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Dynamic algorithm to boost the synergy between biogas plants and photovoltaic plants

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Abstract. This research work proposes an efficient management algorithm for the integration of a biogas and photovoltaic plant for self-consumption. The algorithm is based on the optimization of production and energy use in the plants to meet demand at a reduced cost. The algorithm has been validated using models and simulations, using real data from experimental trials, and comparing the results with simple, non-adaptive control strategies. The results obtained show that the synergy between biogas production and solar energy generation is a promising strategy to increase efficiency and sustainability of electricity production. The algorithm has the potential to overcome technical and economic challenges and is a valuable tool for medium-sized installations. Furthermore, the study found that the algorithm can reduce the cost of electricity by up to 5% on average and even more under certain conditions. Additionally, this research highlights the need for further studies to develop advanced algorithms that are adaptable to different scenarios and weather conditions.

Key words. Renewable energy, Biogas, Photovoltaic systems, Management algorithm, Self-consumption.

1. Introduction

In recent years, concern for climate change and the need to reduce dependence on fossil fuels as a source of energy has grown. As a result, various renewable energy technologies have been developed for the production of electricity, including biogas plants and photovoltaic (PV) systems. These two sources have advantages that allow for synergistic operation with significant improvements in electricity supply.

On one hand, the production of biogas involves the conversion of organic waste into methane gas through an anaerobic digestion process. This gas can be used as a source of energy for electricity generation, heating, or cooking. Additionally, the biogas production process allows for the elimination of waste and reduction of greenhouse gas emissions. From a technical and economic standpoint, this resource is more expensive, but it is manageable and has low dependence on weather conditions. On the other hand, electricity generation from solar energy is done through PV panels, which convert sunlight into electricity. This energy can be used for self-consumption, that is, to meet the energy needs of a building or community without relying on the electrical grid. This source of energy has been widely [1] studied and is considered cost-effective and reliable, but it is not manageable and has high dependence on weather conditions.

Therefore, a promising strategy to increase the efficiency and sustainability of electricity production is the synergy between biogas production and electricity generation from solar energy [2]. This combination allows for the maximum use of available resources and the optimization of energy production and cost. However, the implementation of a biogas and PV plant for self-consumption can present technical and economic challenges [3]. These challenges must be addressed together in the design stage [4], making it crucial to establish an adequate control algorithm for this type of installation to take advantage of its flexibility [5]. There are very few studies that propose an algorithm for managing this mix in an easy-to-implement way for medium-sized installations. The existing studies mainly focus on hybrid systems to achieve self-sufficiency [6]. However, few studies use more comprehensive methods and tackle the problem by considering multiple objectives [7]. Actually, when designing this algorithm, the cost of the systems, the price of energy, and management strategy over several days should be taken into consideration, so that the algorithm can adapt to the needs of each moment. To date, there are no dynamic algorithms that meet these restrictions.

For this reason, in this research work an efficient management algorithm for the integration of a biogas and PV plant for self-consumption is proposed. The algorithm is based on the optimization of production and energy use in the plants to meet demand at a reduced cost. The algorithm has been validated using models and simulations, using real data from experimental trials, and comparing the results with simple, non-adaptive control strategies. The case study selected for this work is based on a rural municipality in Spain, in which a PV plant is being built and a biogas plant has been designed. The results obtained are positive, both for the improvement potential offered by the method and for its versatility for implementation under different scenarios. The obtained results prove the good performance of the expected algorithm under a wide variety of conditions, showing the benefits of the synergy between solar plants and biogas plants. In addition, these results are compatible with other improvements, such as biogas generation optimization or increased solar panels efficiency.

The structure of this research work is detailed below. In section 2, the materials and methods are presented, where the equipment used in the experimental development and research design, and the procedures used to develop and evaluate the proposed management algorithm are described. In the results section, the results obtained through the proposed management algorithm in the case developed are presented and analysed, evaluating the algorithm's performance under various conditions, and comparing the results with non-adaptive control strategies. In the discussion and conclusions section, the results are interpreted, their relevance and significance in the research context are discussed. Also, the main advantages and disadvantages of the proposed management algorithm are highlighted, the main conclusions of the study are summarized, and possible future research lines are suggested.

2. Materials and methods

In this section, the equipment used for the experimental work and the design of the research, and the procedures used to develop and evaluate the proposed management algorithm for the integration of a biogas and PV plant for self-consumption are described. The presented case study has been developed based on data extracted from real measurements in a rural municipality in Spain. The sizes of the equipment for the simulations have been obtained by scaling those of the actual projected equipment, to evaluate the proposed algorithm under various conditions.

For the design of the biogas plant and the PV plant, technical specifications for optimal production of both technologies were taken into account. The biogas plant is based on an anaerobic digestion process of organic waste and a continuous fluidized bed reactor was used. The size of the digester was calculated based on the raw material available in the municipality, mainly farm waste. On the other hand, the size of the gasometer and the generator was chosen to be able to use the biogas during peak demand and without solar input. Nevertheless, in the results section simulations, the performance of the algorithm is analysed when the system has a larger or smaller engine, compared to the electricity demand. On the other hand, the PV system is based on monocrystalline silicon solar panels with a production capacity of 150kWp. Its design was carried out taking into account the availability of space on the municipality lands, the adequacy to the electricity demand, and the cost of the system. The data of both installations are summarized in Table I.

Table I. - Designed equipment data

Minimum gasometer volume	20 m^3
Maximum gasometer volume	400 m^3
Peak power of PV panels	150 kW
Minimum biogas generator power	20 kW
Maximum biogas generator power	120 kW

In order to optimize the production and use of energy in the plant, a dynamic management algorithm with four optimization stages was developed. The algorithm is responsible for balancing the production of biogas and PV energy according to the weather conditions on the target day and the following days, as well as the electrical demand to be covered, with the goal of maximizing efficiency and sustainability of the system. The algorithm uses four stages to optimize the management of the target day. The stages of the management algorithm are described below.

1) Initial data

In order to execute the management algorithm on day k, it is necessary to know the initial volume of gas stored in the gasometer, which depends on the management carried out for day k-1. On the other hand, the weather data for day k+1 allows for the appropriate management strategy to be established, determining the final volume of gas in the gasometer V_{target}. In addition to these two data, the expected hourly electricity demand [8], expected hourly solar generation, and the buy and sell prices of energy for each hour of day k must also be known.

2) Stage 1: Maximization of renewable resources

In the first stage, the algorithm uses the expected PV solar energy to meet the demand for each hour, so for each hour h, the demand that must be met by other sources is calculated with equation (1):

$$r_h = d_h - pv_h \quad (1)$$

In this equation, d_h is the predicted energy demand for hour h, pv_h is the predicted solar generation for that hour and r_h is the demand that is not covered with PV solar generation. If $r_h<0$, then there is a surplus generation that will be sold to the system at the sale price of hour h.

Subsequently, the algorithm assigns the power of the biogas plant generator $p_{b,h}$ to meet the positive values of r_h, subject to the conditions $p_{b,h}<=p_{b,max}$ and if $p_{b,h}<p_{b,min}$, then $p_{b,h}=0$.

3) Stage 2: Stored volume constraints

In the second stage, the algorithm checks for compliance with the storage volume constraints in the gasometer, $V_{min} \leq V_h \leq V_{max}$. If at any time a constraint is not met, the algorithm increases or decreases the power of that hour and previous hours to achieve a first feasible management version.

4) Stage 3: Final volume strategic adjustment

In the third stage, the algorithm adjusts the power of the biogas generator at the last hour (h=23) and earlier until it achieves V_{23} = V_{target}, while maintaining all previous constraints. As a result of this stage, the algorithm reaches a feasible management that optimizes the management of day k+1.

5) Stage 4: Costs optimization

In the final stage, the algorithm goes through the hours of the day trying to increase the power of the biogas engine in the hours when the price of electricity is higher to minimize the purchase of energy from the grid. Additionally, the algorithm can reduce the power in hours when electricity is cheaper to maintain compliance with the restrictions. Furthermore, during hours with a higher selling price, the algorithm can increase electricity production to sell the surplus.

The overall scheme of this algorithm is shown in Fig. 1.

With the described equipment models, the algorithm has been simulated for a typical demand curve of the municipality. All data used is based on real-life tests and measurements from the municipality. The simulations aim to verify the potential of the developed algorithm under different scenarios (weather conditions, plant size in comparison to demand, different prices, etc.).

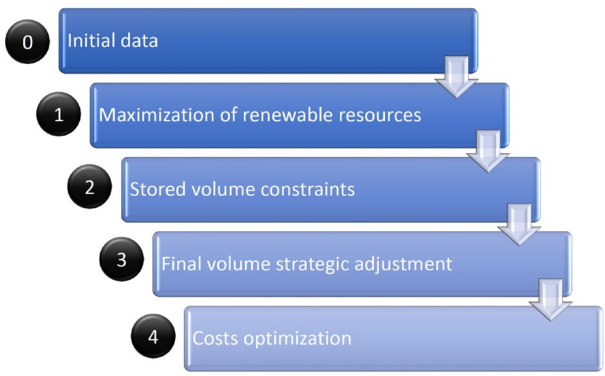

Fig.1. Stages of the proposed optimisation algorithm.

3. Results

The simulation test results for a typical day are shown in Fig. 2.

As seen in this figure, the algorithm has taken advantage of all the solar energy, it has used the necessary biogas, it has imported the necessary energy from the grid and it has exported the most profitable surplus while maintaining adequate levels of stored biogas at all times. Additionally, the algorithm has adjusted the final level of stored biogas to the target value, which is an intermediate value, because the following day was not particularly cloudy.

The management algorithm was applied to the typical day, using the typical load profile and average prices shown in Fig. 2 under various conditions of the previous and subsequent days, always meeting the constraints and minimizing the cost of energy. It is important to note that in this case study, all costs of equipment have been considered in the energy costs: mainly energy buy price, energy sell price, contracted power payment, amortisation of the solar plant and amortisation of the biogas plant. Table II summarizes the main characteristics of the simulations carried out.

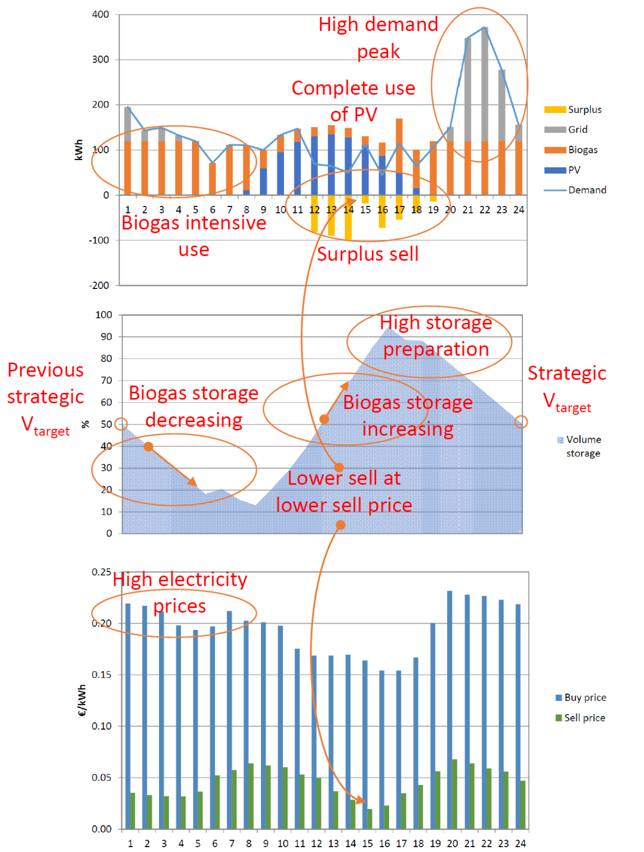

Fig.2. Results of the optimal managements proposed by the presented algorithm

Table II. - Type Sizes

Day			Total energy costs (€)		savings (%)
k-1	k	k+1	simple management	proposed algorithm	
sunny	sunny	sunny	1636.2	1624.7	0.70%
sunny	sunny	cloudy	1685.9	1672.8	0.78%
sunny	cloudy	sunny	1742.8	1729.7	0.75%
sunny	cloudy	cloudy	1800.6	1747.6	2.94%
cloudy	sunny	sunny	1799.7	1737.1	3.48%
cloudy	sunny	cloudy	1857.5	1798.3	3.19%
cloudy	cloudy	sunny	1857.5	1817.7	2.14%
cloudy	cloudy	cloudy	1915.3	1828.2	4.55%

To validate the algorithm, a column has been included in Table 2 that represents the cost reduction achieved by using the algorithm compared to the cost obtained on the day without the optimization stage or the dynamic adjustment of the target volume. As can be seen, the use of the algorithm significantly improves all scenarios, especially in those cases with low availability of solar energy. This is because the fact of setting an appropriate V_{target} for day k-1 has an important impact on total energy costs.

The results shown in table 2 are the average savings achieved in sets of 3 days. However, if the method is evaluated with single days, the savings vary from -10% to 15.6%. The negative savings correspond to days in which the algorithm is preparing the system to get higher savings in the following day. This is the reason why in Table 2, sets of 3 days have been used to evaluate the results.

4. Discussion

This article has discussed the integration of biogas plants and photovoltaic systems as a strategy for increasing the efficiency and sustainability of electricity production. The advantages and disadvantages of these two sources of energy have been explained, as well as the technical and economic challenges of their integration. The proposed solution is the development of an efficient management algorithm for the integration of a biogas and photovoltaic plant for self-consumption. The algorithm is based on the optimization of production and energy use in the plants to meet demand at a reduced cost. To do this, the algorithm operates the plants with a target of stored biogas at the end of each day, depending on the meteorological forecasts for the next days. The results of the simulations show the potential of the algorithm for improving the efficiency and versatility of biogas and photovoltaic plants for self-consumption. The use of this target provides interesting savings when several days are simulated at once.

It is important to note that, due to the design of the algorithm, the savings of a single day can be negative. However, whenever this happens is because the algorithm is preparing the next day to get some greater benefit. Therefore, the validation of the method has been done with sets of three consecutive days (sunny and cloudy) simulated in a sequence. These simulations show higher benefits when there are cloudy days, since the algorithm prepares the conditions to supply energy from the stored biogas. Some slight variations take place in some simulations due to variations in electricity prices, but the most significant factor for the method is the ability to have the desired target of biogas at the beginning of a day. In this regard, it would be interesting to study which moment can be the most interesting one to set up the target value, since the study has been carried out trying to set it for 00:00, but this moment is very far from the sunrise and improving it could create a positive impact on the results.

5. Conclusions

In this research article, an efficient management algorithm for the integration of a biogas and PV plant for self-consumption was proposed. The algorithm is based on the optimization of the production and use of renewable energy, aiming to minimize the cost of energy. The performance of the algorithm was evaluated using models and simulations, contrasting data with experimental trials. The results obtained are positive, both for the improvement potential offered by the method and for its versatility for implementation under different scenarios.

The results obtained in this study show that the synergy between biogas production and PV energy generation is a promising strategy to increase the efficiency and sustainability of electricity production. Given the absence of similar algorithms, the algorithm was compared to a simple, unoptimized management, as well as to a non-adaptive strategy. One of the main highlights of the proposed algorithm is that it is a dynamic algorithm that allows for the establishment of a suitable strategy and a convenient V_{target} value for future day management. On the other hand, it highlights the ability to optimize hourly management by considering costs and purchase and sale prices of electricity.

In general, the use of the algorithm offers electricity cost reductions of almost 5% in the studied case. However, it has been found that under certain circumstances, the algorithm allows to reduce the cost in a wide range of scenarios, achieving savings between -10% and 15.6%, depending on various factors and, especially, on the weather conditions of the day being studied and the adjacent days. It must be noted that negative savings take place in days in which the algorithm is preparing the strategy for the next day, which causes a greater positive saving that compensates this situation. The obtained results can be improved with different sizes of plants, complementary strategies and more profitable conditions and energy prices.

Through this work, it has been demonstrated that the combination of biogas production and PV energy generation allows to make the most of available resources and optimize the use of produced energy and its cost, with a simple and robust algorithm. The algorithm proposed in this study is a valuable tool to achieve this goal, and its implementation can help overcome technical and economic challenges and barriers in the implementation of biogas and PV plants for self-consumption.

It is important to note that research in this area should continue to develop more advanced and adaptable algorithms for different scenarios and weather conditions, considering other sources. Among these future research lines, it is worth highlighting the use of storage systems and the possibility of cooperative management among different communities.

This algorithm will be implemented in the studied municipality to control the designed power plants and can be used in any other facility to improve the synergy between biogas plants and solar plants for self-consumption. During the implementation, the method could be redesigned so that the target of stored biogas is for the sunrise instead of the beginning of the day, since this moment is more crucial and needs special attention.

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