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# Maximizing renewable energy and storage integration in university campuses

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ABSTRACT

The worldwide demand increase and climate change constraints are leading to integration and maximization of renewable energy sources (RESs) share in the energy production. This represents a key aspect to reduce the pollutant emissions and facilitate the transition to a cleaner future. Many agreements and incentives were discussed and imposed in order to limit the fossil fuel use and thus reducing the pollutant emissions to limit global warming. With this considerations, the renewable energy sources are installed with continuous share increase. To support this implementation and used simultaneously with providing a power reserve for these intermittent power sources, energy storage systems are becoming more and more used and necessary. Simultaneously with these changes, hydrogen is becoming more and more used, being a means by which electricity can be produced without generating greenhouse gas emissions (GGE). A power supply system with multiple sources is presented and its operation is analysed, the system contains photovoltaic panels, wind system, fuel cell, hydrogen generator, electricity and hydrogen storage system to supply the consumption of a student dormitory from a university campus in Romania with prosumer possibilities.

## 1. Introduction

To achieve new sustainability and climate resilience solutions, university campuses are installing multi-source test systems for analysing and improve energy solutions in order to innovate the domain. Due to the worldwide demand increase and climate change, the integration and maximizing the share of renewable energy sources (RESs) is also increasing to reduce de dependence on fossil fuels. The development of new renewable energy sources is mainly determined by necessity to limit environmental pollution from fossil fuels and increase of energy consumption simultaneous with economy development. Global initiatives and agreements set aim to limit global warming 2 or preferably 1.5 °C, making the comparison with the pre-industrial situation [1]. To achieve this goal the reduction in pollutant emissions and the use of fossil fuels is imposed. These limitations are set through different initiatives and agreements worldwide, Paris Agreement or Green Deal European Package [2], African Renewable Energy Initiative [3] etc., thus the increase in RESs share is proof of putting into practice the reductions in polluting emissions and dependence on fossil fuels imposed.

In Fig. 1 the worldwide evolution regarding the share of RESs from 2000 to 2023 is presented. The presented data is based on International Renewable Energy Agency (IRENA) [27] statistics. It can be observed that with the passage of time the RES share is increasing from year to year, in 2023 reaching 43 %.

In Fig. 2 the worldwide share of RESs sorted by types is shown. It can be seen that the hydroelectric power, has a high share at the beginning of the 2000s and decreases slightly as the energy produced from photovoltaic and wind systems increases taking a more substantial share. The wind systems gradually increase over time starting with 2 % in 2000 and reaching 26 % in 2023 while the share of photovoltaic systems is 0 % from 2000 to 2004, but rapidly increase from 2005, reaching in 2023, 37 % share. Bioenergy maintains a relatively constant share over the years (around 4–5%), keeping the value almost constant compared to wind systems or solar systems. The tidal and wave energy has not yet reached a significant level of contribution to the global RES

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mix. In the year 2023, it can be observed that a percentage of 37 % energy from photovoltaic systems, 33 % energy from hydro plants, 26 % energy from wind systems and 5 % bioenergy will be reached, marine energy being very little used. The largest part is occupied by solar systems, being much easier to install and integrate due to the possibility of location and without being dependent, for example, like wind systems, on areas with high wind potential, they can also be used in cities, on the roof the buildings, usually unused surfaces.

The system presented in this paper is located in Romania, at a university campus. The share of RESs in Romania is presented in Fig. 3. In can be seen that Solar, Wind and Hydro occupies 61% of the total share. Considering this aspect, through various research and European projects, it is desired to increase the capacity installed in RESs simultaneously with the decrease in the use of fossil fuels and production of pollutant emissions on the electricity production domain. Considering this aspect, the current article focuses on increasing the share of RESs in Romania, encouraging their installation or the resizing of already existing systems in order to increase the share of different green energy sources.

The integration and maximizing of the RESs share is done to reduce polluting emissions from the energy sector due to the increase in consumption. Consumers can be of different types, can be industrial, residential, commercial, institutional or agricultural, universities falling under industrial consumers.

Most university campuses have a considerable energy consumption and dense infrastructures being able to serve as an opportunity for sustainable energy management. Many universities have implemented, through research projects or own funds, systems with multiple generation sources to cover their own consumption and inject surplus energy into the network for a monetary benefit.

The universities have an important contribution in finding and implementing solutions for decarbonization of the urban consumption, as their continuous development and enlargement require installation of RESs for electrical and thermal supply. In addition, the integration of electric vehicles require installing charging stations also within universities, with higher impact on the existing electrical infrastructure. A review of the existing strategies towards reducing carbon emissions in university campuses is conducted in Ref. [4]. In Table 1 different university campuses systems with different sources that have been studied wide world are presented. In each case the used generation source, classical or renewable, is reported. These papers analyse a multi-source RES system to ensure a continuous and reliable power supply concomitant with maximizing RES share to achieve clean energy use concomitant with the reduction of dependence on fossil fuels.

The system proposed within this paper contains and integrates different generation sources that are usually difficult to be analysed in a holistic approach. The proposed system contains: PV system, Wind System, Fuel Cell, Hydrogen Generator, Hydrogen Storage, and a Diesel Generator all being integrated, and their operation observed.

In comparison with the systems reported in Table 1, the contribution of this paper is the integration of multi-sources system, maximizing their share and the observation of their functioning as a unitary whole. The presented system supplies the consumption of the student dormitory and works as follows: the diesel generator, the wind system, the fuel cell, the storage system and the photovoltaic (PV) system can supply the required consumption, the connection with the public grid is also made. The hydrogen generator can charge the hydrogen storage system and also the fuel cell when there is a surplus of energy that is not injected into the public grid, the fuel cell can supply the consumption when needed. The energy storage system (ESS) can be charged from the wind system, the PV system and the fuel cell addressing the intermittent characteristic of the RESs sources. ESS stores surplus energy during peak production periods when injection into the public supply network of the surplus energy generated is not possible (for example during a period of off-peak load during the day) and releases it during peak load periods. In addition, the consumer can function as a prosumer. By harnessing the synergies of PV systems, wind system, storage technologies, including hydrogen generation and fuel cells, this research outlines a blueprint for energy autonomy and efficiency in an educational setting.

## 2. Analysed renewable energy based system

The analysed system is located in Romania, at a university campus, and feeds the consumption of a student dormitory with an average of 100 kWh/day. The system can operate as a prosumer gaining a monetary benefit for the power surplus injected back to the grid and also can cover its own consumption through the power sources installed, with the priority of feeding the primary load. Lower-priority objectives, such as charging the storage system or powering the interruptible load, are left to renewable energy sources. The generator can continue to increase the generated power and sell energy to the grid if it is economically advantageous [28].

The components of the analysed system were purchased through a research project which supports the intelligent development in the field of energy. In Table 2 the installed capacity of the components is reported.

The current system is undersized to be able to support itself or sell the surplus back to gid. This article presents and proposes the extension of the existing system, and the proposed maximization is shown in Table 3.

In Fig. 4 the simplified diagram of the analysed system is presented. The energy from the public grid, diesel generator, wind turbines, and PV panels can be used by the student's accommodation. Energy surplus, from RESs, can be used to generate hydrogen through an electrolyzer, which can then be stored. The fuel cell can convert stored hydrogen back into electricity when needed. Also, the surplus can be injected back to the public grid thus obtaining a monetary benefit.

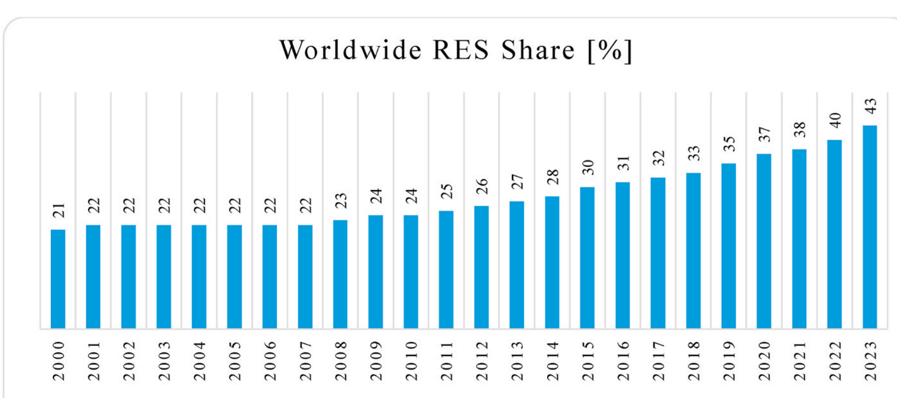


**Fig. 1.** Worldwide RESs share of total generation sources.

## 3. Mathematical modeling of the analysed system

The objective function of the mathematical model (1) is represented by the net present cost (NPC), the optimal solution is chosen by the lowest net present cost. The NPC is the present value of all the costs of installing and using the system over the project life-time, minus the present value of all revenues earned over the same project life-time which is considered to be 20 years [29], and can be expressed as:

$$[MIN]C_{NPC} = \sum_{componente} \frac{C_{ann,tot}}{CRF(i, R_{proj})} \tag{1}$$

where $C_{ann,tot}$ is the total annual cost, $i$ is the annual discount rate, $R_{proj}$ is project lifetime, and $CRF$ is the capital cost recovery factor.

$$CRF(i, R_{proj}) = \frac{i(1+i)^{R_{proj}}}{(1+i)^{R_{proj}} - 1} \tag{2}$$

### 3.1. PV system

The Power produced by the PV System can be expressed as:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\overline{G}_T}{\overline{G}_{T,STC}}\right) \bullet \left[1 + \alpha_p (T_C - T_{C,STC})\right] \tag{3}$$

Modelling the effect of temperature on the PV system is considering the characteristic data of the system. In (3), the terms are: $Y_{PV}$, in kW, is the nominal capacity of the PV system, specifically its power under standard test conditions (STC); $f_{PV}$ [%] is the power reduction factor that takes into account the actual operating conditions of the PV system, factors such as dirt, cable losses, shading, snow cover, aging, etc. ; $\overline{G}_T$[kW $/m^2$] is the incident solar radiation under STC conditions [1 kW/$m^2$]; $\alpha_p$[%/°C] is the power coefficient of the temperature of the PV system indicates the relationship between the power produced by the PV system and the temperature of the PV cell, more precisely the surface of the PV panel. This coefficient has a negative value because the power produced by the PV system decreases with the temperature increase. At each time moment, $\overline{G}_T$[kW $/m^2$] the global solar radiation incident on the surface of the photovoltaic panel is calculated. In this paper $f_{PV} = 80$ % and polycrystalline photovoltaic panels are used for which the average value of the coefficient $\alpha_p = -0.48$ [%].

The temperature of the PV cell is equal to the surface temperature of the PV panel if it is not partially shaded. At night, the PV cell temperature is the same as the ambient temperature, but in broad daylight, the cell temperature can exceed the ambient temperature by 30 °C or more. $T_C$[°C] denote the temperature of the PV system in the current time interval and $T_{C,STC}$ the temperature of the PV system under STC conditions (25 °C).

PV panel manufacturers evaluate the power produced by PV modules under standard test conditions (STC): radiation of 1 kW/m2 at cell temperature of 25 °C and no wind. STC conditions do not reflect typical operating conditions, since the temperature of a PV system that is reached by direct solar radiation is much higher than 25 °C.

### 3.2. Wind turbine

The power produced by the wind turbine is calculated at each time point by calculating the wind speed for the hub-height, the height of the hub is 13m. After that the power produced by the wind turbine at the current wind speed, at the standard value of the air density is calculated and in the end output power value for the actual air density is adjusted.

The wind speed at nacelle height is calculated with:

$$U_{hub} = U_{anem} \bullet \left(\frac{Z_{hub}}{Z_{anem}}\right)^{\alpha} \tag{4}$$

where $U_{hub}$ $[m/s]$ is the wind speed at the hug-hight, $U_{anem}$ $[m/s]$ is the wind speed at the anemometer hight, $Z_{hub}$ is the hub height (in this paper it is considered $Z_{hub} = 13$ m), $Z_{anem}$ [m] is the anemometer height (in this paper it is considered $Z_{anem} = 10$ m), $\alpha$ is the exponent of the calculation process.

Wind speed tends to increase with height above the ground, so if the wind turbine nacelle height is not the same as the anemometer height the wind speed data is adjusted.

After determining the wind speed at the height of the hub, the estimated power of the wind turbines is calculated at the estimated wind speed under standard conditions of temperature and pressure according to the power curve of the wind installation. Power losses of the wind turbine are neglected. As a rule, the power curve of the wind installation is made at standard temperature and pressure (STP) conditions. To

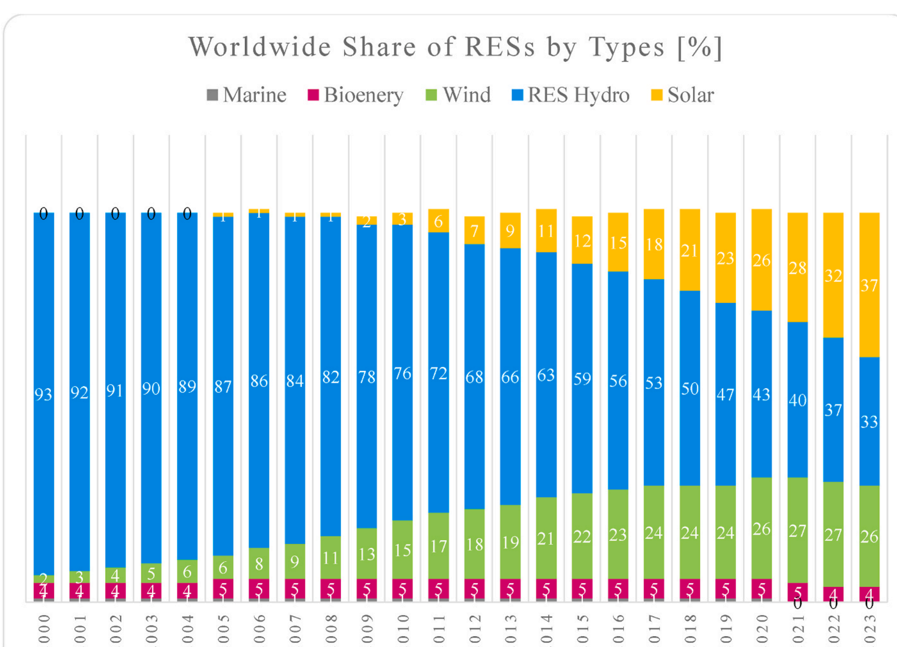


**Fig. 2.** The worldwide share of RESs sorted by sources types.

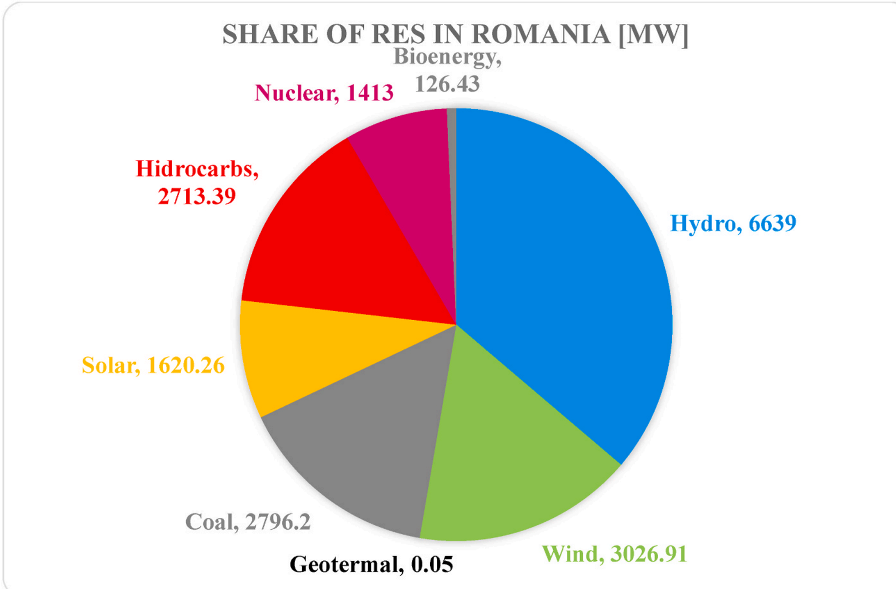


**Fig. 3.** The share of RESs integration in Romania.

**Table 1**
University campuses multi-source systems.

| Country | Year | Generation Sources Installed | Ref. |
| --- | --- | --- | --- |
| USA | 2016 | Coal, Gas, Nuclear, Hydro, Solar | [5] |
| Sweden | 2017 | Fuel cell, Reciprocating Engine, heat pump, Wind System, PV System | [6] |
| Italy | 2019 | PV System | [7] |
| Sweden | 2019 | Micro-combined heat and power, PV System, Energy Storage System | [8] |
| Ireland | 2019 | PV System, Wind System | [9] |
| Spain | 2020 | PV System | [10] |
| Portugal | 2020 | PV system Li-Ion energy storage system | [11] |
| Cyprus | 2021 | PV System, Wind System, Biomass, Energy Storage System | [12] |
| Japan | 2021 | Biomass | [13] |
| Hong Kong | 2021 | Energy Storage System, Hydrogen Vehicle Storage | [14] |
| Canada | 2021 | Biomass, PV System, Wind System | [15] |
| Nigeria | 2021 | Hydrogen Fuel Cell, PV System | [16] |
| Romania | 2021 | PV System, Wind System, Diesel Generator, Energy Storage System | [17] |
| USA | 2022 | Hydrogen, Hydro, Geothermal, Solar, Biomass, Wind | [18] |
| Italy | 2022 | Geothermal System, PV System, Heat Pump, Energy Storage System | [19] |
| China | 2022 | PV System | [20] |
| Nigeria | 2022 | Diesel Generator, Wind System, PV System, Energy Storage System | [21] |
| Mexico | 2022 | PV Solar Bus Shelter System | [22] |
| Saudi Arabia | 2022 | PV System, Wind System, | [23] |
| Italy | 2023 | Hydro, PV System, Biomass | [24] |
| Turkey | 2023 | Biomass | [25] |
| Australia | 2023 | PV System, EV Charging Station | [26] |

adjust the power generated by the wind installation for real conditions, the value of the power forecast according to the power curve is multiplied by the air density ratio, according to the following expression:

$$P_{WTG} = \left(\frac{\rho}{\rho_0}\right) \bullet P_{WTG,STP} \tag{5}$$

where $P_{WTG}$ $[kW]$ is the power generated by the wind turbines, $P_{WTG,STP}$ $[kW]$ is the power generated by the wind turbines in STP conditions, $\rho\left[kg/m^3\right]$ is the actual air density, $\rho_0\left[kg/m^3\right]$ is air density in STP conditions $\rho_0 = 1.225\left[kg/m^3\right]$.

**Table 2**
The components of the existing system.

| Component | Installed Capacity |
| --- | --- |
| Wind Turbine | 3 kW |
| Photovoltaic Panels | 5.04 kW |
| Energy Storage System | 6.74 kWh |
| Convertors | 19.9 kW |
| Diesel Generator | 8.8 kW |
| Hydrogen Generator | 0.4 kW |
| Hydrogen Storage | 0.02 kg |
| Fuel Cell | 10 kW |

**Table 3**
The proposed sizing of the analysed system.

| Component | Installed Capacity |
| --- | --- |
| Wind Turbine | 3 x 3 kW |
| Photovoltaic Panels | 200 kW |
| Energy Storage System | 11 x 6.74 kWh |
| Convertors | 56.8 kW |
| Diesel Generator | 8.8 kW |
| Hydrogen Generator | 0.4 kW |
| Hydrogen Storage | 0.1 kg |
| Fuel Cell | 1280 kW |

### *3.3. Diesel Generator*

The power of the Diesel generator is fixed and the data of the generator does not change. The generator fuel curve calculation describes the amount of fuel consumed to produce electricity [29]. The fuel consumption of the generator in units/h depending on the power produced is:

$$F = F_0 \bullet Y_{gen} + F_1 \bullet P_{gen} \tag{6}$$

Where $F_0$ $[units/h/kW]$ is the intersection coefficient of the fuel curve, $F_1$ $[units/h/kW]$ is the slope of the fuel curve, $Y_{gen}$ $[kW]$ is the rated capacity of the diesel generator, and $P_{gen}$ $[kW]$ is the power generated by the diesel generator.

The efficiency of the generator considered in this paper refers to the

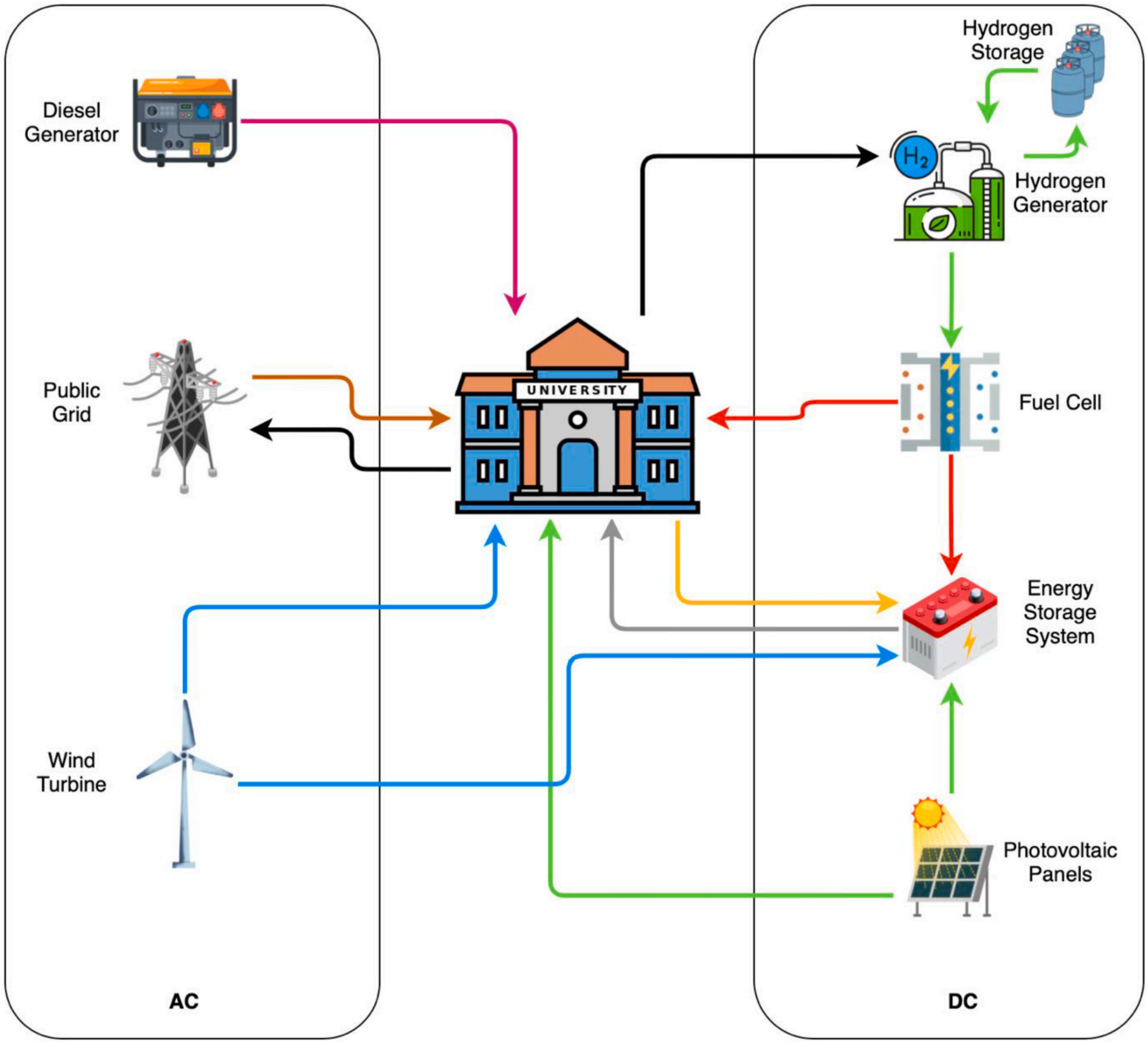


**Fig. 4.** The analysed system.

electrical energy produced divided by the chemical energy of the fuel used and is given by:

$$\eta_{gen} = \frac{3.6 \bullet P_{gen}}{\dot{m}_{fuel} \bullet LHV_{fuel}} \tag{7}$$

where $\dot{m}_{fuel}[kg/h]$ is fuel mass flow rate, $LHV_{fuel}[MJ/kg]$ – lower calorific value of the fuel (as energy value). The fuel mass flow rate depends on $F$ (generator fuel consumption), but the exact relationship depends on the fuel unit. If the fuel unit is kg, then $\dot{m}_{fuel}$ and $F$ are equal. If the fuel unit is the liter (l), the relationship between $\dot{m}_{fuel}$ and $F$ includes the fuel density $\rho_{fuel}[kg/m^3]$ is:

$$\dot{m}_{fuel} = \rho_{fuel} \bullet \left(\frac{F}{1000}\right) \tag{8}$$

### 3.4. Energy storage system

At each point in time, the maximum amount of energy that the storage system can absorb is calculated. The charging power varies from time to time depending on the charging status and charging/discharging history of the storage system. Three separate constraints are imposed on the maximum load power of the storage system. The first constraint refers to the maximum amount of power that can be absorbed by the storage system as:

$$P_{bat,cmax,cmp} = \frac{kQ_1 e^{-k\Delta t} + Qkc\left(1 - e^{-k\Delta t}\right)}{1 - e^{-k\Delta t} + c\left(k\Delta t - 1 + e^{-k\Delta t}\right)} \tag{9}$$

where $Q_1$ $[kWh]$ is the energy available in the storage system at the beginning of the time period, $Q$ [kWh] is the total amount of energy in the storage system at the beginning of the time period, $c$ is the storage capacity ratio, $k$ $[h^{-1}]$ is the storage rate constant, and $\Delta t$ is the time period.

The second constraint concerns the maximum charging rate of the storage system [A/Ah]. The charging power of the storage system corresponds to the maximum charging rate is:

$$P_{bat,cmax,rm} = \frac{\left(1 - e^{-\alpha_c \Delta t}\right)(Q_{max} - Q)}{\Delta t} \tag{10}$$

where $\alpha_c$ $[A/Ah]$ is the maximum load rate of the storage system, and $Q_{max}$ $[kWh]$ is the total system storage capacity [29].

The third constraint concerns the maximum charging current of the storage system. The maximum charging power of the storage system corresponding to the maximum charging current is [29]:

$$P_{bat,cmax,cm} = \frac{N_{batt} I_{max} V_{nom}}{1000} \tag{11}$$

where $N_{batt}$ is the number of batteries in the storage system, $I_{max}$ $[A]$ is the maximum charging current of the storage system, and $V_{nom}$ is the nominal voltage of the storage system.

The maximum charging power of the storage system is:

$$P_{bat,max} = \frac{MIN\left(P_{bat,cmax,cmp}, P_{bat,cmax,rm}, P_{bat,cmax,cm}\right)}{\eta_{batt}} \tag{12}$$

The charging efficiency is denoted by $\eta_{batt}$.

At each time point, the maximum amount of energy (13) that the storage system can discharge is calculated. The maximum discharge power varies at each point in time depending on the state of charge and the charge/discharge history of the storage system.

The maximum power that can be discharged by the storage system is:

$$P_{bat,dmax,cmp} = \frac{-kcQ_{max} + kQ_1 e^{-k\Delta t} + Qkc\left(1 - e^{-k\Delta t}\right)}{1 - e^{-k\Delta t} + c\left(k\Delta t - 1 + e^{-k\Delta t}\right)} \tag{13}$$

The maximum discharge capacity of the storage system is:

$$P_{bat,dmax} = \eta_{batt} \bullet P_{bat,dmax,cmp} \tag{14}$$

### 3.5. Hydrogen generator and hydrogen tank

The autonomy of the hydrogen storage is:

$$A_{htank} = \frac{Y_{htank} LHV_{H_2}(24h/d)}{L_{prim,ave}(3.6MJ/kWh)} \tag{15}$$

where $Y_{htank}$ [$kg$] is the capacity of the hydrogen tank, $LHV_{H2}$[120 MJ/kg] is the energy content (lower heating value) of hydrogen, and $L_{prim,ave}$ [kWh/d] is the average primary load [29].

The hydrogen generator is functioning by using electrolytic water that has an electrical resistivity greater than 1 MΩ/cm, which is either deionized or redistilled water. This electrolytic water is then decomposed at the anode:

$$2H_2O = 4H^+ + 2O^{-2} \tag{16}$$

From the decomposition of the oxyanion ($O^{-2}$), an electron is released, leading to the formation of oxygen ($O_2$). This oxygen is then discharged into the water tank. The water from this process can be reused, and the oxygen is released into the atmosphere through a vent situated on the top part of the device. The hydrogen proton, existing as an aqua ion ($H^+ \bullet XH_2O$), is moved towards the cathode by the electric field, passing through the PEM/SPE ion membrane in the process. Upon reaching the cathode, it gains electrons to produce hydrogen. Subsequently, most of the water is ejected into the gas/water separator. The hydrogen's purity levels reach 99.999 % or higher as it contains minimal water, benefiting from a moisture absorption process in the desiccator. Following treatment with an extremely efficient purifier, the hydrogen's purity level can exceed 99.9999 %.

### 3.6. Fuel Cell

The fuel cell converts chemical fuel to electricity through a chemical reaction in which the fuel is oxidized and electricity is generated.

The fuel consumption of the fuel cell in units/h depends on the power produced as:

$$F = F_0 \bullet Y_{Cell} + F_1 \bullet P_{Cell} \tag{17}$$

where $F_0$ [$units/h/kW$] is the intersection coefficient of the fuel curve, $F_1$ [$units/h/kW$] is the slope of the fuel curve, $Y_{cell}$ [$kW$] is the rated capacity of the fuel cell, and $P_{ell}$ [kW] is the power generated by the fuel cell.

The efficiency of the fuel cell is given by:

$$\eta_{Cell} = \frac{3,6 \bullet P_{Cell}}{\dot{m}_{fuel} \bullet LHV_{fuel}} \tag{18}$$

where $\dot{m}_{fuel}$[$kg/h$] is the fuel mass flow rate, and $LHV_{fuel}$ [MJ/kg] is the lower calorific value of the fuel (as energy value).

Through simulation the covering of the primary load is prioritized and supplied by the generators while lower-priority objectives, such as charging the storage system, are covered after the primary load is fed while minimizing the total costs that takes into account fuel cost, operation, maintenance, and replacement [28]. The generators costs depend on their schedule, operation hours and maintenance costs and if needed the replacements costs. The meteorological aspects are considered in the simulation, data regarding these aspects are recorded and used in the simulation. The power generated by the RESs depend on meteorological conditions in the area, for example, for wind turbines, the area where they are located has a high wind potential, this being in the Dobrogea area where the installation of wind generators is recommended due to the wind conditions offered by the respective area. The photovoltaic panels are not shaded, they are installed on the roof-top of the building, also in an area with considerable solar radiation.

In Fig. 5 the diagram that explains the load following control strategy is presented. Using local meteorological data, real load data and the installed equipment data, the system operation is realized to optimize the utilization of RESs.

When the consumption is exceeding the RESs production, the available stored energy at a time period ($Q_1$) and if there is enough hydrogen stored in the tank ($Y_{htank}$), then the battery is discharged, and the fuel cell is supplying the load in order to minimize the operational costs. If there are no storage conditions fulfilled, the Diesel generator is dispatched ($P_{gen}$) if its operating cost is lower then the electricity cost from the public grid, otherwise the power from the grid in injected to supply the load ($P_{grid}$).

When the consumption is below the RESs production, if there is available stored energy at a time period ($Q_1$), hydrogen production from water is realized (if the tank is not full) or the excess power is sold to the grid. If there is no available stored energy in the battery then the battery is charged ($P_{bat,c}$).

This control strategy is applied at each time period of the analysis horizon.

## 4. Analysed system results and discussion

In the proposed system, the following generation sources, presented in Fig. 6, serve the electrical load, the student dormitory with an average of 100 kWh/day. The PV system production is represented with yellow, grid purchases with black, diesel generator production with red, fuel cell production with grey and the wind turbine production with blue. It can be seen that the PV system supplies the presented system to the greatest extent. The student dormitory can also act as a prosumer with the possibility of injecting the surplus of generated power into the network, as can be seen from Fig. 6, the largest surplus coming from the photovoltaic system. Moreover, the system does not purchase electricity from the public grid.

In Fig. 7 the electrical load is presented, more exactly the needed load and the served load. The load is represented with yellow and the served load with blue. The load is always supplied with no periods when it is disconnected. The supply continuity is ensured through the correct dimensioning of the system. In addition, it can be notice in the following that the system does not purchase energy from the public grid, the connection is made only to be able to sell the energy surplus to the public grid [29,30].

In Fig. 8 the grid purchases (yellow) and sells (blue) are presented. The system does not purchase electricity from the public grid, as mentioned before, but only sells the surplus to it, obtaining a monetary benefit. Considering the maximizing of the existing sources share in order to be able to sell the surplus to the public grid, the university obtains substantial funds that can be used for the benefit of the students concomitant with the reduction on fossil fuel dependence and reduction

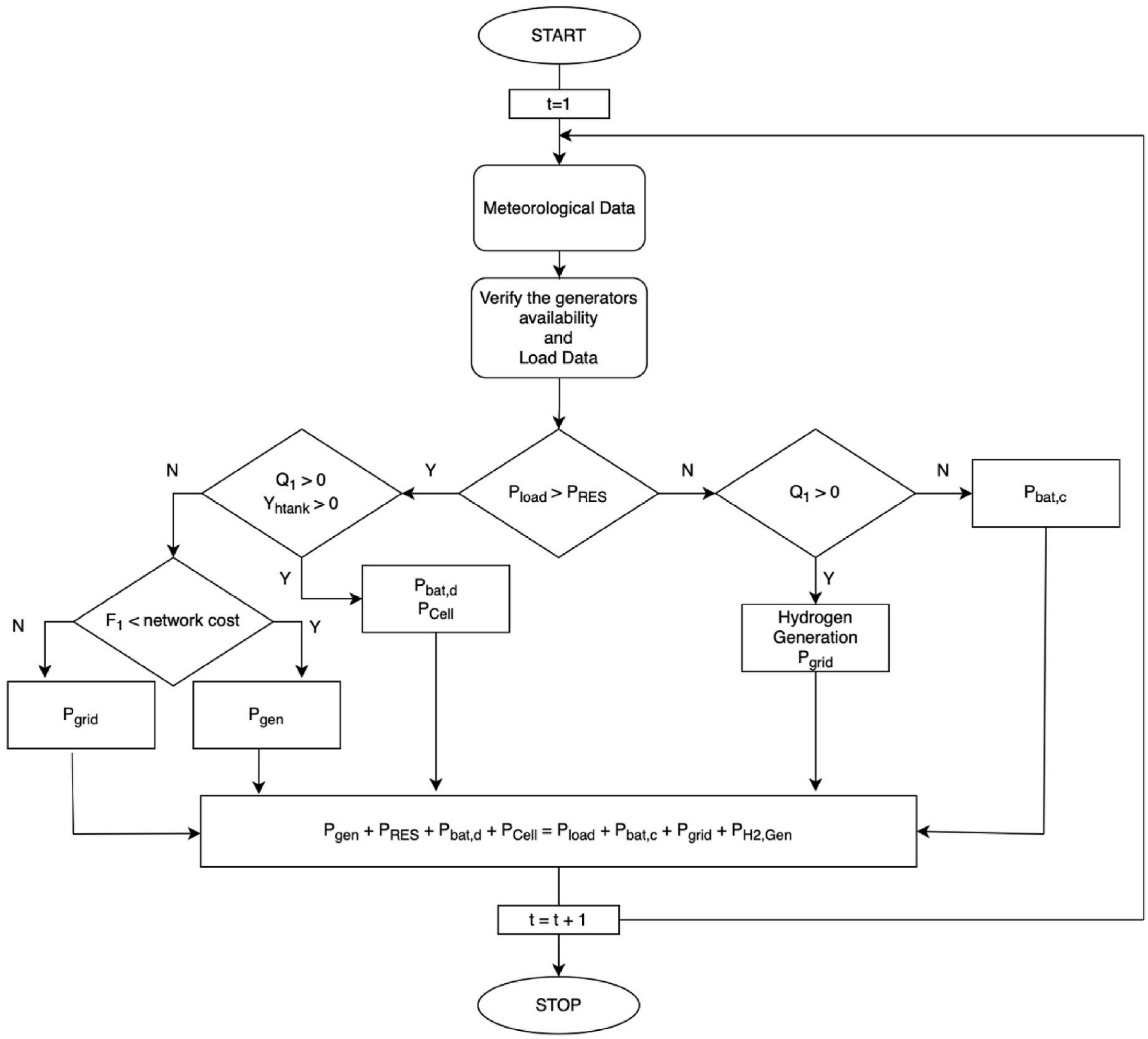


**Fig. 5.** Control strategy.

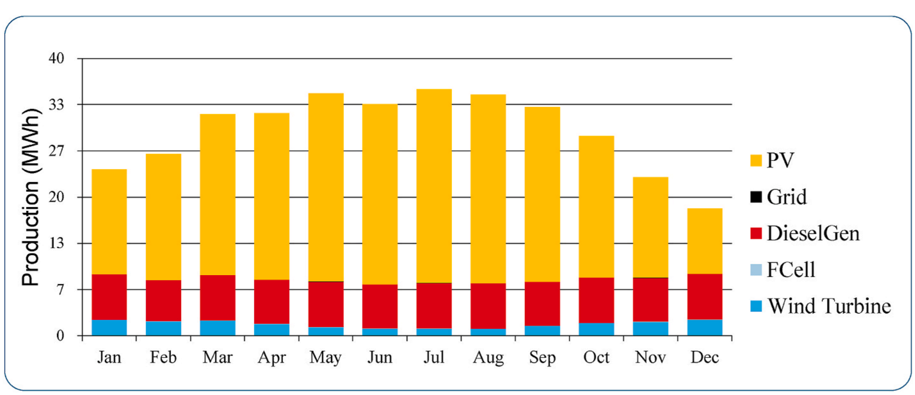


**Fig. 6.** Generation sources serve the electrical load.

of pollutant emissions that are imposed by agreements and incentives.

In Fig. 9 the production of the PV system (yellow), wind system (blue) and the energy storage system (grey) is presented during one moth of the year. Most of the production is governed by the PV system with a few days in which, due to the favourable wind conditions, the wind system produces a considerable amount of electricity. It can be seen that the energy storage system is loaded to be able to supply the analysed system demand when RES cannot produce due to weather conditions.

In Fig. 10 the operation of the fuel cell (blue) and hydrogen storage (yellow) is presented. The amount of stored hydrogen fluctuates, observing days where the stored hydrogen is very low and days where peaks appear. The fuel cell consumption is linked to the stored Hydrogen. Generally, after a peak in hydrogen storage, there is a

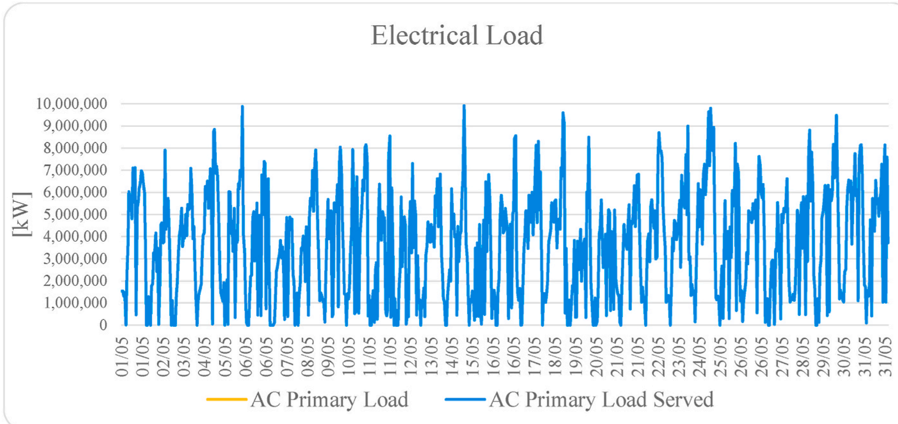


**Fig. 7.** The electrical load variation.

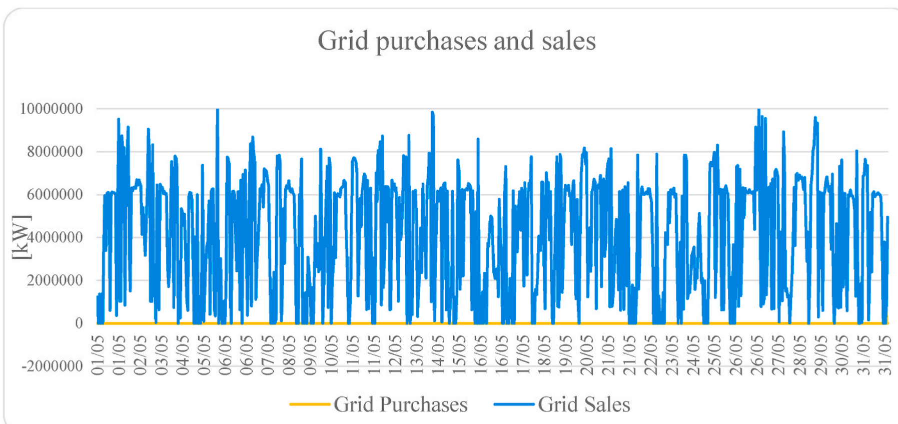


**Fig. 8.** The grid purchases and sales.

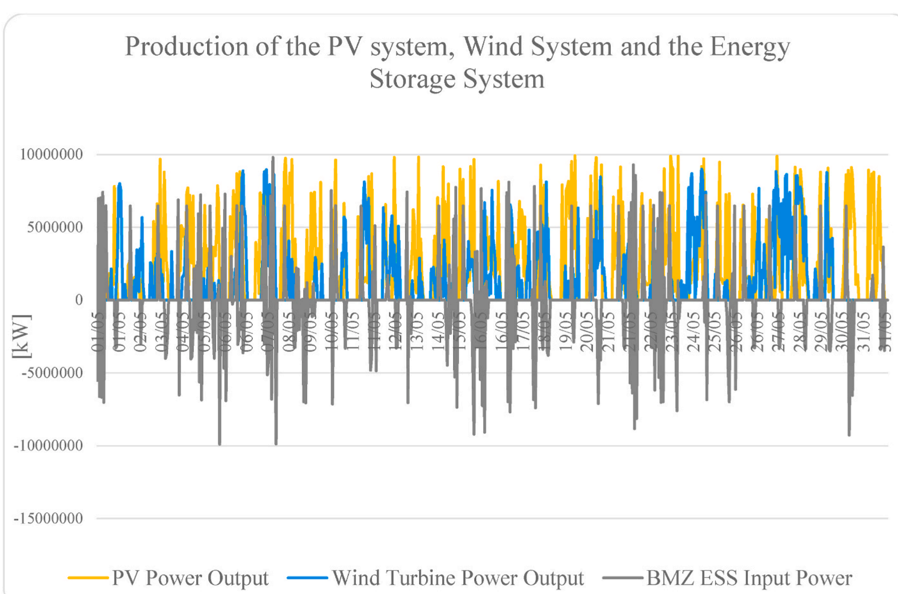


**Fig. 9.** The production of the PV system, wind system and the energy storage system.

corresponding peak in fuel cell fuel usage. This confirms that stored hydrogen is used as fuel for the fuel cell.

In Fig. 11 the output of the Hydrogen Generator (yellow) in kilograms per hour (kg/h) is presented, which corresponds to the production of hydrogen. The operation of the Hydrogen Generator is normally linked to the Stored Hydrogen presented in Fig. 10, which is

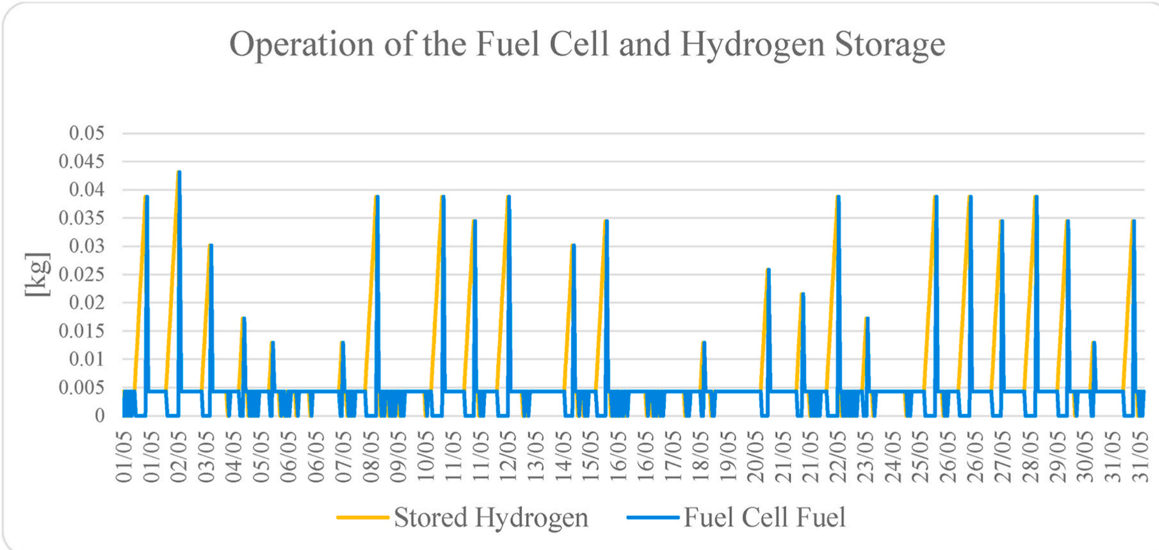


**Fig. 10.** The operation of the fuel cell and hydrogen storage.

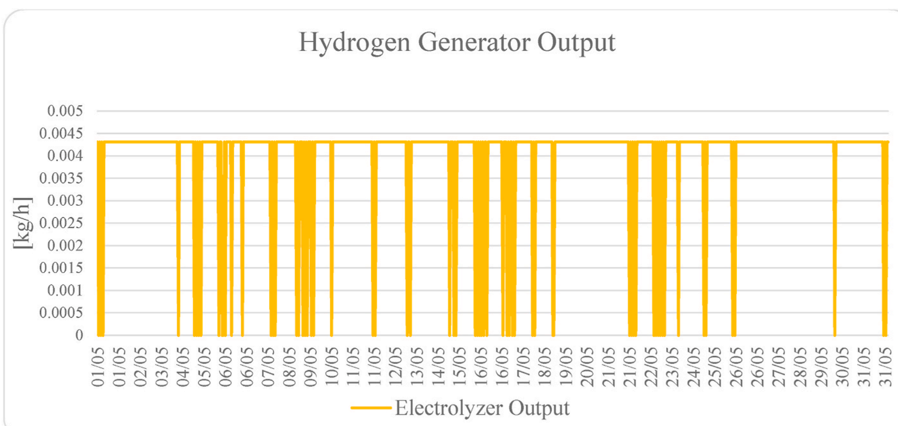


**Fig. 11.** Output of the hydrogen generator.

indicating how much hydrogen is stored over time. The stored hydrogen is increasing in some time periods when the electrolyzer has a high output which is reflecting the fact that generated hydrogen is stored.

In Fig. 12 the operation of the hydrogen generator (yellow) and the fuel cell (blue) can be observed. The fuel cell consumes hydrogen to generate electricity at certain time periods when the power produced by the renewable energy sources is not sufficient to cover the load, this time periods depends on meteorological aspects (clouds, wind, day/night).

In Fig. 13 the cumulative cash flow is presented. It can be seen that the system is increasing the monetary benefit obtained as time passes.

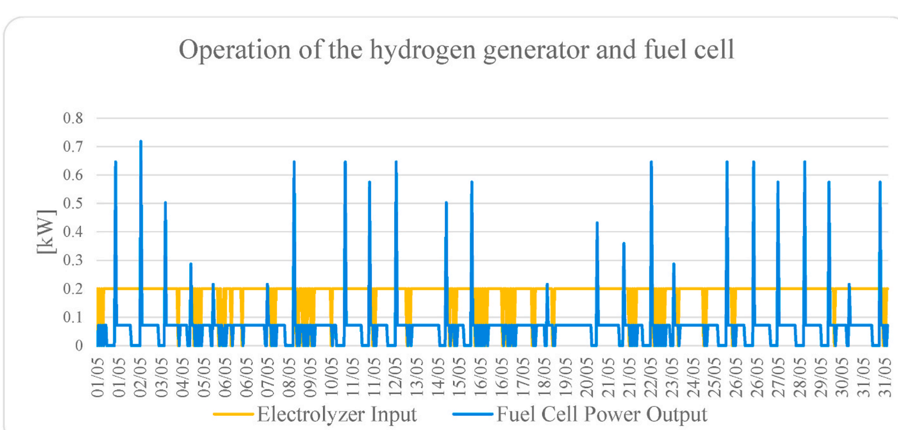


**Fig. 12.** The operation of the hydrogen generator and fuel cell.

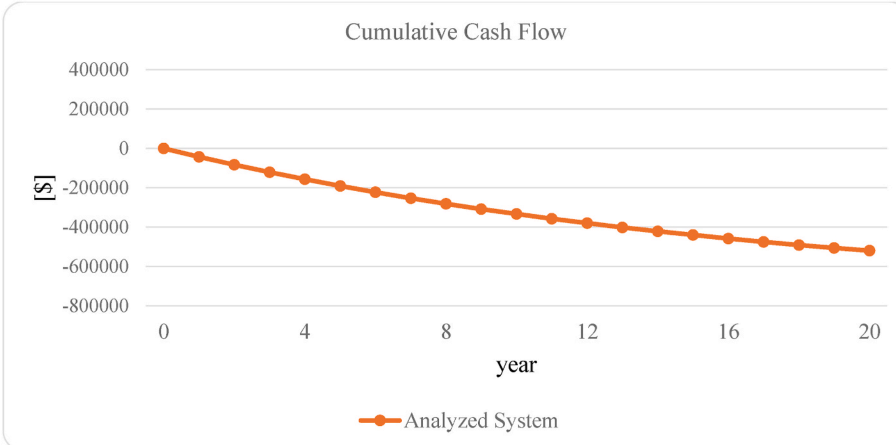


**Fig. 13.** The Cumulative Cash Flow over the lifetime of the project.

The project has the NPC value equal to -$519 711 indicating the monetary benefit obtaining through the project. The "-" indicator shows the savings of the system, the quantity that will be reduced after implementing the system.

The system in which the share of renewable sources is maximized also reduces polluting emissions considering the integration of a greater capacity of sources that produce clean energy. In Table 4 the emissions produced by both systems are presented can be easily compared.

According to emission results presented in Tables 4 and it can be seen that the maximized system is reducing pollutant emissions due to the capacity maximization the of the renewable energy used to supply the load. Carbon Dioxide ($CO_2$) is reduced by approximatively 303 % compared to the existing system, while the Sulfur Dioxide ($SO_2$) is reduced by approximatively 1492 % compared to the existing system and the Nitrogen Oxides ($NO_x$) are reduced approximatively by 45 % compared to the existing system.

There is a small increase in Unburned Hydrocarbons and Particulate Matter values for the maximized system compared to the existing one, but the increase is negligible because the overall impact of this pollutant is insignificant compared to the substantial reductions regarding the $CO_2$, $SO_2$ and $NO_x$.

Considering the limitations imposed through different initiatives and agreements worldwide regarding the pollutant emissions, the Maximized system is clearly reducing the emissions due to the maximized share of the RESs thus improving air quality and it is combating climate change.

## 5. Conclusions

The paper proposes and analyses the resizing of an existing muti-source system, installed at a university campus in Romania, that contains photovoltaic panels, wind system, fuel cell, hydrogen generator, electricity and hydrogen storage system to supply the consumption of a student dormitory from a university campus in Romania with prosumer possibilities.

The resized system (the maximized system) represents the optimal solution related to the system configuration, compared to the existing system. The resized system is maximizing the share of renewable energy sources to face climate change and demand increase. According to the emission results the maximized system is clearly reducing the $CO_2$ (from 36688 kg/yr to −74753 kg/yr), $SO_2$ (from 32.5 kg/yr to −451 kg/yr) and $NO_x$ (from 513 kg/yr to 278 kg/yr) thus contributing in minimizing pollutant emissions in order to comply with the limits set through initiatives and agreements, facing climate change and also providing clean energy to a brighter future.

The proposed system simulation demonstrates successful integration of the maximized multi-source system ensuring demand supply without reliance on the public grid, fact proven by the results obtained regarding the energy purchase of from the public network, which is 0, and the injection of surplus into the public network, which is substantial. The operation of the hydrogen generator and fuel cell highlights hydrogen's potential as a clean energy vector that can be used in areas that require high-density energy storage or where direct electrification is difficult to implement. Through simulation results can be observed that hydrogen contributes to covering the load of the analysed system serving as a non-intermittent clean energy source.

Another important aspect in achieving a clean energy future are prosumers. Enabling consumers to act as prosumers contributes to a more decentralized and participatory energy markets that increases the resilience of the energy system, lower energy costs, and providing the next step to energy communities in Romania concomitant with the monetary benefits obtained after implementing the proposed solution. The NPC value related to the maximized system is expected to be -$519 711, value that is indicating the monetary benefit obtaining through the project.

Future research in this area refers to the study and implementation of ultra fast chargers in the university campus for vehicles that are using hydrogen. The excess hydrogen can be used to ultra fast charge the vehicles giving the possibility to charge a vehicle in minutes, a similar time spent at the classic gas stations. The synergy between hydrogen fuel cells and battery electric vehicles to implement integrated charging infrastructures that can serve both types of vehicles efficiently is a promising subject considering the actual environment challenges.

**Table 4**
Emissions produced by the existing system compared to the maximized one.

| Pollutant Name | Existing System [kg/yr] | Maximized System [kg/yr] |
|---|---|---|
| Carbon Doxide | 36688 | −74753 |
| Carbone Monoxide | 509 | 509 |
| Unburned Hydrocarbons | 18.5 | 18.6 |
| Particule Matter | 30.8 | 30.9 |
| Sulfur Dioxide | 32.5 | −451 |
| Nitrogen Oxides | 513 | 278 |

## CRediT authorship contribution statement

**Alexandra Catalina Lazaroiu:** Writing – original draft, Software, Investigation, Conceptualization. **Cornel Panait:** Supervision. **George Serițan:** Methodology, Investigation. **Claudia Laurenta Popescu:** Writing – review & editing, Supervision. **Mariacristina Roscia:** Visualization, Resources, Investigation.

## 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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