing the operating costs, and the second one was carried on for a viable configuration acquiring real-practice measurements.

3.1. Minimizing the net present costs

3.1.1. On-grid operation of the university community

The analysis is carried on considering the generators and equipments with characteristic data reported din Table 1. The costs associated with the operation of the university campus during the lifetime of the equipments (20 years analysis) is 41 kEuro.

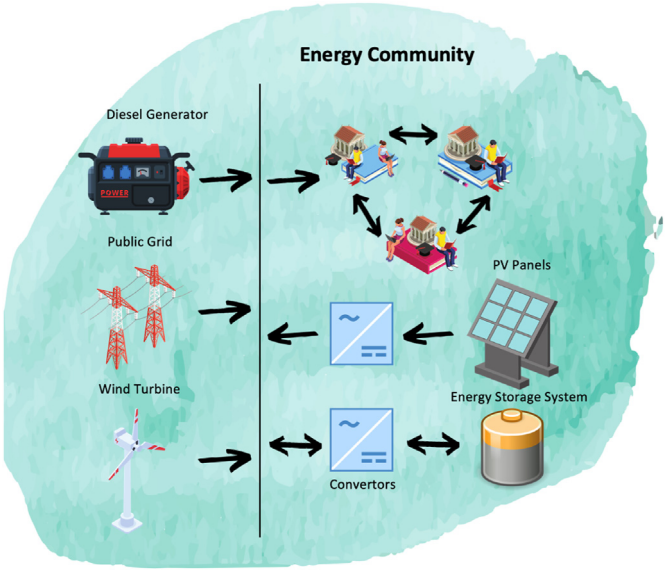

Fig. 8. Layout of the energy community.

Fig. 10 illustrates the variation of supplied demand (blue) and possible load shedding (red). There are periods when the demand is not supplied. In this case, the installation of other types of elements, with higher capacities, must be considered to cover the entire demand in case of an Off-Grid operation. The load shedding presented in Fig. 10 highlights the necessity for upscaling the existent system to have a monetary benefit and to supply all demands with minimum costs. Fig. 11 shows the variation of the power generated by the photovoltaic panels (brown) and the wind turbine (green) together with the demand of the smart grid (black). The variation of power produced by the Diesel generator (magenta) compared to the load (black) is illustrated in Fig. 12. Fig. 13 illustrates the operation of the storage system together with the production of the photovoltaic system (orange) and the wind system (green). At the top of Fig. 13 it can be seen the charging power of the storage system (blue), and at the bottom the state of charge (turquoise). It can be seen the days with clear sky, when the production of the photovoltaic installation is maximum and the days with cloudy sky when the production of PV system is lower.

3.1.2. Islanding operation of the university community

In this case, the analysis is carried on considering the islanding operation of the university campus. This determines the development of renewable energy sources such that to balance the load demand with minimum costs, as well as storing the surplus for further use during load peak periods. For balancing the load demand during day and night periods, with minimum costs, the installation of 50 kWp of photovoltaics, 15 kW of wind generation, diesel generator of 8.8 kW, and storage system of 67 kW are required. The minimum costs associated with this solution for the whole lifetime of the project is 30 kEuros. The characteristic data of the generators are reported in Table 2.

3.1.3. Upscaling of the university community

The second analysis deals with optimizing the university community for increasing renewable energy sources generation and reducing the energy imports from the main supply, reducing greenhouse gas emissions. Thus, 50 kWp of photovoltaic panels and 15 kW of wind turbines are in the process of installation to balance the imports from the main supply and inject the surplus in the upstream grid, as reported in Table 2. The optimized analysis revealed that, considering for the injected electrical energy the average electricity price of ~40 Euro/MWh, a benefit of 7 kEuro will be obtained. Considering the fluctuating electricity price on the spot market, this benefit can even be much higher, also considering the incentives for installing renewable sources towards reaching the Green Deal goals.

Fig. 14 shows the variation of the power generated by the photovoltaic system (brown) and the wind turbine (purple) together with the load of the smart grid (black). Fig. 15 illustrates the variation of energy consumed from the main grid (blue), the amount of undelivered energy (red) and the amount of energy sold (green) by UMC operating as a prosumer. The are no customers disconnected. The amount of energy that is sold to the grid is economically calculated in order that the prosumer can benefit the most out of it (see Table 3).

3.1.4. Comparison of cases 1, 2 and 3

Analyzing the simulation results, Table 4 reports the objective function values for each analyzed case.

In case study 1, the system has the highest operating costs because it is undersized and the is purchased from the public grid.

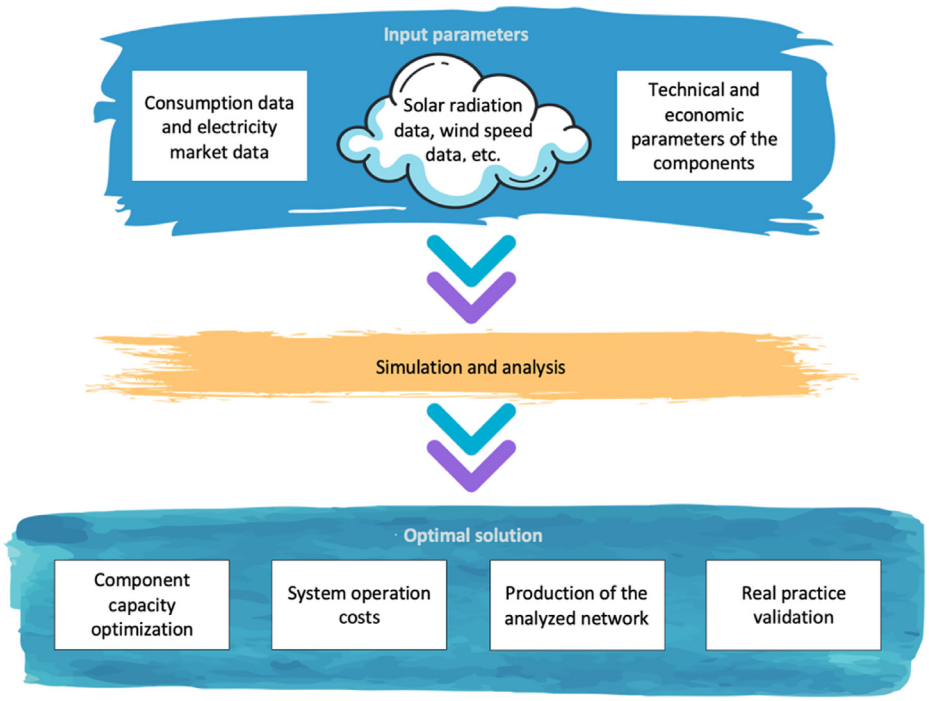

Fig. 9. Simulation and experimental procedure flowchart.

Table 1
Characteristic data of the university community generators for on-grid operation.

Component	Characteristic Data
Wind Turbine	3 kW
Photovoltaic Panels	5.1 kWp
Energy Storage System	6.74 kWh
Inverters	19.9 kW
Diesel Generator	8.8 kW

In the case study 2, the system is islanding operating, thus no electrical energy is purchased from the public grid. Investments in generating units for supplying the whole demand are required. In the case study 3, the network is resized considering the available space and the surplus energy from renewable sources is injected into the public grid, as illustrated in Fig. 16.

3.2. Maximizing the benefits

The electricity market price variation was settled based on the registered values in Romania during 2020. The data are available on the electricity market operator website and gives a price signal for the electrical energy supplied to the final users of retail market. The yearly and hourly price values were managed and aggregated resulting in five scenarios of electricity prices, each scenario with a

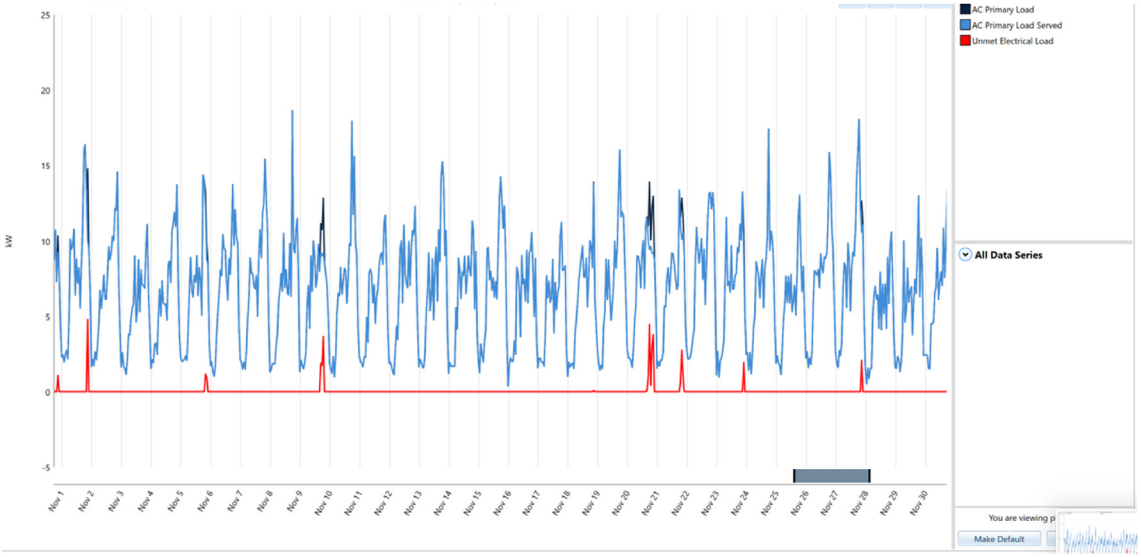

Fig. 10. Variation of supplied demand (blue) and possible load shedding (red).

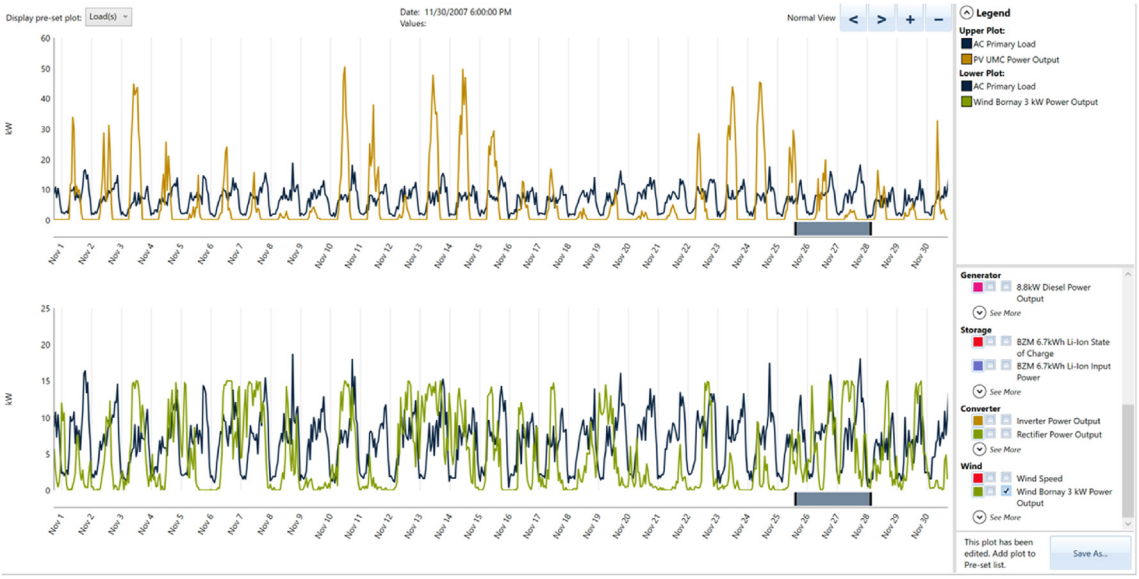

Fig. 11. Variation of power generated by the photovoltaic system and the wind turbine compared to the load.

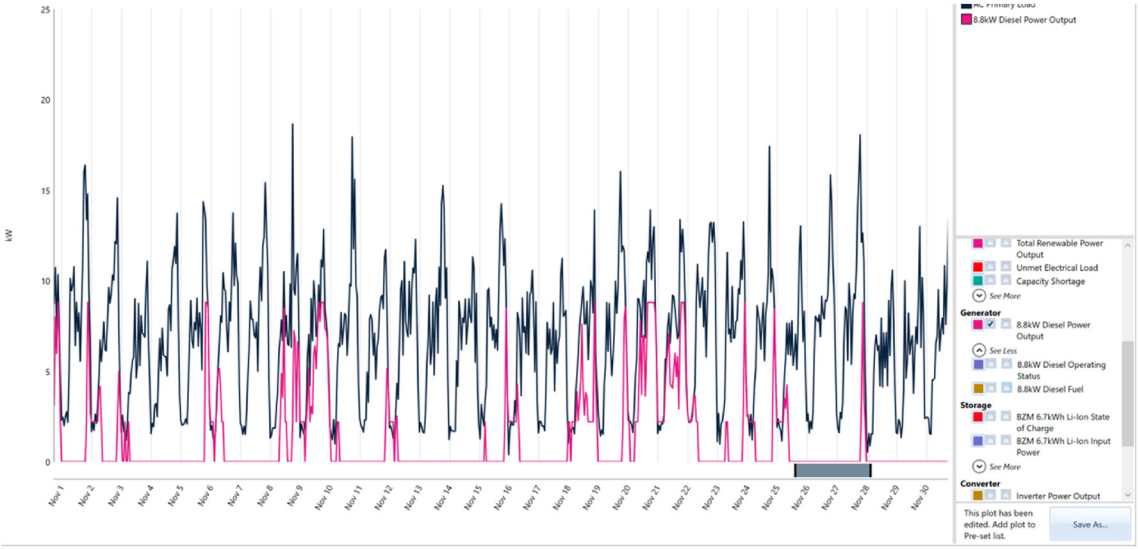

Fig. 12. Variation of the power produced by the Diesel generator compared and the load.

determined probability. The assigned probabilities were $p_1 = 0.1$, $p_2 = 0.15$, $p_3 = 0.2$, $p_4 = 0.25$, and $p_5 = 0.3$.

The hourly variation of the electricity price, for 24 h and in each scenario, is illustrated in Fig. 9. As it can be seen scenario 5 is the most critical one with large values of the electricity price and, given the current evolution of electricity prices in Europe, has the higher probability. As shown, the electricity price follows the current trend of variation where the highest values are occurring during the evening, typical for a residential consumption. The electricity prices represent an input for the optimization problem.

The production from renewable energy sources is highly dependent on the meteorological conditions and a high degree of uncertainty should be considered [47]. However, it is considered that ethe renewable energy sources production is known, and it aggregates the production of the photovoltaic installation and wind generator. As shown in Fig. 17, the production follows the typical production of photovoltaic installation, with a maximum production reached at midday. The production from renewable energy sources represents an input for the optimization problem (see Fig. 18).

Solving the optimization model delivers the exchanged power with the mains supply and the load consumption for 24 h. In addition, the storge system operation has high impact on the operation of the university energy community.

Fig. 19 illustrates the exchanged power with the mains supply. As it can be seen, during short periods, the energy community acquires from the electricity market and during the night it acquires energy from the mains. In most of the times, the community is exchanging energy flows towards the mains supply. This exchange towards the mains is resulting from the local production exceeding the consumption, the surplus being injected into the mains. The local production is sustained from the renewable energy sources and from the diesel generator.

Fig. 20 shows the load consumption variation during the 24 h.

Fig. 13. Variation of the power produced by the photovoltaic system and the operation of the storage system.

Table 2
Characteristic data of the university community generators for islanding operation.

Component	Characteristic Data
Wind Turbine	15 kW
Photovoltaic Panels	50 kWp
Energy Storage System	67.4 kWh
Diesel Generator	8.8 kW

Table 3
Development of the energy community.

Component	Characteristic Data
Wind Turbine	15 kW
Photovoltaic Panels	50.16 kWp
Inverters	46.7 kW

The values of the load are highly dependent on consumption scenario and the variation diagram is highly characteristic for a residential consumer. The results are obtained from the optimization model such that the energy community has the maximum benefit for the analyzed scenarios.

Fig. 21 illustrates the variation of storage charging power. As shown, the storage system is charging during the night period in all scenarios, as well as during afternoon in scenario 2. Fig. 22 shows the variation of the discharging power and the evolution in 24 h. As shown, the battery is discharging towards the end of the day.

4. Power quality in the university community

The power quality measuring campaign was done with the help of power quality analyzers that acquire data in real time.

The variation of the electrical current on each of the three-phase

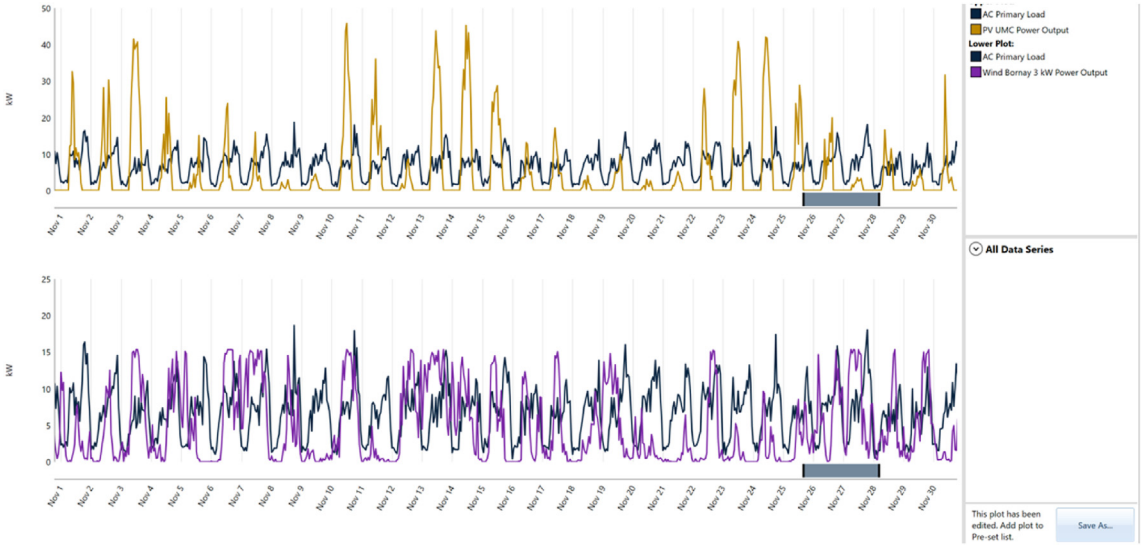

Fig. 14. Variation of the power generated by the photovoltaic panels and the wind turbine compared to the load.

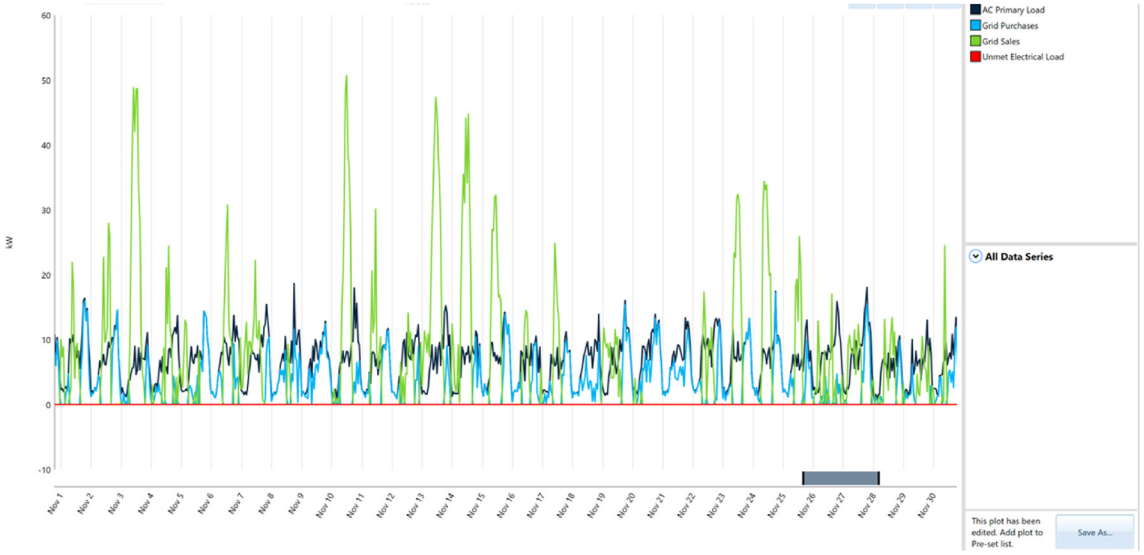

Fig. 15. Variation of the energy sold and consumed from the public electricity network together with the non-supplied consumption.

Table 4
Value of the objective function for the analyzed cases.

Case analyzed	NPC [Euro]
1	41 354
2	30 671
3	−7049

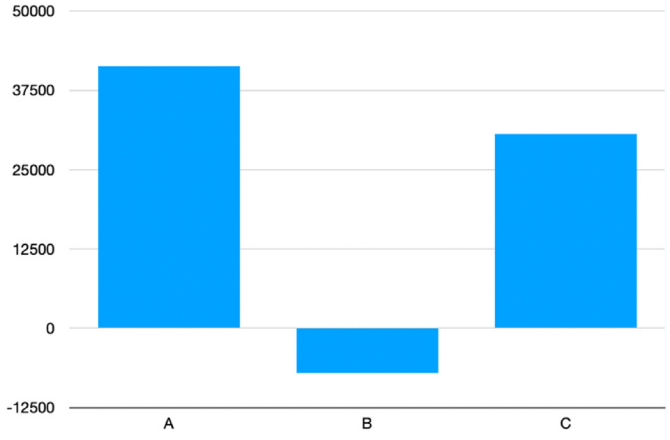

Fig. 16. Costs in each simulated case study.

system in the energy community, during a cloudy day from April, is illustrated in Fig. 23. As shown, the main energy production is determined by the photovoltaic system, highlighting the characteristic production curve of a PV system. The current harmonics follow the trend of variation of the electric current injected by the photovoltaic system. These harmonics have been measured in the internal network of university campus, and their amplitude is attenuated to the point of common coupling (PCC) with the public grid, without causing problems regarding the management of harmonic distortion. The variation of the total harmonic current distortion has a shape in opposition to the current produced by the photovoltaic installation (see Fig. 24). Starting from the definition expression of the total harmonic distortion *THDI* as:

$$THDI = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \tag{16}$$

where I_h is the harmonic component of the electric current and I_1 is the fundamental component of the electric current, it can be observed that the minimum value of *THD* is obtained for a maximum value of the current injected by the photovoltaic installation. It should be noted that the maximum values of THD are recorded at the beginning, respectively at the end, of the production period of the photovoltaic installation. This is determined by the fact that the photovoltaic installation is just starting to produce, respectively ending its production, the value of the fundamental electric current harmonic being very small during these periods.

5. Conclusions

The European Green Deal Package aims to achieve electricity production in Europe by 2050 without pollutants emissions. The need to reduce the impact on the environment, the existence of financial incentives for the integration of renewable sources (photovoltaic panels), the digitalization of the energy sector and the desire of university campus users to reduce electricity costs led to the emergence of “smart” campuses.

The analysis carried on this paper validates through simulations the structure of university energy community at the Maritime Base of Constanța. Renewable and conventional sources with fossil fuels (used in case of a fault or Off-Grid operation) are supplying the load demand. Different cases of network operation with variation of input parameters are conducted starting from real case data. The simulation demonstrates the correct operation of the entire system in different operating strategies: On-Grid and Off-Grid operation, as well as upscaling of the entire system. The importance of the university campus to operate as an energy community is highlighted and an optimization model is formulated for maximizing their benefit in participating in the electricity market under various stochasticity of the electricity price.

The operation of the energy community must fulfill secure and safe supply of the consumers in grid connected mode, as well as in islanding operation. Hence, ensuring power quality represents an

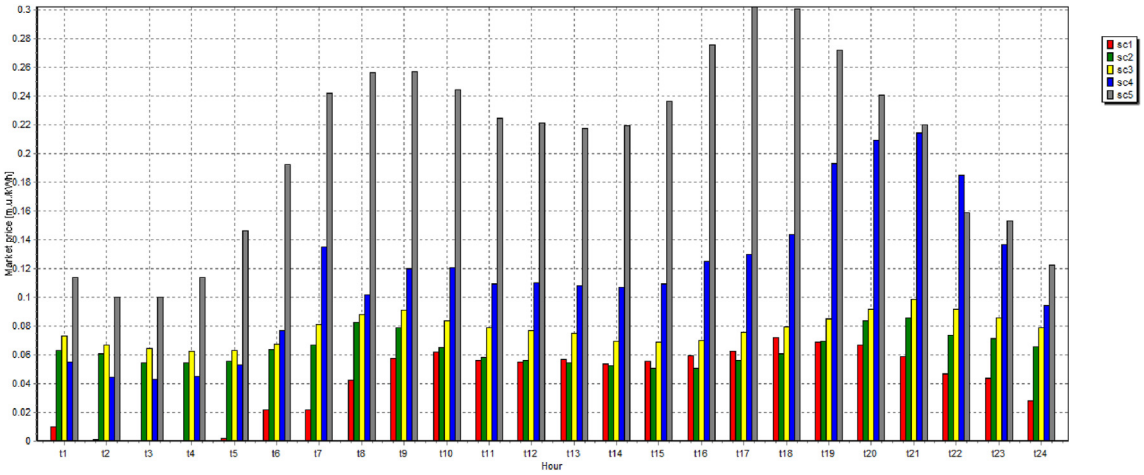

Fig. 17. Variation of the electricity price in each considered scenario.

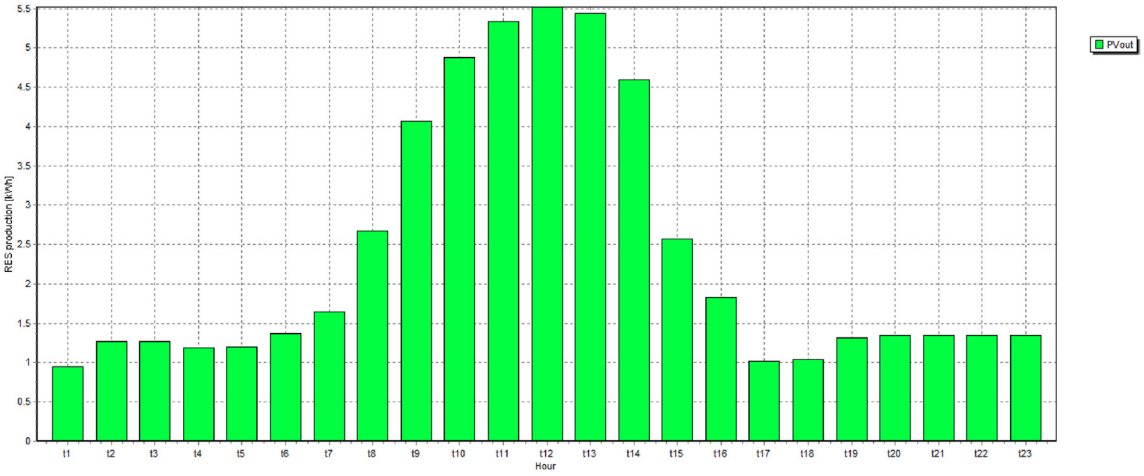

Fig. 18. Variation of the renewable sources production.

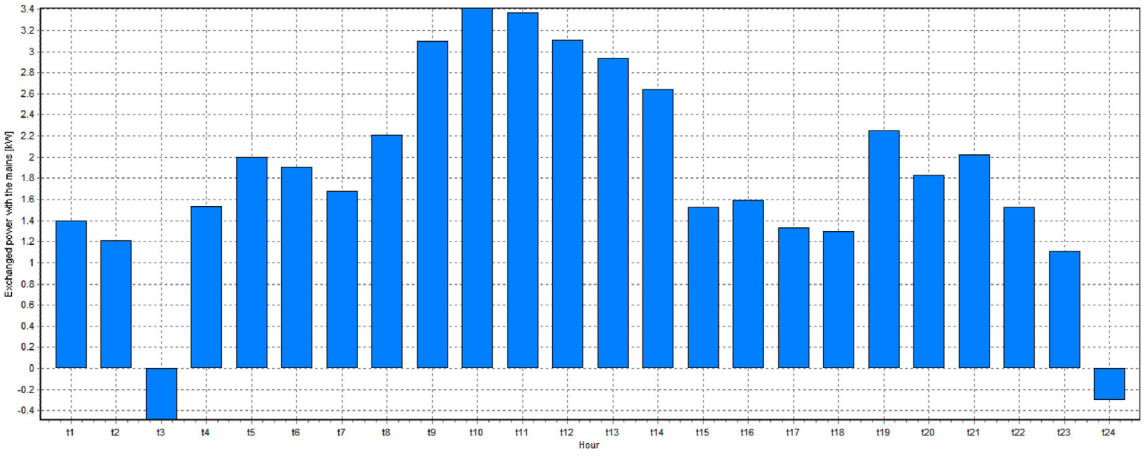

Fig. 19. Variation of exchanged power with the mains.

important task that needs to be controlled locally. Monitoring and controlling the harmonics generated by the converters, as well as the unbalance possibly occurring in the three-phase network due to single-phase generators or consumers need to be carefully addressed to not lead to power losses or damages of the equipments.

The holistic analysis conducted on this university energy community with renewable energy sources and optimizing its

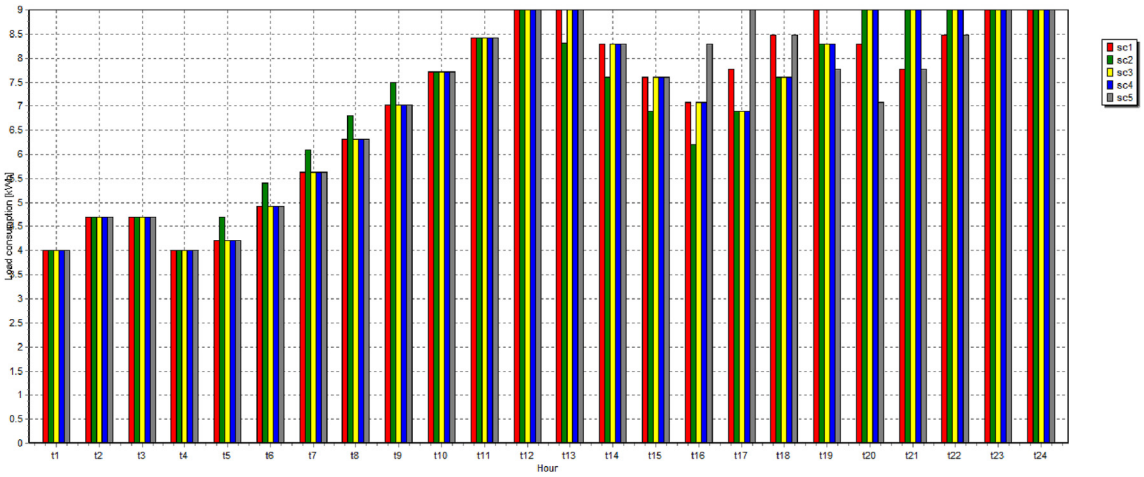

Fig. 20. Variation of the load consumption.

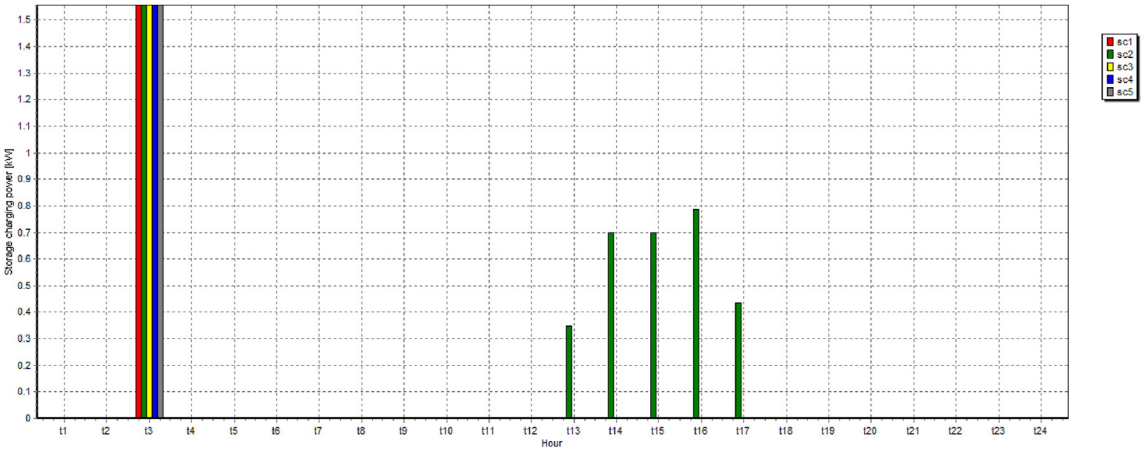

Fig. 21. Variation of the storage system charging power.

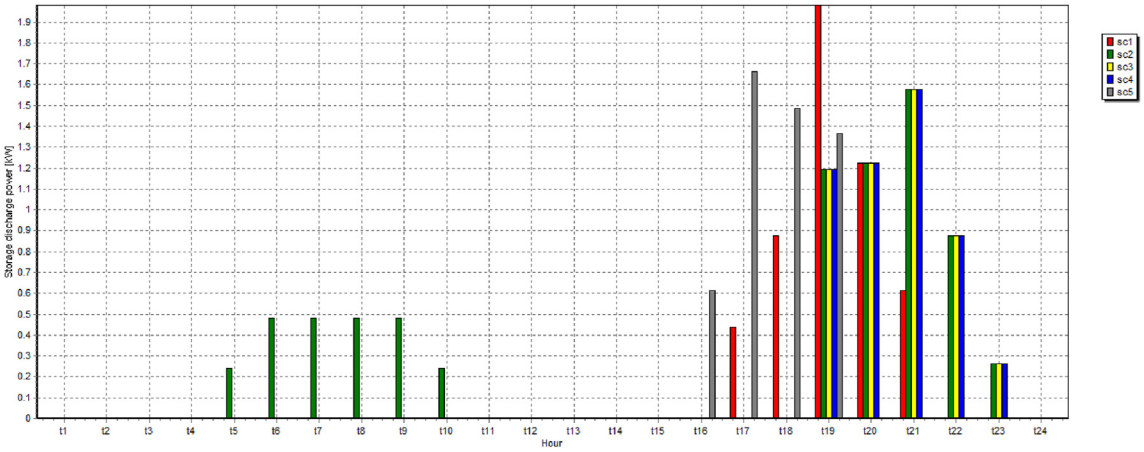

Fig. 22. Variation of the storage system discharging power.

operation can be extended and applied to other university campuses, where energy savings and economic benefits can be obtained. The optimization model is formulated for maximizing their benefit in participating in the electricity market under

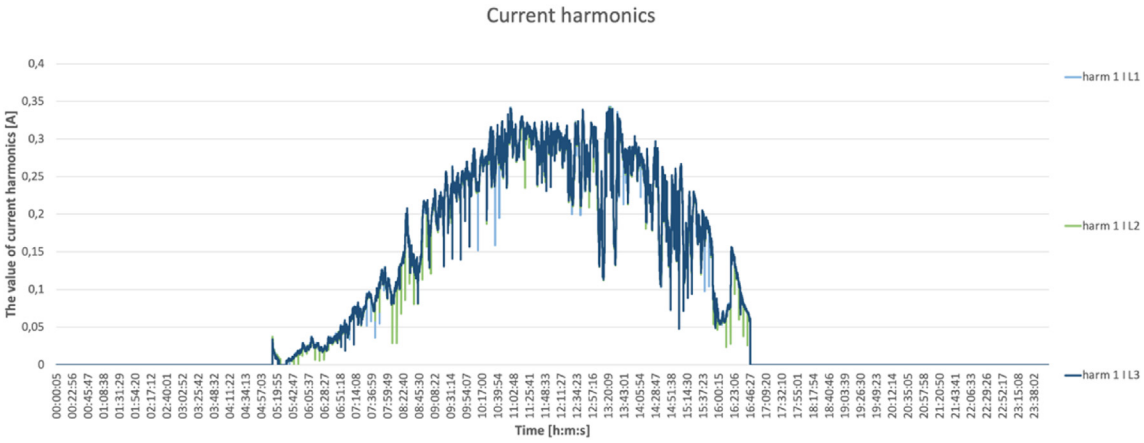

Fig. 23. The variation of the 50 Hz electric current on the three phases in April.

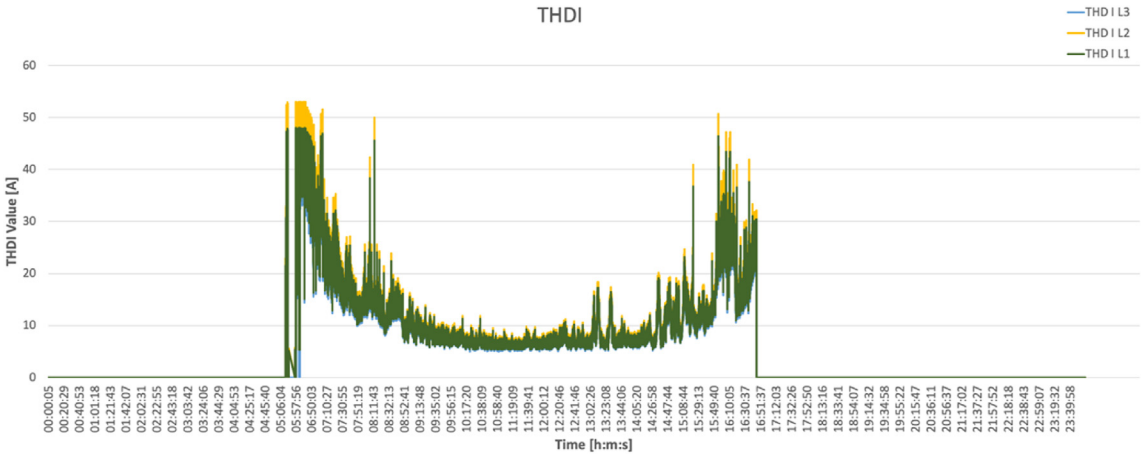

Fig. 24. Variation of the total harmonic current distortion on the three phases in April.

stochastic variation of the electricity price. The energy community analysis is carried on a university campus, which represents a timely case study from administrative and educational point of views.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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