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A Flexible-Reliable Operation Model of Storage and Distributed Generation in a Biogas Power Plant

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Abstract: This paper presents a novel methodology for planning and operating biogas energy systems based on the transactive energy concept to determine multilevel operating regimes for distributed generation. The developed model is used to manage the production, storage, and dispatch of biogas energy systems to meet the load demands of the biogas producer and support the operation of the distribution network operator. An Integer Linear Programming (ILP) is fitted to optimize the biogas production of the biogas producer, including the operation of the biogas storage systems and their interaction with the network operator. The model's objective is to maximize benefits for the participating agents in a transactive energy context. The model's effectiveness is validated using seven case studies involving biogas systems having different operating ranges and modes to achieve enhanced flexibility and reliability for the system operation with a large proportion of intermittent energy resources. The simulation results showed that the approach could effectively manage the operation of biogas systems and their interaction with the network operator. The developed model is suitable for systems fostering net metering charging and real-time pricing.

Keywords: biogas; energy storage; distributed generation; optimization; transactive energy

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1. Introduction

1.1. Literature Review

The distribution system (DS) is undergoing substantial changes with new technological advances implemented to accommodate the high-share integration of renewable energy resources (RES), including distributed generation (DG) and energy storage systems (ESS) [1–4]. Intermittent energy sources have variable behavior in terms of uncertainty in energy production. Consequently, energy supplied by RES could be greater than the load demand at one point in time and become insufficient at another time. This uncertainty makes it more challenging for the network operator to manage the reliability and security of the systems [5–8]. According to [9], the massive adoption of RES brings challenges regarding efficiency, resilience, and flexibility to operating systems.

Currently, the development of microgrids as decentralized distribution networks is paving ways to better integrate RES into the DS with greater flexibility of balancing energy generation and loads locally [10]. Microgrids can be in islanded mode as well as be connected to the main grid, depending on the predefined agreement between the microgrid and network operators for economic and technical reasons [11].

Also, there are possibilities for increased RES in the distribution systems regarding the capability of the ESS systems. Many ESS technologies can be utilized with scalable capacities to store the energy in mechanical, thermodynamical, electrochemical, or electromagnetic form. Presently, pumped storage represents the majority of installed capacity, while batteries are second [4]. Batteries present satisfactory performance, although they have a high cost. Each ESS have their advantages and disadvantages and must be chosen according to specific needs, analyzing all parameters involved in the process, as well as the various interests of the stakeholders [12].

Biogas is a low-cost element allowing greater flexibility in electrical energy storage and utilization. In fact, research interest in electrical power generation from biogas plants has been growing recently. One of the reasons is that biogas supports sustainable energy development and is eco-friendly. Instead of burning biomass wastes, the utilization of biogas power plants decreases garbage treatment costs and pollutant emissions [13]. However, higher-quality biogas must be guaranteed to be efficiently used from existing decentralized anaerobic digesters for electricity generation. In this sense, feedstock pre-treatment, co-digestion, and user operational practices of small-scale digesters can improve biogas production and utilization efficiency [14].

An emerging concept called transactive energy (TE) has been adopted in pilot programs to maximize the benefits of all agents in DS [15]. It consists of an economic and control mechanisms system that allows the dynamic balance between supply and demand, using economic value as a key operational parameter. A major advantage of transactive energy is ensuring reliability and flexibility [9,16]. The transactive energy concept is very suitable and can be implemented in systems with smart grid technologies [17], incorporating bilateral energy exchange, market decentralization, and broad end-user participation [18].

1.2. Research Gap and Motivation

The current DS operation allows new services of prosumers of RES such as biogas DG to transact energy. A biogas DG is usually provisioned with ESS to store energy from the biogas at some point and generate electricity at another time in the future. This energy storage provisioning is indicated to complement intermittent DG [19–22] and can also facilitate transactive energy among interconnected microgrids [23]. Although prosumers (i.e., a consumer who is a producer) can generate energy to meet their own demand and offer the surplus energy to the DS [24], ineffective dispatch management of the DGs can cause several negative impacts on DS, like frequency instability, variation in voltage levels, and electrical losses [25–32].

Studies in [19,33–39] presented approaches that include using ESS with intermittent DG to minimize these impacts, where the ESS is operated to balance the systems generation and load. Seasonal energy storage through biogas from water waste treatment plants (WWTP) as an alternative to ESS is studied in [40] to facilitate the technical, economic, and commercial potentials of the hybrid systems. Research such as [19,33,38,39,41–44] has also developed optimization approaches for using ESS to enhance the DS operation. In [33], a compressed-air ESS is employed as an ancillary service in the electricity market to relieve congestion. In [39], generic storage is used with wind generation in DS to minimize daily operation costs. Both studies in [33,39] are based on mathematical modeling, including integer linear programming (ILP).

In [45], the authors investigated the possibility of reaching 100% renewable energy generation at a WWTP, composed of a photovoltaic unit, wind generator, and storage with battery and hydrogen. A bi-level model is developed to solve the optimization problem. In the first level, the renewable sources of energy self-sufficiency ratio are maximized while net present cost is minimized in the second level. Finally, they conclude that high renewable-based wastewater systems have the opportunity to provide several benefits in terms of flexible services to electric and district heating networks.

Different from [45], a study in [46] analyzed a scenario using biogas to produce heat and electricity in WWTP from the anaerobic digestion process in Italy. The research utilized a compressed air storage system and demand-response to increase flexibility and reduce electricity costs. The objective of the study is to maximize net present value and primary energy saving by optimizing electricity consumption. The study indicated that biogas integration would increase the economic profitability of the investment.

WWTP is a vast field to explore combined heat and power (CHP) generation from biogas. Another example is [47], where an energy optimization process for WWTP is studied in Poland. The study considered solar, biogas, and geothermal renewable energy sources with the goal to sell surplus energy to the power grid as a means of reaching net-zero energy on WWTP with viable economic benefits.

DG technologies are integrated and studied on sustainable buildings in [48], including biogas, solar, and wind energy, as well as storage systems. In this case, biogas is used mainly for heat production. The systems were sized, and an operation-optimized model was designed. The model considered the embedded nonlinear behavior of the equipment and dynamics of the storage units. The solution was a multi-objective and multi-scenario mixed-integer nonlinear optimization approach. An optimal coordinated multi-energy conversion with a biogas-dominated hybrid renewable microgrid for multi-carrier energy supplies in off-grid remote areas was proposed in [13]. Although biogas was not utilized directly to generate electricity, a hierarchical multi-energy management strategy was presented to dynamically optimize the production, conversion, storage, and consumption of energy flow.

Another example is an implicit model-based predictive control for DG and non-electrical power storage systems owned by third parties (i.e., a biogas plant and a water tower) developed to balance power supply and demand and limit overvoltage instances in a low voltage power distribution grid [49]. As biogas continues to gain wider attention in recent time, some systems are provisioned with vast areas for agribusiness enterprises, where waste from these businesses are indicated to have high potential for biogas production. This type of renewable energy resources would contribute to the diversification of the future energy matrix as DGs or microgrids such as in [50]. Although the previous studies [19,33,38–47] have addressed different RES proliferated including biogas-based systems with ESS capabilities, however, despite their achievements, it is still important to develop methodologies and approaches for managing biogas systems with ESS considering the operational regimes of the DG, including determining the ESS charging and discharging criterion at different operation horizons to support the biogas systems optimal use.

1.3. Contribution and Paper Organization

This paper proposes a novel optimization method for biogas energy storage systems (bioESS) to determine multilevel operational regimes (MOR) for DG. The modes (regimes) have one to three operating intervals along the day. The DG operates only with biogas fuel. The proposed methodology uses ILP to determine the power and periods the energy stored in the bioESS can be transacted inside a microgrid or sold to the distributor. This strategy allows the distributor to know which bioESS plant can be operated and for how long this energy will be guaranteed by increasing the operational safety of the system in the presence of intermittent generation sources. The major contributions of this paper are:

- Development of an optimization methodology applicable to biogas energy storage systems to determine operating regimes for DG that uses biogas as fuel and is adjustable to any type of load curve of the biogas producing property and biogas production curve.
- Encouraging the use of biogas generation systems not only for energy generation but also as an energy storage system, aiming to contribute to the operation of systems that have the participation of intermittent generations.
- Application of biogas energy storage systems for integrated use between biogas producing property and electricity distributor through the reservation of part of DG generation potential to the distributor in pre-established periods, regardless of variations in weather conditions.

Different from the research introduced in Section 1.2, this study presents multilevel operational regimes for a biogas DG. Many papers include compressed air, electricity, heat, and hydrogen storage systems [39,45,47]; however, this research utilizes biogas as storage. These characteristics promote a reliable and flexible operation for the consumer and distributor.

The rest of this paper is organized as follows. The proposed methodology is detailed in Section 2, including mathematical formulation and restrictions for MOR. In Section 3, the results of seven case studies are presented, with different operation intervals and modes. The analysis of the results is discussed in Section 4. Finally, conclusions are shown in Section 5.

2. Materials and Methods

The methodology proposes an innovative management strategy for the storage and dispatch of energy production from biogas-based DG. A smart grid scenario is considered where the bioESS energy is transacted with the main grid. An objective function to optimize the use of biogas stored is developed from the biogas production curve where the energy produced can totally or partially serve the load of the biogas property. An ILP optimization is implemented to fulfill these requirements. The restrictions on the objective function depend on the bioESS management operational characteristics, which include the minimum, maximum and initial biogas stock. Furthermore, a multilevel operational regime for DG is obtained using the fitted ILP optimization. This includes the amount of available power and the operation horizons for which the network operator can be guaranteed to buy the energy stored in the bioESS.

Figure 1 shows the flowchart of the proposed model. For the load curve of the biogas property, typical commercial curves are obtained online for simulations. The daily and hourly biogas potential are set, including the DG operation time and the intervals and availability of energy to the network operator. Subsequently, the mathematical modeling of the biogas operation is fitted using the ILP algorithm. Finally, results involving the operational regimes of DG, generation curves, gasometer size, power, and periods of available to the network operator, are obtained.

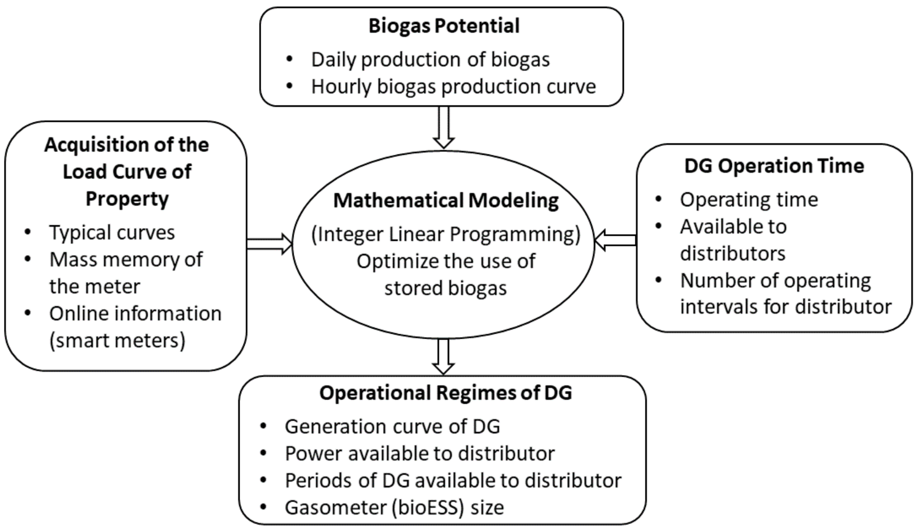


Figure 1. Structuring of the optimization method applied to bioESS to determine MOR for DG.

The development of the methodology is performed according to the steps presented in Figure 2. Initially, the MOR models are defined with the desired characteristics for the operational regimes of biogas DG. Then, the DG generating curve is determined based on relevant mathematical equations for each available period, as well as the value of biogas consumption by the DG. The mathematical modeling considers the decision variables, objective function, limits, and restrictions on the DG system, respectively.

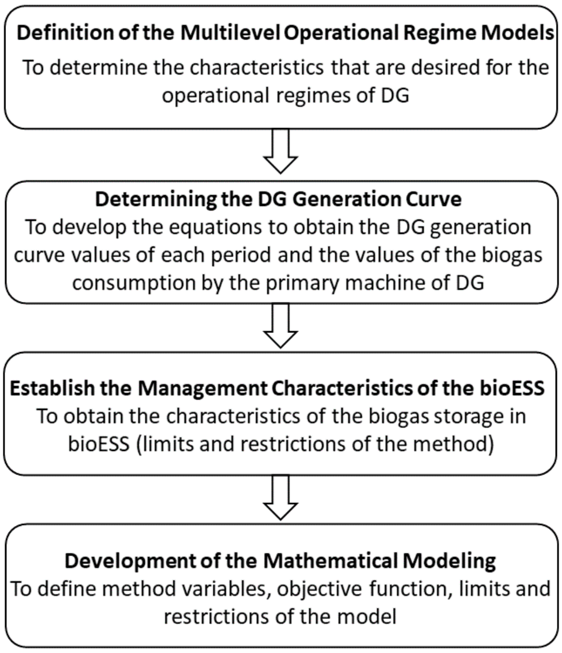


Figure 2. Steps for the development of the proposed methodology.

2.1. Definition of the Multilevel Operational Regime Models for Biogas DG

To perform the mathematical modeling of the method, it is necessary to determine the desired characteristics for the operational regimes of the DG. In this sense, two models of MOR are analyzed where biogas DG priority is to meet all or part of the load curve of the biogas producing property. Furthermore, the operational modes provide a constant power value (with stored biogas stock) for the network operator to use when necessary, according to the determined number of DG operation ranges and periods of the day.

2.1.1. Multilevel Operational Regime: Model 1

This operational regime consists of DG having an operation of fewer than 24 h, divided into one, two, or three operating intervals, considering the load curve of the property, and simultaneously with the ability to dispatch a constant power to the network operator according to the bioESS stock. In this model, in the periods of the day when the DG is not activated, the electrical energy needed to supply loads of the biogas property is supplied by the local power distributor or network operator. While DG is operating, the power generated is sufficient to meet the load curve of the biogas property and simultaneously produce a constant power that can be exported into the DS.

Figure 3 shows an example of MOR Model 1 with one operating range for the biogas DG and Figure 4 with two operating intervals. For these models, the energy is provided by the network operator when there is no generation. Based on Figures 3 and 4, the total power generated is the sum of the variable power to service the biogas property, added to the constant power (ΔPDG) that can be made available to the network operator.

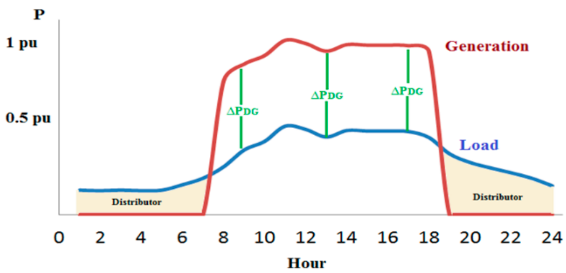


Figure 3. MOR Model 1 with one operating interval for the biogas DG and availability to distributor.

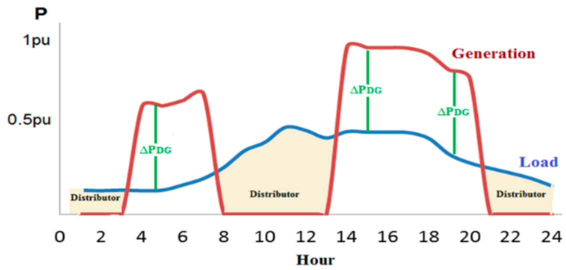


Figure 4. MOR Model 1 with two operating intervals for the biogas DG and availability to distributor.

2.1.2. Multilevel Operational Regime: Model 2

This MOR model consists of DG meeting the load curve of the biogas property for 24 h per day, with the capacity to make the energy stored in the form of biogas available to the network operator or energy distributor through a constant power value in only some periods. Figure 5 shows MOR Model 2 with one operating interval with energy available to the distributor and Figure 6, with two operating ranges.

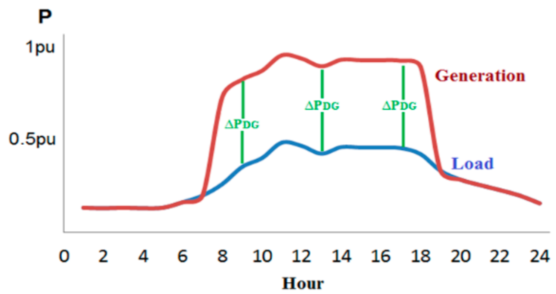


Figure 5. MOR model 2 with one operating interval available to distributor.

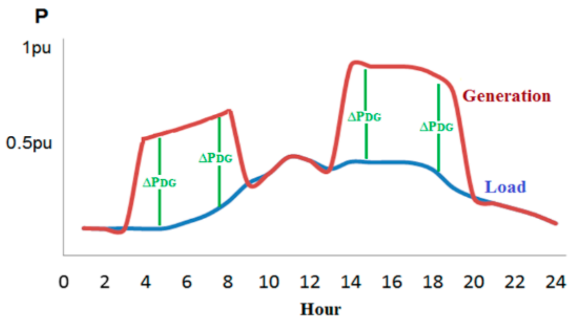


Figure 6. MOR model 2 with two operating intervals available to distributor.

Therefore, the power generated by the DG must meet all the load curves of the biogas property while at the same time providing a constant power (ΔPDG) to the distributor only during some periods of the day.

2.2. Determination of the DG Generation Curve

In Model 1 and Model 2, the power generated by the DG in each period is the power required to meet loads of biogas property in addition to the power available to the distributor. For this MOR model, a 24-h generation curve is obtained in the interval of 1 h. This does not mean that the periods exactly match the hours of the day. The method allows the first period to be any time. Then, the obtained data of both the biogas production curve and load curve of the biogas property is adjusted so that the value of the first period coincides with the starting time, counting the interval of 24 h, as shown in Figure 7. Therefore, 24 available periods for the operational regime (*NP*) are considered, and the set of planning periods (*PE*) from one to *NP*: *NP* = 24 and *PE* = {1, 2, 3, . . . *NP*}.

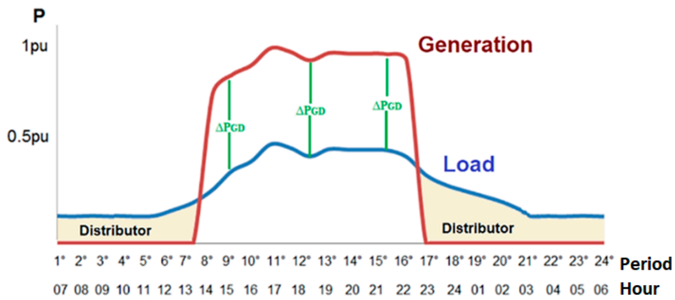


Figure 7. DG generation and load curve versus periods/hours.

The DG power generation in each period can be calculated using Equation (1):

$$PDG_j = PDGP_j + \Delta PDG_j \,, \forall j \in PE, \tag{1}$$

where PDG_j is DG generation power per period j, $PDGP_j$ is DG's capacity to serve the load of biogas owner per period, and ΔPDG_j is the constant power of DG available to the distributor per period.

Since the production of electric energy from a biogas DG depends on the induction generator and the primary machine (PM) coupled to it [51], the PM biogas consumption is directly proportional to the electric power produced. The cm is defined by the amount of biogas needed to generate electricity to meet the load curve of the biogas property (CP) added up to the amount of biogas needed to produce the constant electric power available to the distributor (cd). Therefore, the cm is calculated using Equation (2):

$$cm_j = CP_j + cd, \ldots \ \forall j \in PE \tag{2}$$

Once the load curve of the biogas property is known, the CP_j can be calculated using Equation (3):

$$CP_j = \frac{PP_j \times 3600}{PCI \times \eta \times 4.1868}, \quad \forall j \in PE, \tag{3}$$

where PP_j is the load curve power of the biogas property per period, PCI is the calorific power of biogas (in this case, PCI = 5500 kcal/Nm^3), η is generating group yield (about 23%), and 4.1868 is the conversion factor from kcal to kJ. With the CP value, it is necessary to determine electric power available to the distributor, cd_j, to obtain cm_j and consequently ΔPDG_j. Thus, bioESS management characteristics must be observed, including storage limits and physical restrictions.

2.3. BioESS Management Characteristics

The bioESSs are also called gasometers. They can have different shapes and be separated or attached to the anaerobic digesters. BioESSs use flexible membranes of various types, such as polyvinyl chloride laminate, ethylene propylene diene monomer, high-density polyethylene. Regardless of the material used, the bioESS inflates like a balloon according to the biogas production and the biogas consumption of the PM. Its operation will occur between a maximum and minimum value of storage: maximum stock (E_{max}) and minimum stock of biogas (E_{min}). The E_{max} is the maximum volume of storage defined according to the biogas production, storage period, biogas consumption of the PM, and operating pressure of the bioESS. E_{max} is guaranteed through flare, which is responsible for the burning of the excess biogas produced that cannot be stored at moments when the gasometer has already reached its maximum storage capacity for its operating pressure. To avoid its complete emptiness, a minimum volume of biogas storage E_{min} is defined as necessary to maintain the operating pressure of the bioESS. Then, the remaining biogas in the bioESS at the end of each period is used as the initial volume of biogas for the next period. The E_0 is the biogas stock existing when the DG begins to generate electrical energy, also known as the set point of the bioESS.

Figure 8 shows the DG with bioESS and the factors considered for determining biogas storage. At the initial stage, liquid wastes from a farm enter the biodigester to produce biogas. The biogas is then passed through a filter and goes to the primary machine to generate electrical energy by DG. This power flows in part to feed the biogas property loads, and a portion feeds the distribution network. The fermentation waste from the biodigester is utilized as fertilizer on the farm.

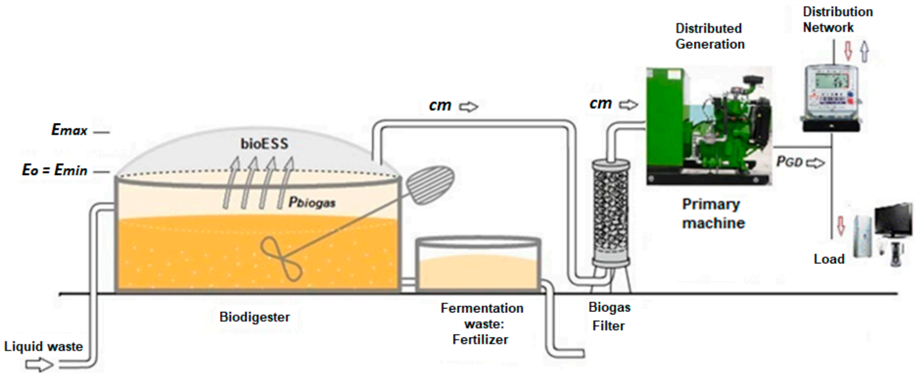


Figure 8. DG with bioESS and factors that influence its management.

To develop the proposed method, it is necessary to know the hourly biogas production per period (PBh_j). This is calculated using Equation (4), depending on the daily production of biogas (PB) in Nm^3 and hourly production rate (T_{prod/h_j}) in percentage:

$$PBh_j = PB \times T_{prod/h_j} \qquad \forall j \in PE \tag{4}$$

The stock of biogas (e_j) stored in a gasometer at any time can be calculated using Equation (5). This depends on initial biogas stock in the bioESS (E_0), PBh_j, and consumption of biogas by the primary machine, cm_j:

$$e_j = E_0 + \sum_{j=1}^{NP} \{PBh_j - cm_j\} \quad \forall j \in PE \tag{5}$$

Using Equation (6), the stored biogas that must remain in the bioESS at the end of any period is calculated, considering existing stock in the previous period (e_{j-1}), whether or not there is biogas production and consumption by the PM in this period.

$$e_j = e_{j-1} + PBh_j - cm_j, \qquad \forall j \in PE \tag{6}$$

According to the characteristics of the bioESS, in any period, the value of e_j must be kept within the minimum and maximum stock of biogas stored in bioESS, E_{min}, and E_{max}, respectively, as in constraint (7):

$$E_{min} \le e_j \le E_{max} \tag{7}$$

Since it is a daily multipath operational regime, it is necessary to establish that the initial conditions of the regime are the same at each 24-h interval while satisfying the condition in constraint (8), where e_f is the final biogas stock in bioESS:

$$e_f = e_{j=24} = E_0 = E_{min} \tag{8}$$

This restriction helps the method adjust the biogas stock in the last period of the current day so that it is equal to the initial stock in the first period of the next day. In addition, this restriction allows the process to start with the gasometer being with the minimum stock.

2.4. Mathematical Modeling

To obtain the MOR, once the values of the biogas consumption of the primary machine serving loads of the biogas property, CP_j, are known, it is necessary to determine the maximum value of the consumption of biogas from the primary machine to produce the constant electric power available to the distributor, cd, (consequently ΔPDG) and in what periods this consumption can occur. This is an optimization problem regarding using stored biogas to maximize the value of cd during the DG operating time available to the distributor (TD_{op}), irrespective of the number of generations operation intervals that are considered. The solution used to determine the MOR is based on an ILP model in [26], as presented in Figure 9. First, the data acquisition is done, including the potential of biogas production and the load curve from the biogas property. The modeling steps are as follows: definition of the parameters and sets, determination of variables, determination of Objective Function (OF), represented by z, the definition of the limits and restrictions of the variables, maximization of OF through ILP. Lastly, the results are obtained, considering the quantity of biogas and power made available to the distributor, besides the DG power generation curve.

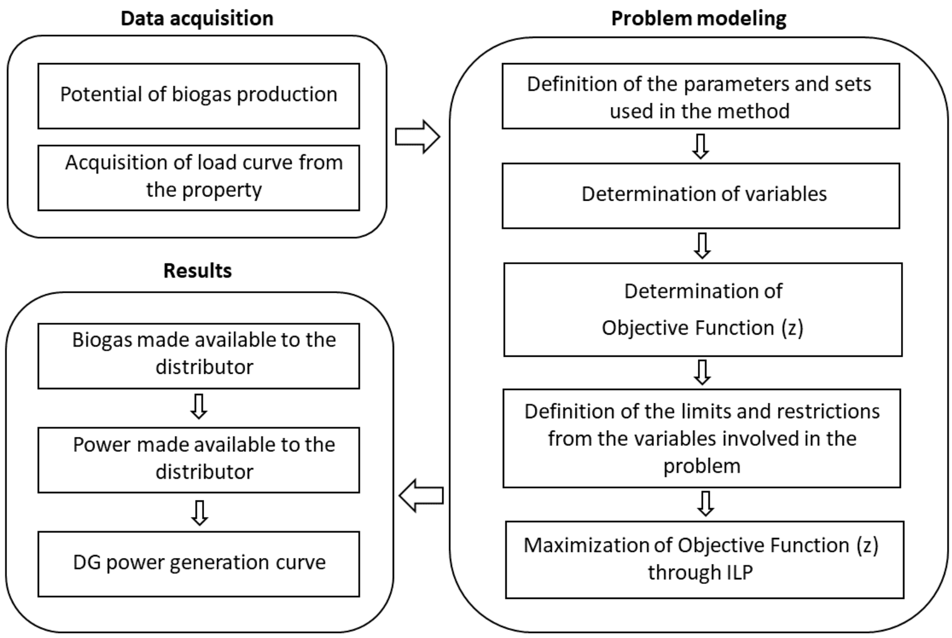


Figure 9. Development of mathematical modeling.

2.4.1. Determination of Decision Variables

The decision variables of the objective function and the model restrictions are determined according to the need to obtain the cd and the periods the DG is available to supply power to the distributor while respecting the management characteristics of bioESS. Therefore, the decision variables used and their characteristics include:

$$e_j, \qquad \forall_j \in PE_0, \qquad e_j \in \mathbb{R},$$

where PE_0 represents the planning periods plus the initial period: $PE_0 = \{0 \ldots NP\}$;

$$cd \in \mathbb{R},$$

tc_j indicates whether it has the biogas consumption to attend the distributor:

$$tc_j, \qquad \forall_j \in PE_0\,, \qquad tc_j \in \{0,1\},$$

io_j indicates the start operating interval of the DG to distributor:

$$io_j, \qquad \forall_j \in PE_0\,, \qquad io_j \in \{0,1\},$$

$$e_f = e_{j=24}, \quad e_f \in \mathbb{R}$$

In addition, M is defined as a numeric value used to validate restrictions when combined with certain integer variables. It can be calculated using Equation (9):

$$M = 10 \times \{E_{min} + (NP \times PB)\} \tag{9}$$

2.4.2. Objective Function

The OF (10) is a weighted sum involving the constant electric power available to the distributor (*cd*), the total energy produced (sum of all $e_j, \forall\, j = 1, \ldots, NP$), the final energy stock (e_f), and the number of bioESS activation ramps (io_j). The OF determines the best solution for the system according to pre-established conditions. The developed OF is composed of four parcels, each with different weights.

The first term is composed of the variable *cd*. This is maximized to obtain the best solution, considering the initial parameters and restrictions proposed for this model.

The second term, which refers to the total stock of the *NP* periods through the sum of the partials e_j, seeks to reduce the accumulated value of biogas stock; thus, this plot has a negative sign in the objective function.

The third term aims to minimize the final stock e_f, which is related to the variable e_j of the last period, that is, $e_{j=24}$.

The fourth term involves the variable io_j, in an attempt to minimize the number of bioESS activation ramps.

Associated with these four terms are the corresponding weighting factors (P_1, P_2, P_3, and P_4) in order to make the OF defined in (10) more or less influenced by one of these terms.

$$max\ \ z = \{P1 \times cd\} - \left\{P_2 \times \sum_{j=1}^{NP} e_j\right\} - \left\{P_3 \times e_f\right\} - \left\{P_4 \times \sum_{j=1}^{NP} io_j\right\} \tag{10}$$

The weighting factors of the objective function must be arbitrated for each portion of z. These weighting factors serve to determine the contributions of each portion for the OF, which means they determine which portions will contribute more in the analysis in a way that the model responds to a given commitment.

The method is based on daily operating modes. The biogas stock at the end of the day (period j = 24) must be as close as possible to the initial stock and equal to the minimum stock. The relation of them is defined in Equation (8). For this reason, final biogas stock is very representative in OF.

2.4.3. Definition of Limits and Restrictions of Quantities Involved in the Problem—Model Restrictions

For the mathematical modeling, the following restrictions are defined for MOR Model 1:

$$e_{j=0} = E_0 \tag{11}$$

$$tc_{j=0} = 0 \tag{12}$$

$$i_{Oj=0} = 0 \tag{13}$$

$$\sum_{j=1}^{NP} i_{Oj} = N_{io} \tag{14}$$

$$\sum_{j=1}^{NP} tc_j \geq TD_{op_{min}} \tag{15}$$

$$\sum_{j=1}^{NP} tc_j \leq TD_{op_{max}} \tag{16}$$

$$e_j \geq E_{min} \tag{17}$$

$$i_{Oj} \geq \{tc_j - tc_{j-1}\} \tag{18}$$

$$e_{j-1} + PBh_j \geq e_j + cd + (CP_j \times tc_j) - M(1 - tc_j) \tag{19}$$

$$e_{j-1} + PBh_j \leq e_j + cd + (CP_j \times tc_j) + M(1 - tc_j) \tag{20}$$

$$e_{j-1} + PBh_j \leq e_j + \{M \times tc_j\} \tag{21}$$

$$e_{j-1} + PBh_j \geq e_j + \{M \times tc_j\} \tag{22}$$

$$cm_j \geq cd + (CP_j \times tc_j) - M(1 - tc_j) \tag{23}$$

$$cm_j \geq (CP_j \times tc_j) - M \times tc_j \tag{24}$$

where N_{io} is the number of DG operating ranges available to the distributor, $TDop_{min}$ is the minimum time each DG-to-distributor operation interval can take, while the maximum time is $TDop_{max}$.

Restrictions (11)–(13) aim to link these variables to the zero value at the initial time, meaning DG is off and there is no biogas consumption.

The restriction (14) requires that the number of "no consumption/consumption" transitions is equal to N_{io} at most. The constraints (15) and (16) adjust each operation interval to have a pre-established number of periods between $TDop_{min}$ and the $TDop_{max}$.

The restriction (17) ensures that the biogas stock resulting in the bioESS at the end of each period is equal or greater than the pre-established minimum stock. The (18) assists the method to define the periods when the beginning of the operation intervals will occur. It happens by analyzing the difference between the variables tc_j (current period) and tc_{j-1} (previous period).

Restrictions (19) and (20) are equivalent to the energy conservation equation for the biogas production, the primary machine consumption (cm_j), and the remaining stock in each planning period. The linkage of (19) and (20) with MOR Model 1 is given by the use of plots ($CP_j \times tc_j$) and $M(1 - tc_j)$ whenever the model defines that there will be consumption (tc_j = 1). In this case, the property load will be considered in the equation along with the value of cd, and the value of M will be eliminated to make this restriction active.

In case MOR Model 1 there is no consumption in the corresponding period, tc_j = 0, restrictions (19) and (20) are made inactive due to the presence of the value of M, and become valid restrictions (21) and (22) to performing energy conservation in each period. These two define that the biogas stock of a certain period without primary machine consumption is equal to the previous period's stock added to the current biogas production period.

The constraints (23) and (24) help the method determine the value of cm_j in all periods. The constraint (23) will be valid in the periods when the method determines that there can be generation to the distributor. The (24) will be valid for periods when there will be no generation for the distributor.

To obtain a MOR with the characteristics of Model 2, we utilized the same objective function (10) of Model 1 and also its Equations (11)–(18), including Equations (25)–(30).

$$e_{(j-1)} + PBh_j \geq e_{(j)} + cd + CP_j - M(1 - tc_j) \tag{25}$$

$$e_{(j-1)} + PBh_j \leq e_{(j)} + cd + CP_j + +M(1 - tc_j) \tag{26}$$

$$e_{(j-1)} + PBh_j \leq e_j + CP_j + M \times tc_j \tag{27}$$

$$e_{(j-1)} + PBh_j \geq e_{(j)} + CP_j - M \times tc_j \tag{28}$$

$$cm_j \geq cd + CP_j - M(1 - tc_j) \quad (29)$$

$$cm_j \geq CP_j - M \times tc_j \quad (30)$$

Restrictions (25) and (26) have the same functions for the method when compared with constraints (19) and (20) of Model 1. However, to meet the characteristics of Model 2, the variable tc_j is not multiplied by *CPj*, since in Model 2, the load curve of the property is met by DG through all *PE*.

The (27) and (28) adjust the value of the biogas stock in the periods when there is no generation of the DG to the distributor. In (27) and (28), it is necessary to consider *CPj* in the second inequation plot since there will be consumption of biogas to serve the biogas property during the 24 periods.

Restrictions (29) and (30) are used to determine *cm* value in all periods. The restriction (29) is valid in the periods when the method determines that there can be a generation to the distributor, while constraint (30) is valid for the periods in which there will be no generation to the distributor.

After defining the parameters, sets, decision variables, objective function, and the model constraints, the mathematical model is solved using the built-in optimizer (Solver function) in the *MS OpenOffice Calc* software environment.

2.5. Case Study

For the proposed model, data from a rural pig farm located in Itapiranga City, Brazil, is used to validate its effectiveness. The biogas property participates in the Research & Development program of the National Electric Energy Agency with the Federal University of Santa Maria and Eletrosul—Power Plants S.A.—Brazil.

The rural biogas property considered in this study has the following operation characteristics:

- 2100 swine herds;
- PB = 786.24 Nm^3;
- Average electricity consumption of 9254 kWh/month.

In addition to the characteristics of the biogas property, the following parameters are considered:

- Biogas property load curve = Typical commercial curve; E_{min} = 5% of PB = 39 Nm^3;
- PBh_j = constant;
- Process starting arbitrarily at 1 a.m.

From the initial data, the method is used to solve seven MOR cases for DG as follows:

- Case 1: MOR Model 1 with T_{op} = 10 h; one operating range and $E_0 = E_{min}$;
- Case 2: MOR Model 1 with T_{op} = 10 h; two operating ranges and $E_0 = E_{min}$;
- Case 3: MOR Model 1 with T_{op} = 10 h; three operating ranges and $E_0 = E_{min}$;
- Case 4: MOR Model 2 with T_{op} = 10 h; one operating range and $E_0 = E_{min}$;
- Case 5: MOR Model 2 with T_{op} = 10 h; two operating ranges and $E_0 = E_{min}$;
- Case 6: MOR Model 2 with T_{op} = 10 h; three operating ranges and $E_0 = E_{min}$;
- Case 7: MOR Model 1 with T_{op} = 10 h; two operating ranges and E_0 = 80 Nm^3.

Therefore, in cases 1, 2, 3, and 7, Model 1 is set, while in cases 4, 5, and 6, Model 2 is set in the simulations. Regarding E_0, exceptionally in case 7, it is different from E_{min} compared to the other cases. This value is arbitrated to analyze the behavior of the biogas DG in this model with a higher initial condition for E_0.

3. Results

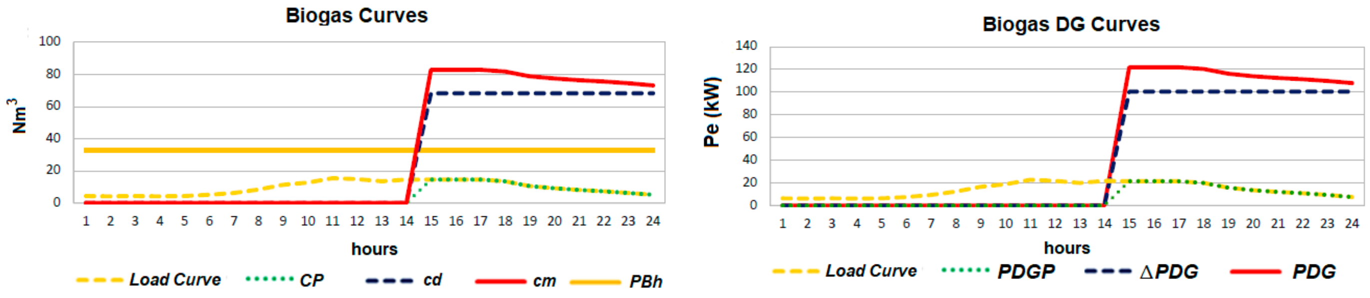
The hourly simulation results obtained for the seven cases, including the biogas property hourly load curve (PP_j) and biogas consumption to generate electric energy to meet the biogas property (CP_j) are presented in Table 1.

Table 1. Values calculated for CP_j to attend the property load curve.

Hour	PP_j (kW)	CP_j (m^3)
	6.27	4.26
2	6.14	4.17
3	6.27	4.26
4	6.14	4.17
5	6.27	4.26
6	7.67	5.21
7	9.34	6.35
8	12.27	8.34
9	16.59	11.28
10	18.82	12.79
11	22.73	15.45
12	21.89	14.88
13	19.94	13.55
14	21.61	14.69
15	21.47	14.59
16	21.47	14.59
17	21.33	14.50
18	19.8	13.46
19	15.62	10.62
20	13.39	9.10
21	11.99	8.15
22	10.74	7.30
23	9.34	6.35
24	7.39	5.02

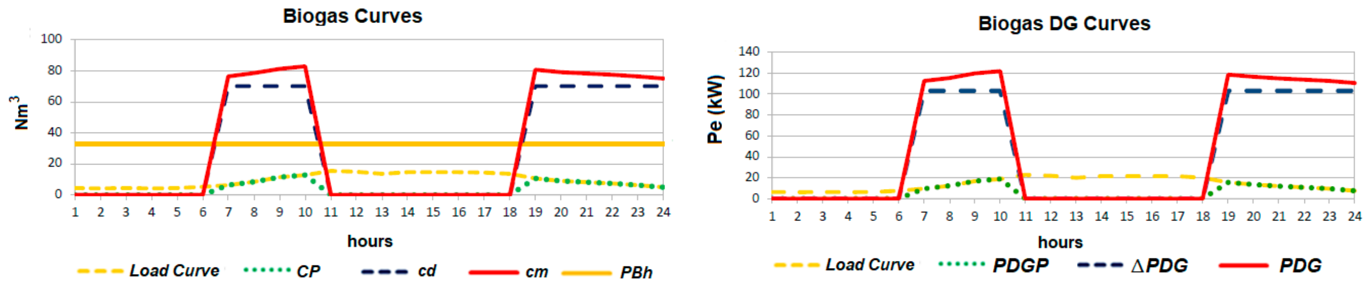
For the curves, they are presented as biogas energy (in Nm^3), generated from biogas DG for each hour of the day, utilized by DG, and electric power, *Pe*, in kW. The biogas curves depict the load curve, biogas consumption from the primary machine to serve loads of the biogas property (*CP*) and to produce the constant electric power available to the distributor (*cd*), biogas consumption by the primary machine (*cm*), and hourly biogas production (*PBh*). Also, the DG generation curves show the DG generation power (*PDG*), constant power of DG available to distributor (ΔPDG), DG capacity to serve the load of biogas property (*PDGP*), and load curve. Figures with these results for each case are shown as follows:

- Case 1: biogas curves in Figure 10a and power curves of MOR from biogas DG in Figure 10b;
- Case 2: biogas curves in Figure 11a and power curves of MOR from biogas DG in Figure 11b;
- Case 3: biogas curves in Figure 12a and power curves of MOR from biogas DG in Figure 12b;
- Case 4: biogas curves in Figure 13a and power curves of MOR from biogas DG in Figure 13b;
- Case 5: biogas curves in Figure 14a and power curves of MOR from biogas DG in Figure 14b;
- Case 6: biogas curves in Figure 15a and power curves of MOR from biogas DG in Figure 15b;
- Case 7: biogas curves in Figure 16a and power curves of MOR from biogas DG in Figure 16b.



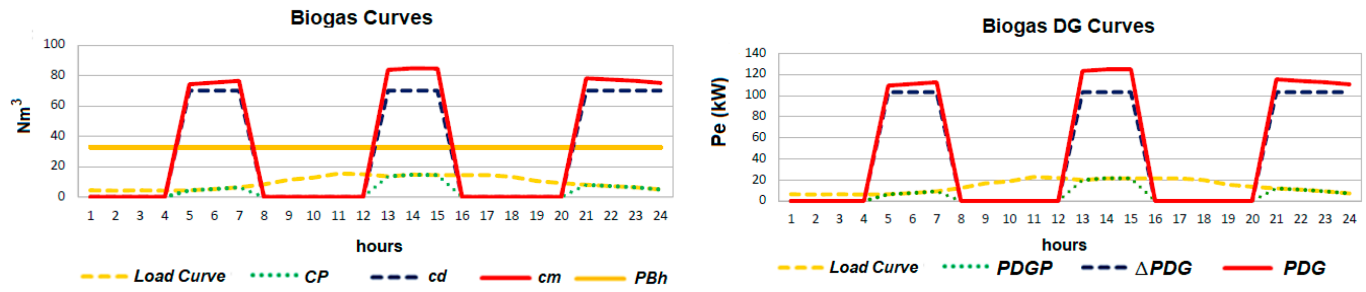
(**a**) (**b**)

Figure 10. Case 1: (**a**) Biogas curves; (**b**) MOR from biogas DG.



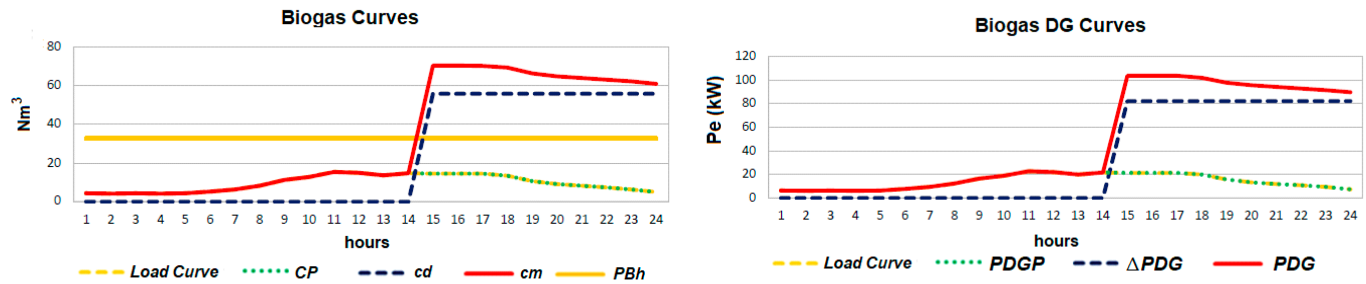
(**a**) (**b**)

Figure 11. Case 2: (**a**) Biogas curves; (**b**) MOR from biogas DG.



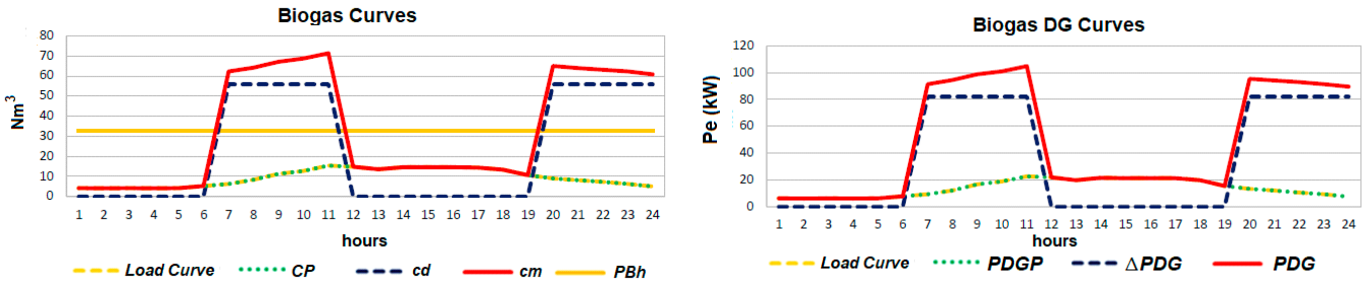
(**a**) (**b**)

Figure 12. Case 3: (**a**) Biogas curves; (**b**) MOR from biogas DG.



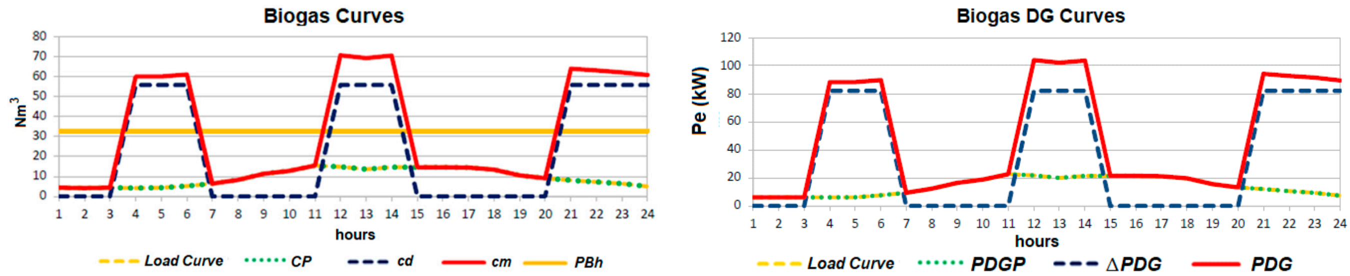
(**a**) (**b**)

Figure 13. Case 4: (**a**) Biogas curves; (**b**) MOR from biogas DG.



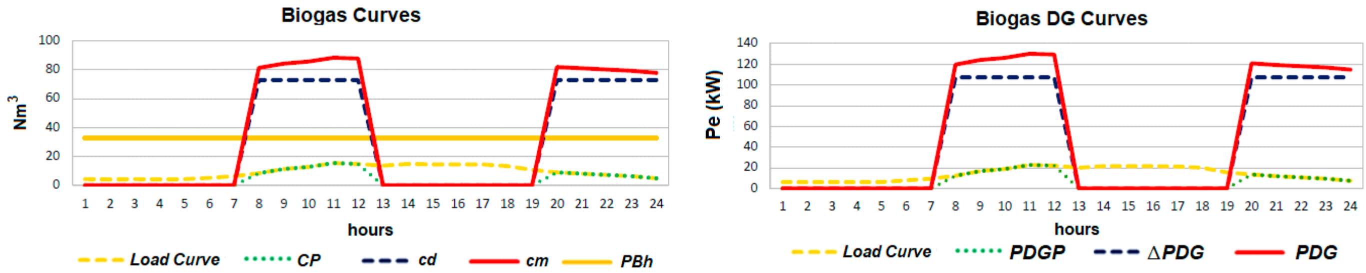
(**a**) (**b**)

Figure 14. Case 5: (**a**) Biogas curves; (**b**) MOR from biogas DG.



(**a**) (**b**)

Figure 15. Case 6: (**a**) Biogas curves; (**b**) MOR from biogas DG.



(**a**) (**b**)

Figure 16. Case 7: (**a**) Biogas curves; (**b**) MOR from biogas DG.

The simulation results confirmed the priority of meeting the property load curve on the operating ranges for all cases, while the surplus energy is offered to the distributor for strategic utilization. Electric power generation only occurs on determined ranges for cases 1, 2, 3, and 7. In cases 4, 5, and 6, the DG is used to meet the load curve of the biogas property for 24 h. In case 7, the initial biogas stock is observed to be higher than the minimum stock, and the simulation results were successfully obtained as well. By observing biogas curves, it is noticed that biogas production is constant along the day, but the PM operation to generate energy is set according to the MOR and optimization method. The simulation results are for Models 1 and 2 proposed for this analysis with their respective characteristics.

In Table 2, there are the numerical results for Case 1, according to the hour of the day. Throughout the beginning of the day, the bioESS accumulated biogas until the moment when the DG was activated. From that moment on, the energy from the DG met the property's loads, and the surplus was injected into the grid. This behavior is clarified with the values in Table 2.

Table 2. Detailed results for Case 1 (MOR Model 1 with one operating range).

Hour	Biogas (m^3)		Primary Machine Consumption (m^3)			bioESS (Nm^3)	Power DG (kW)		
	PBh_j	Load Curve	CP_j	cd	cm_j		$PDGP_j$	ΔPDG	PDG_j
1	32.76	4.27	-	-	-	71.76	-	0.00	0.00
2	32.76	4.17	-	-	-	104.52	-	0.00	0.00
3	32.76	4.27	-	-	-	137.28	-	0.00	0.00
4	32.76	4.17	-	-	-	170.04	-	0.00	0.00
5	32.76	4.27	-	-	-	202.80	-	0.00	0.00
6	32.76	5.21	-	-	-	235.56	-	0.00	0.00
7	32.76	6.35	-	-	-	268.32	-	0.00	0.00
8	32.76	8.34	-	-	-	301.08	-	0.00	0.00
9	32.76	11.28	-	-	-	333.84	-	0.00	0.00
10	32.76	12.80	-	-	-	366.60	-	0.00	0.00
11	32.76	15.45	-	-	-	399.36	-	0.00	0.00
12	32.76	14.88	-	-	-	432.12	-	0.00	0.00
13	32.76	13.55	-	-	-	464.88	-	0.00	0.00
14	32.76	14.69	-	-	-	**497.64**	-	0.00	0.00
15	32.76	14.60	14.60	68.25	82.85	447.55	**21.47**	**100.42**	**121.89**
16	32.76	14.60	14.60	68.25	82.85	397.46	**21.47**	**100.42**	**121.89**
17	32.76	14.50	14.50	68.25	82.76	347.46	**21.33**	**100.42**	**121.75**
18	32.76	13.46	13.46	68.25	81.71	298.51	**19.80**	**100.42**	**120.22**
19	32.76	10.62	10.62	68.25	78.87	252.40	**15.62**	**100.42**	**116.03**
20	32.76	9.10	9.10	68.25	77.35	207.80	**13.39**	**100.42**	**113.80**
21	32.76	8.15	8.15	68.25	76.41	164.16	**11.99**	**100.42**	**112.41**
22	32.76	7.30	7.30	68.25	75.55	121.36	**10.74**	**100.42**	**111.15**
23	32.76	6.35	6.35	68.25	74.61	79.52	**9.34**	**100.42**	**109.76**
24	32.76	5.02	5.02	68.25	73.28	39.00	**7.39**	**100.42**	**107.81**

Table 3 presents some results obtained for each proposed regime, including the consumption of biogas from the primary machine to produce the constant electric power available to distributor (*cd*), the constant power of DG available to distributor (ΔPDG), biogas energy stored (bioESS), and the working periods.

Table 3. Results of the studied operating modes.

MOR	*cd*	ΔPDG	bioESS	Periods
Case 1	68.25 Nm^3	100.42 kW	497.64 Nm^3	15–24°
Case 2	70.09 Nm^3	103.12 kW	309.54 Nm^3	7–10° 19–24°
Case 3	70.07 Nm^3	103.09 kW	215.08 Nm^3	5–7° 13–15° 21–24°
Case 4	55.89 Nm^3	82.22 kW	373.00 Nm^3	15–24°
Case 5	55.89 Nm^3	82.22 kW	209.21 Nm^3	7–11° 20–24°
Case 6	55.82 Nm^3	82.13 kW	158.69 Nm^3	4–6° 12–14° 21–24°
Case 7	72.68 Nm^3	107.19 kW	309.32 Nm^3	8–12° 20–24°

4. Discussion

In the study, the proposed optimization method is applied to obtain seven operation possibilities. These include case 1, case 2, and case 3, all based on the MOR Model 1. Cases 4, 5, and 6 are based on Model 2, while case 7 is based on Model 1, but with an initial condition different from Model 1 and 2.

As shown in Table 3 for cases 1, 2, and 3, the consumption values of biogas from the primary machine to produce the constant electric power available to the distributor, cd, and ΔPGD vary slightly for the same time of operation on DG available intervals for the distributor (TD_{op} = 10 h). This is probably due to the variation in the load curve of the biogas property.

However, case 3 allows distribution of the TD_{op} during the day due to the three operating intervals. This MOR allows greater flexibility of the use of DG by the distributor and to transact energy. In addition, case 3 enables the use of a lower storage capacity on bioESS. On the other hand, cases 4, 5, and 6 resulted in lower ΔPGD than in cases 1, 2, and 3. In these cases, the property became self-sufficient in electric energy, leading to a larger biogas destination for the biogas property. Besides the difference in ΔPGD, the DG available periods for the distributor are also different.

Case 7 demonstrates that if E_0 becomes larger than E_{min}, the method allows setting a new value for ΔPGD in the next 24 periods so that e_f turns to be equal to the E_{min}, returning the next day with $e_f = E_{min}$.

When comparing Model 1 and Model 2, the distributor has more benefits on the amount of available power to DS. Model 2 prioritizes the biogas property energy consumption all day long. However, Model 1 looks more attractive for this prosumer if the tariff to transact energy is high.

Analyzing other research, we notice some similarities between them and the present work. The study from [39] also has an ESS, injects surplus energy to the DS, and the analyzed time is 24 h. However, it didn't include biogas, and the optimization model was stochastic mixed ILP, utilized in the 70-bus DS. In [49], the authors simulated a control for DS with mixed-integer nonlinear programming, where biogas plant and water towers were assets of the system. In [47], besides biogas, they implemented another DER and made available to the distributor the surplus from generation as well.

The present study can mitigate the fluctuating outputs of renewable energy sources, as shown in [13], through biogas and its storage. The analysis of the results proves the management strategies' potential for reaching the power supply with biogas DG, a flexible asset, as presented and discussed by [49]. Unlike [48], where biogas mainly generated heat power, this research focused on biogas as a strategic storage system. It was also able to generate electricity when suitable, following the established modes.

Therefore, according to the results obtained in the evaluated cases, we highlight that the proposed methodology presented the following characteristics:

- Fits any type of load curve and any type of biogas production curve;
- Allows DG to meet all or part of the property load, depending on initial settings;
- BioESS represents flexibility in storage, once it can be utilized to generate electrical energy in programmed periods;
- It makes it possible to determine new values of power reserved to the distributor in cases where there is an initial stock different from the one defined in the beginning, guaranteeing the return of the initial pre-established conditions for the next PE;
- Determines in advance the times that the distributor can rely on this energy, regardless of variations in weather conditions;
- Allows that the energy made available to the distributor can be delivered during the day, according to the number of established operating ranges, which makes its use more flexible so that the distributor can plan the utilization of this energy on complementing intermittent DG sources or flatten peak demand curve;
- Allows the determination of the bioESS size when choosing to use a MOR permanently, and also the reduction of the bioESS in cases where more than one DG operation interval to the distributor is utilized;
- Allows the availability times to be changed since the method uses periods, and it is possible to shift times concerning the periods.

The development of this paper identified as future research directions the expansion of model restrictions considering implementation, operation, and maintenance costs as well as electricity tariffs. Then, new periods of available energy reserve to distributors could be obtained. Additionally, an extension of the developed methodology for any renewable DG source coupled with ESS could be implemented. Another feasible option is to utilize the heat produced by biogas. This could be done through CHP units, complementing the system. Thus, the heat could match the system's needs, especially in the digestor processes.

5. Conclusions

Intermittent energy sources in the power grid bring about more challenges, such as maintaining integrity and flexibility. Transactive energy is an emerging system that can contribute to the grid and facilitate energetic flows between participants. In this analysis, the bioESS converts biogas to electrical energy only when DG is activated. This method can be used in systems that use net metering charging or real-time pricing.

According to the results presented in the case studies, the developed method allows a MOR to be established, in which DG can meet all or part of the biogas property load. With the optimized method implemented through ILP, it is possible to use biogas stock and provide a power value in certain periods for the distributor to use if necessary. When the DG was activated, the maximum powers available to the distributor varied between 82.13 kW (Case 6) and 107.19 kW (Case 7).

According to the seven cases simulated, if digestors operators want to guarantee load supply, Model 2 is more indicated to implement. Nonetheless, if the priority is to transact energy with the grid, Model 1 should be chosen. The number of operating intervals didn't present large differences in the same model's simulations. This methodology allows any load and biogas production curve to be used, and even the available energy to the distributor can be delivered during the day according to pre-established requirements. The distributor can manage and use it to complement intermittent DG sources, regardless of variations in climatic conditions. Thus, the method presented a strategy that allows greater flexibility and reliability in DS. Also, the method allows new values of available power to the distributor that can be adjusted when an initial stock different from the one established for the operation in regime occurs, guaranteeing the return of the initial pre-established conditions for the next day. In addition, the availability times obtained may be changed since the method uses periods, and it is viable that there is a shift of the schedules about the periods. Finally, the developed method makes it possible to use bioESS with reduced sizes in cases where more than one DG operating range available to the distributor is implemented.

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Abbreviations

The following abbreviations are used in this manuscript:

bioESS	Biogas energy storage system
CHP	Combined heat and power
DER	Distributed energy resources
DG	Distributed generation
DS	Distribution system
ESS	Energy storage system
ILP	Integer linear programming
MOR	Multilevel operational regimes
OF	Objective function
PM	Primary machine
TE	Transactive energy
WWTP	Wastewater Treatment Plant

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