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Integration of renewable resources into the electricity energy matrix. Practical case applied to a small rural municipality

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Abstract. Climate change is a global problem, which is being mitigated over the last decades. To this end, several regulations are being developed to make an energy transition towards renewable resources. In this framework, more and more energy communities are being created in Europe, with the aim of reducing energy consumption based on fossil fuels and promoting the use of renewable energies. This work proposes the design and management of renewable resources to introduce them into the energy matrix. This energy matrix based on renewable energies aims to cover the energy demand of a small rural municipality in the Valencian Community (Spain), for which the annual consumption is known. The results show the possibility of achieving a high percentage of self-consumption in rural municipalities, minimising dependence on the general electricity grid.

Key words. Energy matrix, self-consumption, rural area, renewable energy.

1. Introduction

In recent decades, climate change has become a global problem that needs to be mitigated. One of the most effective and developed ways to reduce dependence on fossil fuels in recent years is through a transition to renewable energy sources [1]. Specifically, in Europe, extensive efforts are being made to drive this energy transition [2], such as the European Directive 2018/2001/EU. This directive sets out the strategic actions for 2020-2030 known as "Clean Energy for All Europeans." The main objectives of these actions are to promote renewable energy, mitigate climate impact, and reduce dependence on fossil fuels, to achieve a sustainable energy system. These measures are focused on the long-term goal of making the European Union climate neutral by 2050. Because of these new policies, the number of energy communities that are emerging in Europe is increasing [3].

Energy communities are groups of people who produce, distribute, and consume energy jointly, with the aim of being more self-sufficient and reducing their dependence on large energy companies and non-renewable resources. They can contribute to improve energy efficiency, reducing energy costs, and fostering innovation in energy production and use. In addition, they can help to promote citizen participation and to promote sustainability and local development. These communities can use a variety of technologies to produce energy, such as solar, wind, hydroelectric, and biogas energy. All these technologies enable the generation of electricity in a clean and sustainable way, as they do not produce harmful emissions or toxic waste during operation. However, these systems have some disadvantages when it comes to self-consumption [4], such as:

- Many of them cannot function independently due to their intermittency. Solar and wind energy are intermittent, meaning that their availability depends on weather conditions, and they are not always available when needed.
- They cannot guarantee a reliable electricity supply.
- They cannot completely replace conventional energy resources. Although the installed capacity of renewable energies is growing rapidly, it has not yet caught up with the power generation capacity of conventional sources.
- Variability and dependence on uncontrollable factors require large-scale storage systems, so they need to be combined [5].

In other words, to achieve real self-consumption using only renewable energies, it is necessary to design and manage an energy matrix that can cover all demand. The energy matrix refers to the way energy is produced, transported, and consumed in a society or in a specific geographic region. This work proposes the design and management of renewable resources into the energy matrix to provide the self-sufficiency of a small rural municipality in the Valencian Community (Spain). With the implementation of this combination of renewable resources (PV, wind, biogas, and hydroelectric), it is intended that the municipality makes use of the available energy resources, to achieve a sustainable consumption that allows energy independence from fossil fuels. Furthermore, this work aims to establish the foundations of a sustainable energy matrix that can be replicated later in other municipalities.

This research work is structured into 4 sections. Section 2 presents the materials and methods, where the studied municipality is described, as well as the design and management of the renewable resources-based energy matrix. Section 3 shows and analyses the results obtained when using the renewable energy matrix to supply the municipality. The limitations of this work are also indicated. Finally, in section 4, the main conclusions of the study, its relevance, and possible future work are summarized.

2. Materials and methods

In this section, the need to establish a renewable resources-based energy matrix in the municipality of Aras de los Olmos (Valencia, Spain) is described. Additionally, the renewable technologies used for the design and management of the energy matrix are also specified.

A. Case study description

Aras de los Olmos is a small rural municipality in the Valencian Community (Spain), which has less than 400 registered inhabitants. It is in the northwest of the province of Valencia (Valencian Community, Spain), bordered to the north by the province of Teruel (Aragon, Spain), and to the west by the province of Cuenca (Castilla La Mancha, Spain). The selection of this municipality of the Valencian Community has been made based on the following reasons:

- It is located at the end of a 20 kV power distribution line, which has caused numerous outages and problems with the reliability and quality of the electricity supply.
- The location of the municipality presents ideal characteristics for the implementation of renewable resources. On the one hand, there is free land available for the construction of renewable energy plants (wind, PV and biogas). On the other hand, a large part of the economy is based on livestock farming, which means that large quantities of animal manure are available to produce biogas. Finally, close to the municipality there is a river with a steep area, which has a level of more than 100 m, ideal for a hydroelectric power plant.

In view of the needs and the ideal conditions of the municipality due to its location, the design of a matrix based on renewable resources including photovoltaic (PV), wind, hydro and biogas energy is proposed. For the correct design of renewable resources-based energy matrix, the following must be considered:

- Energy consumption and its evolution.
- Technical implementation.
- Management of energy matrix.

B. Energy consumption study

To improve the quality and reliability of the electricity supply, it is first necessary to know the energy consumption of the municipality. To this end, the demand of the entire municipality has been recorded for a whole year to characterise the energy consumption. Fig. 1 shows the accumulated monthly energy consumption of the municipality. Fig. 2 shows the weekly energy consumption during the whole recorded year. This figure represents the average hourly consumption value, as well as two bands where 75 % and 90 % of the hourly consumption is accumulated for each day of the recorded year. Fig. 2 also presents how the total energy consumption of the municipality decreases in the central hours of the day. the total energy consumption of the municipality falls in the middle of the day. This is due to the presence of ten small PV installations of 20 kW each, which inject the surplus into the grid. These installations are in the farms of the municipality, which are far from the urban centre.

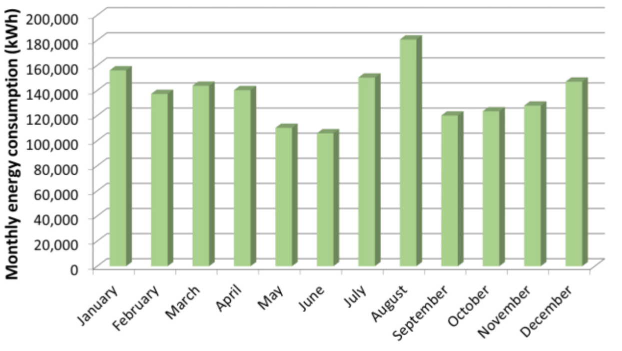

Figure 1: Monthly energy consumption of Aras de los Olmos

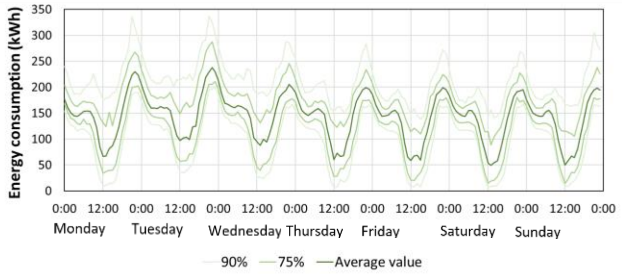

Figure 2: Energy consumption of Aras de los Olmos

Finally, it is necessary to know the expected annual increase in consumption. This is because society is tending towards greater electrification, and therefore greater energy consumption. Fig. 3 shows the annual consumption from 2019 to 2022. To obtain the percentage evolution of energy consumption, the value for 2020 has not been considered, since due to the extraordinary situation of the COVID-19 pandemic it is not considered representative data. It is estimated that the annual percentage increase in the municipality's energy consumption will be 1.4% per year.

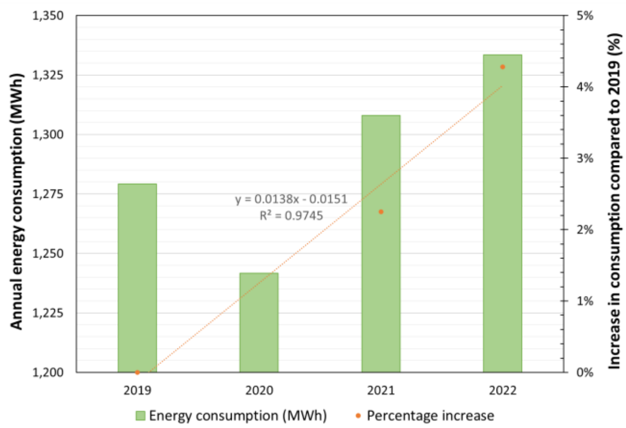

Figure 3: Evolution of annual consumption of Aras de los Olmos

C. Technical implementation

After verifying the need to improve the quality and reliability of supply in the municipality of Aras de los

Olmos, and knowing its energy consumption and its evolution, it is possible to design an energy matrix.

In this case, a system based on renewable resources is chosen, as the municipality has the ideal geographical resources for its installation. The main characteristics of the renewable energy installations designed to supply the demand of Aras de los Olmos are detailed below. Fig. 3 shows the energy matrix designed.

1) PV power plant

The PV plant only generates energy in the central hours of the day if there is sunshine and cannot store it. From Fig. 2 we can see that 95% of the weekly consumption for the year studied at these hours is around 200 kW. However, the energy demand at those hours is so low due to the presence of ten 20 kW PV installations in the farms of the municipality that inject the generated surplus into the grid. Therefore, if we do not consider the ten existing PV installations, 95% of the consumption in the central hours of the day would be around 400 kW.

Considering a lifetime of 30 years for the PV panels, and a percentage increase in energy consumption of 1.4% per year (Fig. 3), the PV power required to be able to supply energy for 30 years can be obtained. This power is given by the equation (1).

$$PV_{30} = PV_{base} \cdot (1 + yi)^{30} \quad (1)$$

In this equation, PV_{30} is the minimum installed power required for the selected lifetime of 30 years, PV_{base} is the rated power for the central hours at present (400 kW) and yi is the yearly increase per unit of the analysed demand (0.014). The minimum PV power required to supply the municipality for 30 years is 607 kW. Due to the nominal power of the PV panels and the distribution of the strings, it was decided to install a power of 700 kW.

2) Wind power plant

The wind power plant can generate electricity during all hours of the day if the wind speed can cause the wind turbine movement. If we analyse the terrain of the municipality and the environmental regulations of the Valencian Community, there is only one possible area for the installation of the wind power plant. However, most of this area is occupied by a privately managed wind power plant.

In order to comply with technical and environmental regulations, a 200 kW wind turbine was chosen due to space limitations.

3) Biogas power plant

Biogas generation varies depending on the organic matter used for anaerobic digestion [5]. In this case, animal waste from farms of the municipality (rabbits, pigs and chickens) will be used. The estimated total waste is 9,880 t/year (27.07 t/day), according to data provided by the municipality's town council.

To determine the reactor volume, a retention time of 30 days is estimated for the waste with a density of approximately 1000 kg/m^3. Thus, the required reactor volume is 812 m^3. A cylindrical reactor of 14.38 m and a useful height of 5 m will therefore be used, with a double PVC membrane that will be used as a gasometer. It will have a maximum storage capacity of 400 m^3 of biogas. A minimum storage volume of 50 m^3 is established for use in case of emergency. The production of biogas in Nm^3/day is given by equation (2).

$$Q = q \cdot m \quad (2)$$

Where q=0.228 is the methanogenic capacity and m=3800 kg/day is the feed rate of volatile solids of the waste. This gives a biogas production of 867 Nm^3/day.

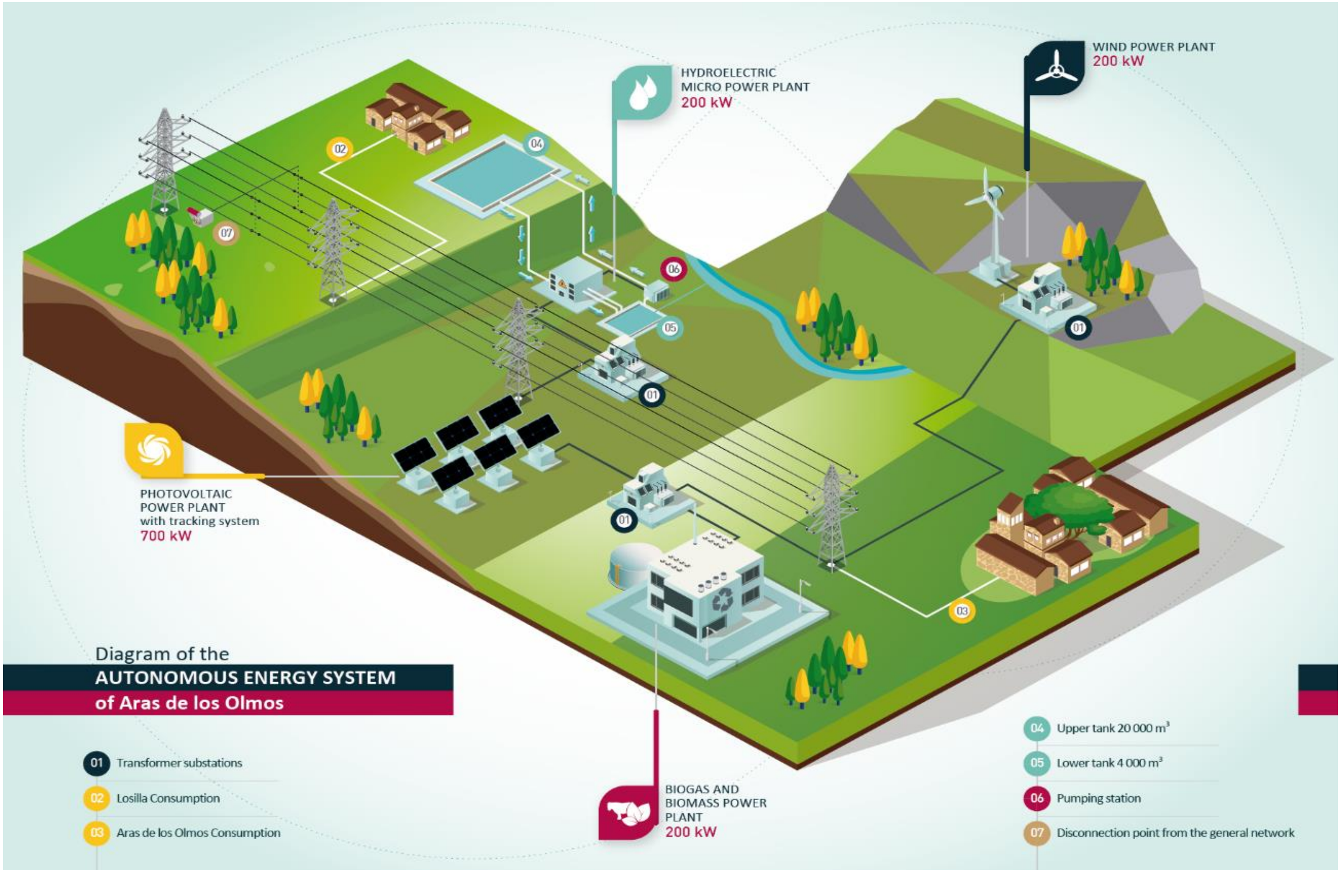

Figure 3: Energy matrix based on renewable resources

Considering that biogas has between 45% and 70% methane, an average value of 60% is taken. Biogas has a lower calorific value of 5.6 kWh/Nm^3, therefore the available energy is E=8094 kWh/day. With an internal combustion engine coupled to a generator with an efficiency of 29%, the available electrical energy is E_e=2509 kWh/day. It is stipulated that the generator must be able to operate for 12 h/day at full power, so it must have a useful power of 200 kW.
Special mention should be made of the fact that this digester will use strategically bioaugmented microbial strains resulting from the EU-funded project: Natural and Synthetic Microbial Communities for Sustainable Production of Optimised Biogas (Ref.: 1010004706) [6].

4) Hydroelectric power plant

The hydroelectric power plant will be used as a storage system for the surplus energy generated by the other renewable sources, and as a generator in times of generation shortages from renewable sources. It will therefore consist of two reservoirs (upper and lower), a turbine and a vertical pump.
The plant will be located near the municipality, at the 180 m high waterfall of the Arcos River. The design project for the hydroelectric power plant has already been completed, with a 200 kW pumping and turbine capacity.

5) Evacuation of energy

The evacuation of energy will be carried out at high voltage, through the construction of four new 20 kV lines, which will be connected to the existing distribution line in the municipality. Each evacuation line supports up to 2.5 times the maximum power that the new renewable power plants can generate. The design of the lines has been carried out by a specialised company. The existing lines have sufficient capacity to carry the new power generated without the need to extend them, according to data provided by the electricity company. Three new transformer stations will also be built.

D. Management of energy matrix

When designing the energy sources for a grid, the management of these sources must be considered to optimise the design [7]. For the management of the energy generated by the different renewable resources, the diagram shown in Fig. 4 is used. This diagram is executed by a control system that permanently checks the conditions.
Since solar and wind generation do not allow for energy storage, an energy balance must be made between the generation of these resources and the energy consumption of the municipality. Subsequently, the system must check whether the biogas storage has reached its capacity limit, and two scenarios are possible.
Scenario 1: If the biogas storage is at its maximum, the biogas will be burned in the plant's generator, and an energy balance with solar, wind and biogas generation will be made with the demand of the municipality. In case this renewable energy generation does not meet the demand of the municipality, it will be necessary to import the remaining energy from the grid. If surplus energy is available, it will be used to pump water to the hydroelectric power plant if possible or to inject the surplus into the grid.
Scenario 2: If the biogas storage is not at its limit, it is checked whether there is a surplus of solar and wind generation compared to the demand of the municipality. If there is surplus energy, it will be used to pump water into the hydroelectric power plant if possible or inject the surplus into the grid. On the other hand, if there is no surplus of solar and wind generation, it is checked whether it is possible to turbine at the hydroelectric power plant, as this energy has been obtained mainly from pumping water through surplus renewable energy generation. If turbinating at the hydroelectric power plant is not possible, it would be necessary to use the biogas from the plant for electricity generation if the minimum storage volume has not been reached. If the minimum volume had been reached, it would be necessary to import the missing energy from the grid.

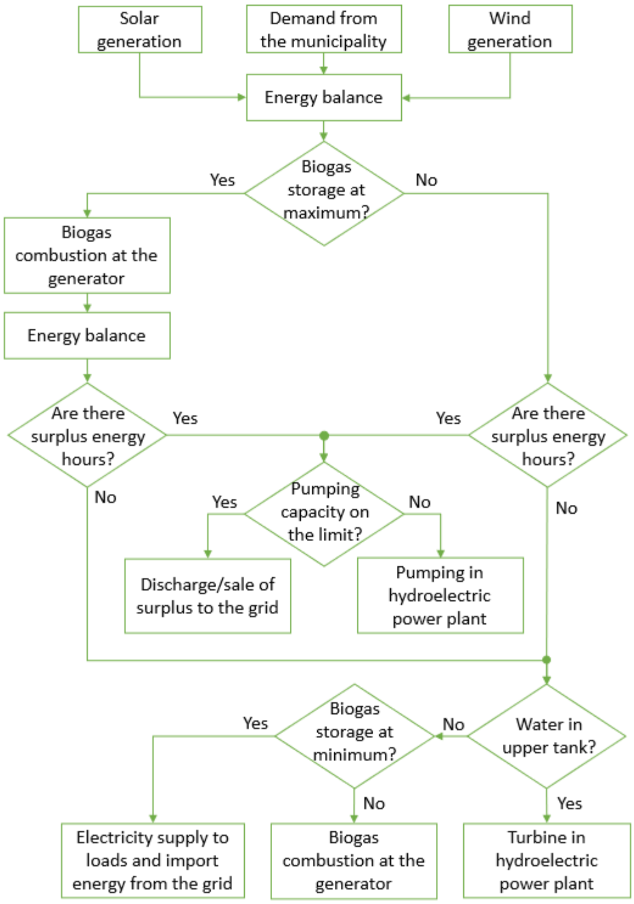

Figure 4: Energy matrix management diagram

3. Results and discussion

The results obtained from the proposed method of design and management of the energy matrix are shown below, as well as the discussion of these results.
On the one hand, solar and wind generation depends exclusively on weather conditions. Therefore, it is necessary to use this energy first. Since there are times when the generation with both resources can be higher than the municipality's own demand, the surplus is used for pumping water in the hydroelectric power plant. When the pumping power is reached, this surplus is discharged to the grid. To this energy surplus, the surplus from the flaring of biogas must be added if the stored volume reaches the limit of 400 m^3. On the other hand,

the upper reservoir of the hydroelectric power plant is always filled from the existing surplus of renewable energy. Therefore, it can be assumed that this energy has not cost. This leads to the fact that at times when there is no surplus energy, this resource is used before biogas, if the biogas has not reached the maximum storage capacity. Finally, if the municipality's energy needs cannot be supplied from renewable resources, energy is imported from the grid.

Once the energy balance of the production of the renewable resources designed and the electricity demand of the municipality has been carried out following the diagram in Fig. 4, the percentages of use of each resource are obtained. Fig. 5 shows the energy mix resulting from the use of renewable resources in the energy matrix of Aras de los Olmos.

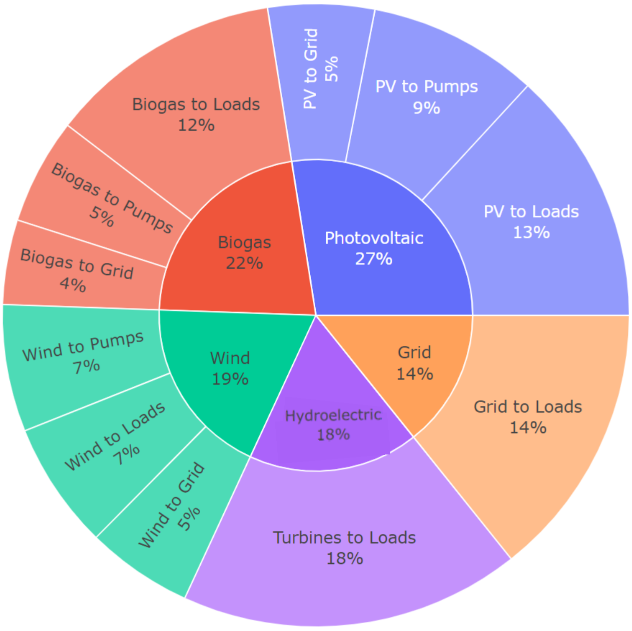

Figure 5: Energy mix of the energy matrix

Although the available solar capacity is 3.5 times greater than the capacity of other renewable resources, it only accounts for 27% of the energy mix. This is because part of the energy generated in the solar plant is used for pumping water to the upper reservoir in the hydroelectric plant, not for direct consumption by the municipality. Moreover, it is only available during sunlight hours, so it is not available throughout the day to be consumed. In contrast, the storage available at the biogas and hydroelectric plants allows the production of both to be managed, enabling more efficient use.

Despite the oversizing of the generating plants, Fig. 5 shows that 14% of the energy is supplied by the grid. Two main aspects stand out from this fact:

- The meteorological influences and the operation of renewable resources do not allow for 100% self-consumption through distributed renewable energy resources. To achieve real self-consumption, it would be necessary to have a larger biogas digester or a more powerful hydroelectric power plant, but the lack of natural and economic resources makes this solution unfeasible.
- The energy exported to the grid coincides approximately with the energy imported from the grid. Therefore, although self-consumption cannot be ensured, self-sufficiency can be achieved. It is not possible to disconnect from the grid on a large scale nowadays.

The energy balance proves that it is possible to achieve self-sufficiency with a system based exclusively on renewable resources. In addition, due to the oversizing of the generating plants, there are hours when a part of the energy is exported to the general grid, allowing an economic benefit to be obtained. It should be noted that the power plants have been oversized in relation to the electricity demand of the current municipality. This oversizing has been done for the following reasons:

- The renewable sources have been designed to be able to supply the municipality for the next 30 years.
- Due to the influence of environmental conditions, renewable sources do not operate at maximum power during all hours of the day. Therefore, the useful power obtained from them is lower most of the time.
- Guarantee self-sufficiency in case one of the renewable resources is not available. This may be due to adverse weather conditions, or the need for maintenance of the elements of the power plants themselves.
- In the future, it is intended to carry out a community management with other municipalities to minimize operating costs and increase the reliability of the supply.

Although it is true that the energy matrix designed presents a series of advantages for achieving self-sufficiency in a municipality, it has a series of limitations, such as the following:

- The necessary administrative procedures make it difficult and prevent it from materializing in the short term.
- The construction and combination of this type of generating plants require a large initial investment and the availability of the necessary land.
- The area in which it is implemented must have a series of conditions that allow the correct operation of all the plants.
- While solar, wind and water resources can be secured in the future, the availability of organic matter for the biogas plant depends to a large extent on the activity of the municipality. Therefore, this resource may cease to exist in the future if the farms are not continued or may be expanded and the capacity of the biogas reactor may have to be increased. Therefore, although biogas is an excellent resource for grid stability, it is strongly linked to uncertain parameters in the future.
- The work carried out did not consider possible maintenance/problems that would prevent the plants from operating. Therefore, despite demonstrating that self-sufficiency can be achieved, the aim is not to disconnect the municipality from the grid, as this connection is still necessary to ensure reliability in specific cases. In addition, there are also hours of surplus energy, which should be fed into the grid.

4. Conclusions

This work has developed the design and management of renewable resources (PV, wind, biogas and hydroelectric) into the energy matrix. For this purpose, the case of a rural municipality has been analysed, determining its energy needs and establishing the management system for renewable resources. The results show the possibility of achieving self-sufficiency in rural municipalities, minimising dependence on the general electricity grid. However, it has been noted that it is not possible to achieve full self-consumption from renewable resources on a large scale nowadays. Although the application of this case has been shown for a specific municipality, it is necessary to study for the future the cooperative management with neighbouring municipalities, with the aim of minimising costs and maximising the reliability of the system.

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