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Energy Flows Optimization in a Renewable Energy Community with Storage Systems Integration

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Abstract. Currently, there is increasing implementation of renewable energy communities, where consumers and producers come together to form energy cooperatives. This growing trend has been accompanied by several studies aiming to optimize energy exchanges and sharing inside the community, always taking into account the most favorable tariff regimes for community members. This paper presents an analysis that, based on applying a linear programming model, optimizes energy transactions in a renewable energy community with the integration of storage systems. The results show the developed model's effectiveness, presenting substantial profits for the community.

Key words. Optimization, Renewable Energy Community, Energy Storage System.

1. Introduction

Electrical power systems are undergoing an evolution from a centralized production model to a more sustainable and distributed model. In the past, the electrical grid had a simple structure, with energy flowing from large production plants to consumers, with energy sources based on fossil fuels.

The growing concern in achieving the energy transition and the increase in environmental awareness has led the European Union to define targets that encourage the inclusion of renewable energy sources close to the consumption location, which, in addition to giving consumers a more active role, contributes to the fulfillment of European environmental objectives. On December 11, 2018, Directive (EU) nº 2018/2001 of the European Parliament and Council was published, which promotes greater use of energy from renewable sources, allowing consumers of renewable energy to produce, consume, store, share and sell energy without being faced with disproportionate burdens. The aforementioned regime enshrines the definition of the concepts of individual and collective self-consumption of energy and renewable energy communities (REC) [1].

In [2], a mathematical model is proposed to optimize wind energy production for self-consumption in a high-rise building, maximizing the return on investment. The proposed approach finds the most profitable location to install the wind turbines on the roof of the building, and the optimization model determines the optimal wind turbine type and the energy storage systems (ESS) to be installed. The results guarantee an investment payback period of around seven years, with huge savings across the system's useful life.

In [3,4,5], the maximization of the profitability of wind generation is addressed, namely in the design of onshore wind farms minimizing the costs of installation and active and reactive power losses during the lifetime of the farm, considering one or several substations, with or without ditch sharing. The results show that the optimization model allows significant savings.

Energy communities with the integration of ESS play an important role in the success of the energy transition. Several studies show the importance of REC in improving energy management [6,7]. It is expected that shortly a large amount of energy production will be decentralized, leading to a mismatch between energy production and demand, which according to the authors, needs to be addressed with energy flexibility options. Therefore, the development of optimization models using energy management systems play an important role in establishing the space-time flexibility of energy resources. The study results indicate that from a technical point of view, developing a controller capable of effectively implementing the management of energy flows in a community represents a challenge due to the need for real-time coordination between buildings. However, from an economic point of view, the benefits increase substantially with the integration of ESS. In this sense, optimization systems are a tool capable of overcoming the challenges imposed by energy flexibility.

In [8], the authors present a linear optimization model based on the constitution of a REC with the integration of ESS. The model considers, as decision variables, in each period, the amount of energy purchased from the grid, the amount of energy taken from the battery, the amount of energy injected into the battery, as well as the state of the battery. The energy purchase price to the grid and the variation of the market price are considered. From the analysis of the study, it can be concluded that RECs can reduce total energy costs by 15%, allowing them to achieve a 34% reduction in total carbon dioxide emissions.

According to [9], energy communities are identified by the European Union as a key element in increasing the consumption of energy from renewable sources. In this study, the possibility of trading energy between community members and the energy market is analyzed. The storage of energy surplus in batteries allows energy savings between 11 to 13%, which can be increased to 25% if combined with the peer-to-peer model.

Moncecchi et al. [10] evaluate from the point of view of the feasibility of implementing a community through the application of a genetic algorithm. The main conclusion of this study is that storage systems improve the net present value (NPV) and reduce prosumers' dependence on the power grid.

The optimization problem developed in this paper is based on mixed-integer linear programming. The objective function corresponds to the maximization of REC profit considering the use of production units for self-consumption and ESS. The optimization model was solved using the Xpress Optimization tool. The optimal solution determines the energy flow between the self-consumers, the grid, and the storage systems. It is also possible to determine, based on the prices of the adopted tariffs and the energy sale price defined by the Iberian market, the periods in which it is more advantageous to buy energy from the grid or to discharge the battery.

2. Mathematical Model

In this section the optimization model is presented. The goal is to maximize the CER's profit, considering the use of production units for self-consumption and ESS. It is intended to determine when and how much energy to buy/sell to the grid and charge/discharge the battery, based on the demand, the production, the adopted tariff prices, and the energy selling price, considering the costs associated with the integration and maintenance of the ESSs.

A) *Problem Data*

- $H = \{1, \cdots, nh\}$, set of hour periods per day, where $nh = 24$;
- $M = \{1, \cdots, nm\}$, set of months per year, where $nm = 12$;
- $TB = \{1, \cdots, nb\}$, set of available ESS module type, where $nb = 6$;
- $B = \{1, \cdots, nbt\}$, set of available batteries, were $nbt = \sum_{i \in TB} ni$ and $ni = 3$ is the number of available modules of type $i,\ i \in TB$;
- kbt_i, the storage capacity of battery $i,\ i \in B$;
- $cmbt_i$, maintenance cost of battery $i,\ i \in B$, over 10 years;
- $cabt_i$, cost of battery $i,\ i \in B$;
- Kbt_i, storage capacity of battery $i,\ i \in B$;
- D_{ij}, energy demand, kWh, in period *i* of month j, $i \in H, j \in M$;
- PF_{ij}, photovoltaic production, kWh, in period *i* of month $j,\ i \in H, j \in M$;
- co_{ij}, selling price of energy on the market (OMIE) to the RESP (€/kWh), in period *i* of month $j,\ i \in H, j \in M$;
- ce_i, price for the purchase of energy from the RESP (€/kWh), in period i , $i \in H$;
- cc, price for the purchase of energy (€/kWh) within the community ($cc = 0.11081$).
- Max, is a big constant.

B) *Decision Variables*

For each $i \in H, j \in M$, let:

- x_{ij}, amount of energy purchased from the grid (kWh), in hour *i* of month *j*;
- xx_{ij}, binary variable that takes the value 1 if there is energy purchased from the grid in the hour *i* of month *j*, it takes value 0 otherwise;
- y_{ij}, amount of energy sold to the grid, in hour *i* of month *j*;
- yy_{ij}, binary variable that takes the value 1 if there a sale of energy to the grid in hour *i* of month *j*, it takes value 0 otherwise;
- bi_{ijb}, amount of energy injected into battery *b*, with $b \in B$, in hour *i* of month *j*;
- bbi_{ijb}, binary variable that takes the value 1 if there is an injection into the battery *b*, with $b \in B$, in hour *i* of month *j*, it takes value 0 otherwise;
- bs_{ijb}, amount of energy leaving battery *b*, with $b \in B$, in hour *i* of month *j*;
- bbs_{ijb}, binary variable taking value 1 if there is power going out of the battery *b*, with $b \in B$, in hour *i* of month *j*, it takes value 0 otherwise;
- ssb_{ijb}, amount of storage energy in battery $b \in B$, at the beginning of hour *i*, in month *j*;
- BSt_{ij}, binary variable indicating whether there is energy output from batteries at hour *i* in month *j*;
- BIt_{ij}, binary variable indicating whether there is energy injection into batteries at hour *i* in month *j*;
- w_b, binary variable taking value of 1 if the battery *b* is used; otherwise it is 0, with $b \in B$;
- z_{ij} , amount of energy sold to the community at hour *i* in month *j*.

C) *Constraints*

The system constraint that guarantees that the energy demand by self-consumers is satisfied is represented by Eq. (1). It ensures that the amount of energy produced by the photovoltaic modules plus the energy bought to the RESP and the energy discharged by the battery is equal to the demand plus the amount of energy injected into the battery and the energy sold to the RESP.

$$PF_{ij} + x_{ij} + \sum_{b \in B} bs_{ijb} = D_{ij} + \sum_{b \in B} bi_{ijb} + y_{ij},\ i \in H, j \in M \quad (1)$$

Constraints (2) link variables yy and y, ensuring that if in period ij there is a sale of energy to the grid, then the variable yy_{ij} takes value 1; otherwise, it takes the value 0. Constraints (3) link variables xx and x, ensuring that if in a period ij there is an energy purchase from the grid, then the variable xx_{ij} takes the value 1; otherwise, it takes the value 0. Constraints (4) prevent buying and selling power in the community at the same time period.

$$\boldsymbol{yy_{ij} \leq y_{ij} \leq yy_{ij} \cdot Max, \quad i \in H, j \in M} \quad (2)$$

$$\boldsymbol{xx_{ij} \leq x_{ij} \leq xx_{ij} \cdot Max, \quad i \in H, j \in M} \quad (3)$$

$$\boldsymbol{xx_{ij} + yy_{ij} \leq 1, \quad i \in H, j \in M} \quad (4)$$

Constraints (5)–(12) ensure the correct operation of the storage system. Constraints (5) ensure that the battery stock in the initial period is zero. Constraints (6) ensure that the amount of energy in stock in the battery cannot exceed its storage capacity. Constraints (7) are the balance equations ensuring that the energy stock in period i+1 corresponds to the sum of the energy in stock in period i, with the injected energy in that period, excluding the discharged energy. Constraints (8) ensure that in the last period of the day, the amount of energy in stock in the battery is equal to zero.

$$\boldsymbol{ssb_{1jb} = 0, \quad j \in M, b \in B} \quad (5)$$

$$\boldsymbol{ssb_{ijb} \leq kbt_b \cdot W_b, \quad i \in H, \ j \in M, b \in B} \quad (6)$$

$$ssb_{i+1jb} = ssb_{ijb} + bi_{ijb} - bs_{ijb}, i \in H, i < nh, \ j \in M, b \in B \quad (7)$$

$$ssb_{24jb} + bi_{24jb} - bs_{24jb} = 0, \quad j \in M, b \in B \quad (8)$$

Constraints (9) relate variables bbi and bi, and restrict the amount of energy injected into the battery from being greater than its storage capacity. Similarly, constraints (10) relate variables bbs and bs, and bound the amount of energy leaving the battery by its capacity. Constraints (11) relate variables BIt with bbi, assuring that if, in a period, there is energy injection in a battery then BIt_{ij} takes the value 1; otherwise, it takes the value 0. Constraints (12) relate variables BSt with bbs, assuring that if, in a period, there is energy acquisition from a battery then BSt_{ij} takes value 1; otherwise, there is no energy acquisition from any battery and so then BSt_{ij} takes the value 0. Constraints (13) and (14) prevent charging and discharging from taking place at the same time period, by battery and by all the batteries, respectively.

$$bbi_{ijb} \leq bi_{ijb} \leq bbi_{ijb} \cdot kbt_b, \ i \in H, j \in M, b \in B \quad (9)$$

$$bbs_{ijb} \leq bs_{ijb} \leq bbsi_{ijb} \cdot kbt_b, \ i \in H, j \in M, b \in B \quad (10)$$

$$BIt_{ij} \leq \sum_{b \in B} bbi_{ijb} \leq BIt_{ij} \cdot nbt, \ i \in H, j \in M \quad (11)$$

$$BSt_{ij} \leq \sum_{b \in B} bbs_{ijb} \leq BSt_{ij} \cdot nbt, \ i \in H, j \in M \quad (12)$$

$$bbs_{ijb} + bbi_{ijb} \leq 1, \quad i \in H, j \in M, b \in B \quad (13)$$

$$BIt_{ij} + BSt_{ij} \leq 1, \ i \in H, j \in M \quad (14)$$

Constraints (15) ensure that the lifetime of the batteries, stated by the manufacturer, is not exceeded. It provides that the total charges and discharges during the planning period, ten years, can be, at most, the recommended number of cycles for the battery, which is 4500.

$$\sum_{i \in H \ j \in M} bbi_{ijb} + bbs_{ijb} \cdot 10 \leq 4500 \cdot W_b, \quad b \in B \quad (15)$$

D) Objective function

The objective function intends to maximize the REC profit, L, which is given by the difference between the revenue from the sale of energy to the grid and the cost of purchasing energy, including the cost of acquiring and maintaining the batteries, considering ten years (lifetime of a stored system considering its technical specifications).

$$\max \quad L = 305 \sum_{i \in H \ j \in M} (y_{ij} \cdot co_{ij} - x_{ij} \cdot ce_i) - \sum_{i \in B} w_i \cdot (cabt_i + cmbt_i) \quad (16)$$

3. Case Study

The REC under analysis is located in southern Portugal, has 7 self-consumers, and the data corresponds to 2021. This REC has a total contracted power of 182.8 kVA, where all members present the daily cycle and the bi-hourly tariff. REC's annual aggregate consumption is 221 MWh. About 70% of the energy is consumed during peak hours, and only 30% is consumed during off-peak hours.
Figure 1 shows the aggregate consumption of the community for one working day of each month. These days will be considered later when the optimal solution is analyzed, emphasizing the energy flow between the self-consumption production units and the storage systems on some of these days.

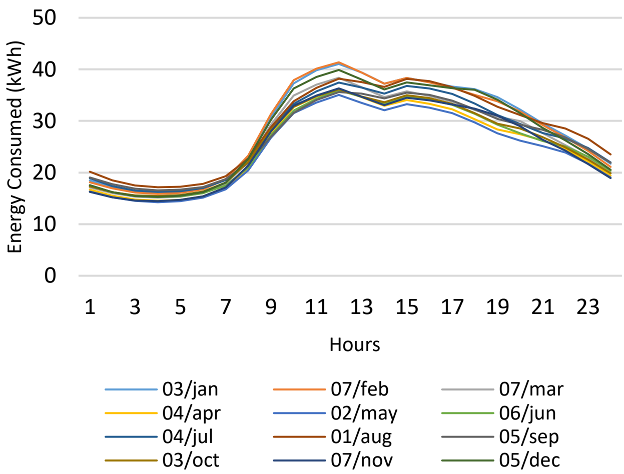


Fig. 1. Aggregate consumption of the 7 self-consumers corresponding to one working day of each month.

Only the possibility of installing photovoltaic (PV) systems on the buildings' roofs were initially considered. However, it was quickly concluded that the places with the highest contracted power had reduced surface areas. Therefore, the possibility of installing in areas close to the Point of Common Coupling (PCC) was studied, obtaining a total surface area of 2703 m^2. The PV systems are made of monocrystalline photovoltaic modules with a peak power of 545 W. The REC was sized for an installation with 309 modules, which corresponds to a 168.40 kWp total installed power.

Based on the formulation used in [11], all the calculations that allowed obtaining the maximum power produced by the PV system were performed. The summer months, particularly June and July, show higher energy values produced, Figure 2. On the other hand, there is a significant reduction in solar resources in the winter months; therefore, the production in these months can be 60% lower than in the summer

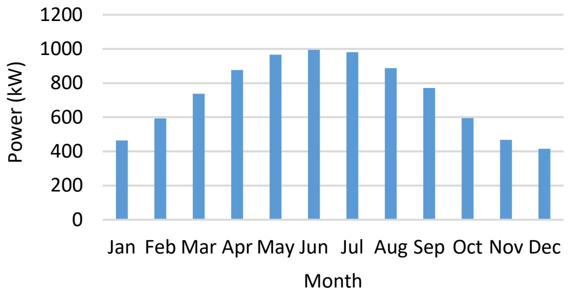


Fig. 2. Daily energy production for each month over a year.

Regarding the storage systems, the LUNA2000-5/10/15-S0 battery was used. The flexibility of modular expansion characterizes these systems, and their storage capacity can range from 5 kWh to 30 kWh, corresponding to the set *TB* of battery types, defined in Section 2. The number of available batteries for each class, n_i, and their acquisition and maintenance costs vary according to the values presented in Table 1.

Tab. 1. Purchase and maintenance costs of LUNA2000-5/10/15-S0 batteries, set *TB*.

Type	n_i	Battery capacity (kWh)	Purchase cost (€)	Maintenance cost (€)
1	3	5	3500	350
2	3	10	6000	600
3	3	15	8500	850
4	3	20	12 000	1 200
5	3	25	14 500	1 450
6	3	30	17 000	1 700

4. Results

In this study, two scenarios were considered. The first scenario, designated by *A1*, considers the REC constituted only with the integration of energy production systems for self-consumption. The second scenario, *A2*, also considers the integration of ESS in the facilities. Furthermore, in scenario A2 is applied the optimization model presented in Section 2.

A. Scenario A1 – REC with production facilities for self-consumption without storage units

Analyzing Figure 3, it can be seen that in the period between 10:00 am and 3:00 pm, energy production is greater than energy consumption, with a surplus of 152 kWh for the day under analysis. The energy consumed during periods without PV production is imported from the grid. Around 54% of the energy consumed comes from the grid and the remaining 45% comes from the production units for self-consumption.

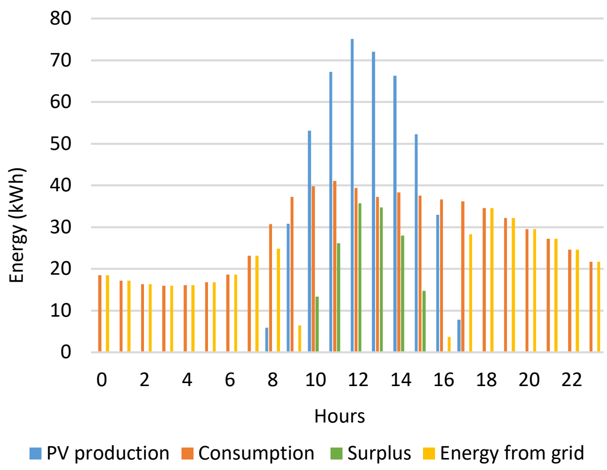


Fig. 3. Production data, consumption, surplus energy and energy purchased from the grid on a January day, analysis without optimization, scenario *A1*.

Figure 4 shows the energy behavior of the community for a summer day, corresponding to July. In this month, surplus energy is higher than in January, with an increase of 413 kWh. About 36% of the energy consumed comes from the grid, and the remaining 64% comes from PV production, indicating that the system has a high autonomy with incorporating photovoltaic systems.

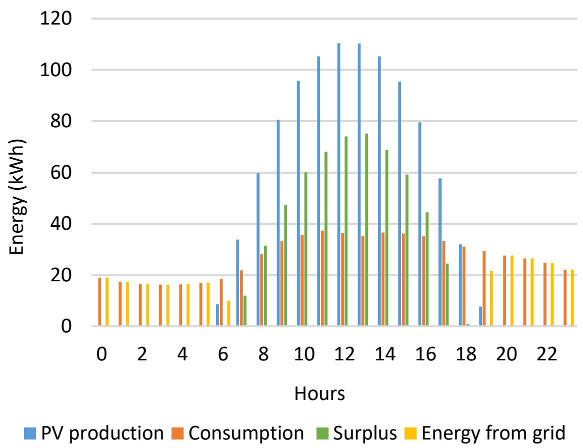


Fig. 4. Production data, consumption, surplus energy and energy purchased from the grid on a day in July, analysis without optimization, scenario *A1*.

After comparing the two months, it is concluded that in January there is an increase of 18% in consumption coming from the grid when compared to July to cover the energy needs of the community.

B. Scenario A2 – REC with production facilities for self-consumption and energy storage systems, applying the optimization model

In the optimal solution obtained by the optimization model, five batteries with different storage capacities are used, three with a capacity of 15 kWh and two with a capacity of 30 kWh, corresponding to a total storage capacity of 105 kWh.
Through the analysis of Figure 5, it is possible to conclude that at hour 7, immediately before the peak period, the

optimization model suggests the purchase of 54.42 kWh from the power grid, with consumption for that hour being 23.18 kWh. So, the model determines the energy purchase of 31.24kWh more than it needs, which is used to charge the batteries.

The purchase of energy from the network during off-peak periods is due to the lower tariff, opting to store this energy to meet consumption during peak periods when prices are higher. Figure 5 shows the behavior of the energy flow in the battery (charges and discharges). It is possible to see that the periods where photovoltaic production is higher than consumption, between hours 10 and 15, are mostly the periods when the battery charges. After hour 15, there is a decrease in production, and the batteries discharge to safeguard community consumption. Between hours 16 and 21, the system chooses to discharge the battery instead of importing energy from the grid, as this time interval falls within peak hours, where energy prices are higher.

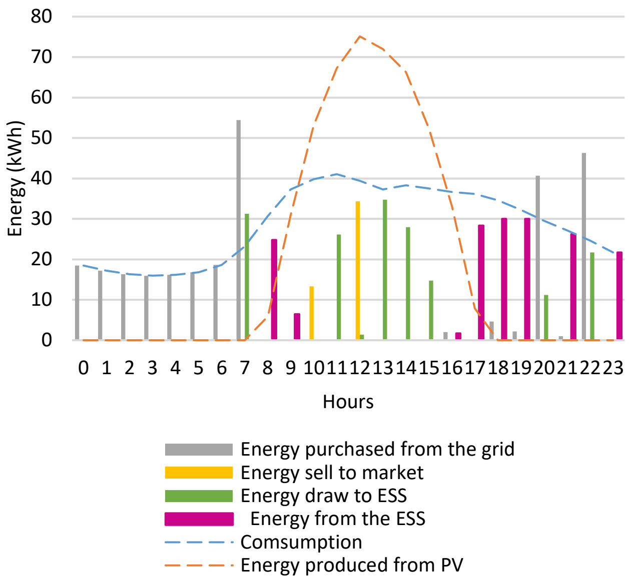


Fig. 5. Energy data with ESS, for a working day in January, scenario A2.

It is concluded that the system minimizes the energy purchase from grid during peak hours where prices are higher, opting for the purchase of energy mainly at the periods when the price is lowest, in off-peak periods, with the value of 0.1917 €/kWh and 0.1044 €/kWh respectively. The graph of Figure 6 shows the variation in the purchase and sale energy price over the day analyzed in Figure 5.

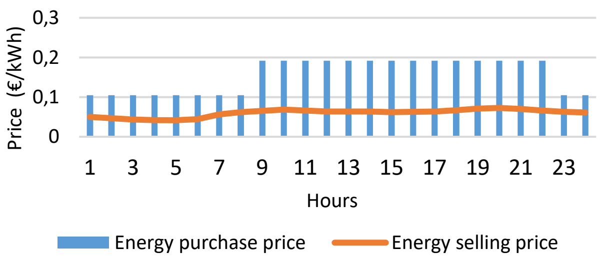


Fig. 6: Price of energy purchase from grid and price of sale of energy on the market (OMIE), referring to a business day in January 2021.

The graph of Figure 7 shows the batteries energy flow, which reach their maximum storage capacity of 105kWh at hour 16.

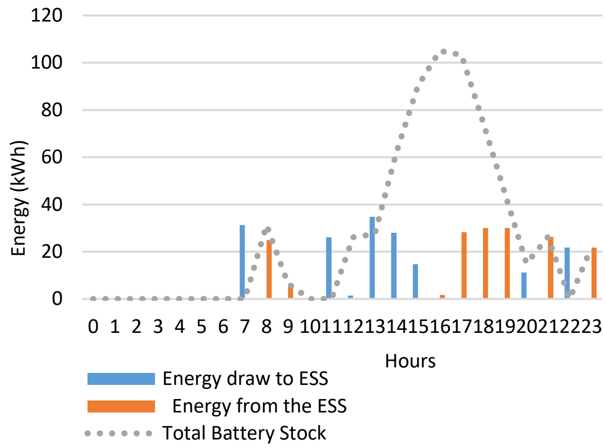


Fig. 7. Daily battery charge and discharge profile for January 2021 business day.

Initially the batteries are charged at hour 7 with 31.23kWh, this stored energy was purchased directly from the grid during the off-peak period, Figure 7. In the following hour, the first peak hour, there is an energy deficit of 24.82kWh. Consequently, the system chooses to discharge the battery instead of purchasing energy from the grid at a higher price. At hour 10 is the first hour of the day when production meets demand, with a surplus of 13.29kWh. The market price for hour 10 is 65.97€/MWh and for the following hour is 63.93€/MWh, Figure 6. Since, in hour 10 the price is higher than in hour 11, surplus energy is sold to the grid, Figure 5. On the other hand, at hour 11 the surplus is 26.15kWh and the market price is 0.01€/MWh lower, compared to hour 12, in this situation the energy is stored.

It is concluded that the battery charge and discharge flows depend not only on the photovoltaic production but also on the energy trading prices. Thus, whenever energy prices are economically attractive, the system optimizes exchanges between the grid and storage units in order to maximize community profits.

Finally, Figure 8 shows the net consumption of the REC, that is, the amount of energy imported from the grid in scenario A1 and A2, for the obtained solutions.

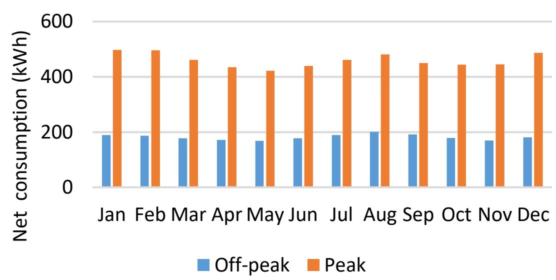
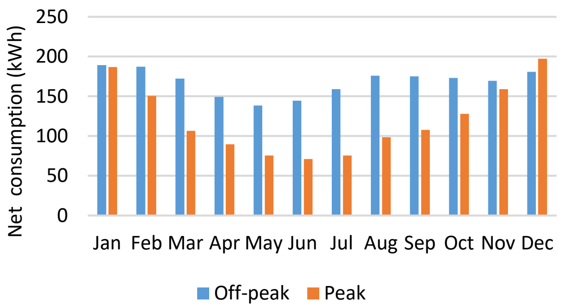


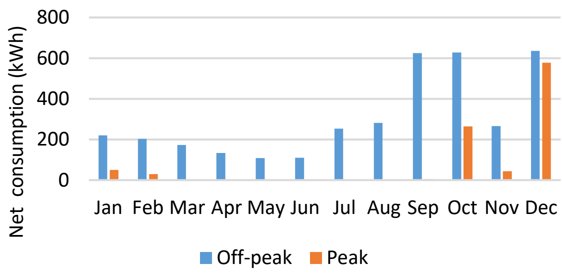
Fig. 8. Net consumption during off-peak and peak hours for one working day of each month, in the scenario without the integration of PV systems.

By analyzing Figure 8, it is possible to verify that without the introduction of PV systems, around 72% of the energy

purchased from the grid is included in off-peak periods and the remaining 28% corresponds to the purchase of energy during off-peak hours.
Regarding scenario A1, Figure 9 (a), it is concluded that with the introduction of PV production systems for self-consumption it is possible to reduce energy imports during peak hours, by around 73% compared to the scenario without PV. This reduction has a positive impact on the energy bill since photovoltaic production takes place during periods where the tariff price for the end customer is higher. With the implementation of storage units, Scenario A2, it is possible to reduce about 67% of energy imports in peak periods compared to scenario A1. Analyzing the graph of scenario A2, Fig. 9 (b), it can be seen that between April and August, during 5 months, the import of energy during off-peak hours is zero. On the other hand, it appears that there is an increase in energy imports during peak hours by over 1622.5 kWh compared to the A1 scenario. Since, in the off-peak period, the price is lower compared to the peak price, this increase does not have a significant impact on the energy bill, Figure 9.



(a)



(b)

Fig. 9. Comparison between net consumption during off-peak and peak hours for one working day of each month, in scenario A1 (a) and A2 (b), respectively.

5. Conclusion

This paper aims to create a tool using linear programming capable of optimizing the energy flows of a REC. Two scenarios were considered. Scenario A1 considers the REC with the integration of energy production systems. Scenario A2 also considers the integration of ESS, and the proposed optimization model is applied to maximize the CER's profit. The goal was to determine when and how much energy to buy/sell to the grid and charge/discharge the battery based on the demand, the production, the adopted tariff, and the energy selling price, considering the costs associated with the integration and maintenance of the ESSs. Concerning scenario A1, it was concluded that of the total energy purchased from the grid in January, about 49.7% of the energy fell in the off-peak periods. This value decreases by 17.7% if a summer month is analyzed. This means that considering only the integration of photovoltaics, the import of energy from the grid in the winter months is quite high, which makes the system not very autonomous.
In scenario A2, ESS with a total capacity of 105 kWh is used. Through data analysis, it is concluded that it is possible to reduce about 67% of energy imports in peak hours compared to scenario A1. On the other hand, there is an increase in net consumption during off-peak periods when energy prices are significantly lower. Thus, when the energy sale price is competitive, the batteries discharge by injecting the energy into the grid. Conversely, battery charging can occur before peak periods when energy purchase prices are lower, maximizing community profits.

Acknowledgement

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