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OPTIMIZATION BASED ON AN OPEN-SOURCE SOLVER FOR A MICROGRID WITH A PHOTOVOLTAIC SOLAR SYSTEM AND HYBRID ENERGY STORAGE

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ABSTRACT

The use of python-based solvers is increasingly used to formulate and solve optimization problems in the different areas of applied science. Open source tools like Pyomo are flexible in incorporating new syntaxes, allowing contributions, improving their functions, and correcting errors. In this article, we propose to use the MINLP convex solvers (MINLP-BB, KNITRO, BONMIN, and FIlMINT) connected to the PYOMO-NEOS server. Numerical comparisons are made, and an optimization problem is solved for a grid-connected photovoltaic microgrid with hybrid storage (lead-acid battery and Supercapacitor) to reduce the consumption of energy absorbed from the electricity grid, but also the bill paid by the consumer in the northern region of Colombia. The numerical results obtained demonstrate the potential of the Python-based solver and its application in optimization problems of hybrid renewable energy systems.

I. INTRODUCTION

Modern society depends on the supply of safe and high-quality electric power. However, there are growing concerns about the shortage of primary energy and global warming. Thus, countries are seeking to generate electricity through renewable energy sources (solar, wind, biomass, etc.). Worldwide investments in photovoltaic solar energy have increased the installed capacity from 303GW in 2016 to 402GW in 2017, with 99GW. In 2017, China, Europe, and the United States accounted for almost 75% of the world's investment in renewable energy and fuels. However, countries like the Marshall Islands, Rwanda, the Solomon Islands, Guinea-Bissau, among others in development, are investing more in renewable energy when measured per unit of domestic product (GPD). These positive trends must be expanded for a global energy transition(REN21, 2017).

The use of renewable energies (solar, wind, biomass) in Latin America is being used to satisfy the demand for electricity at the public services level and the residential level. Specially photovoltaic solar energy has seen steady growth (Ferreira et al., 2018)(Alemán-Nava et al., 2014).InMasson et al.(Masson et al., 2007), a reportwaspublishedpointingtocountriessuch as Chile, Mexico, Colombia, Venezuela, Brazil, and Ecuador as attractivefortheinvestment and development of photovoltaicenergy.The report was made according to the size of the electricity market and the competitiveness of the cost of photovoltaic power.A microgrid is a form of distributed power generation capable of operating connected to the grid and off-grid. In a grid-connected mode of operation, a microgrid can exchange energy with the electrical grid (to absorb or inject energy); when power generation and demand are the same, the energy transferred between the microgrid to the electricity grid is nil (Hatziargyriou, 2014).

Interconnected photovoltaic systems are used as a complement in conventional power generation in many countries (Tsilingiridis & Ikonomopoulos, 2013)(Luna, Diaz, Savaghebi, et al., 2017)(Martins et al., 2008)(Takigawa et al., 2019). It has been applied from the small generation in remote areas to the large-scale installation of photovoltaic generation near populated areas. Today, there is considerable interest in urban consumers connecting to distributed generation, with the installation of photovoltaic systems on the roofs of buildings or residences and a variety of hybrid energy solutions (Mayer et al., 2015)(Bagarella et al., 2016)(Raghuwanshi & Arya, 2020).The use of lead-acidbatterybankissuitablefor a photovoltaicpowersystem, duetoitslowcost and betterthermalstability. However, the charge and discharge cycles cause stress, which reduces the battery (Dufo-López et al., 2014). The Supercapacitor and battery have complementary technical characteristics. It is reasonable to combine them to create a hybrid energy storage system (HESS) where the battery absorbs / supplies long-term continuous energy, and the Supercapacitor responds quickly to dynamic energy demands and snapshots (Ma et al., 2015).

There are a wide variety of commercial languages known as GAMS(Brook et al., 1988), AIMMS(Bisschop, 2006),AMPL(Fourer et al., 1989), and MATLAB(Boumal et al., 2014) to solve optimization problems, and their algorithms are patented and are not open source. Instead, open-source tools like PYOMO in Python(Hart et al., 2017) and juMP in Julia(Dunning et al., 2017) are flexible to incorporate new syntax, components, and processing (Nicholson et al., 2018). Table 1 shows essential works involving optimization (mathematical programming and metaheuristic algorithms) with photovoltaic microgrids with the hybrid energy storage system.

Our objective is to use convex MINLP solvers (MINLP-BB, KNITRO, BONMIN, and FIlMINT) connected to the PYOMO-NEOS server. Numerical comparisons are made, and an optimization problem is solved for a grid-connected photovoltaic microgrid with hybrid storage (lead-acid battery and Supercapacitor) to reduce the consumption of energy absorbed from the electrical grid but also the bill paid by the consumer in the northern region of Colombia.

This article is structured as follows. Section 2 describes the methodology for the design of the microgrid connected to the local grid with HESS is presented, and the optimization problem is implemented in PYOMO with the different solvers. Section 3 presents the Simulation and discussion of results. Finally, in Section 4, our conclusions are presented.

Table 1. The list of principal works in photovoltaic optimization with the hybrid storage system.

Autor	Applied Algorithm	Interface	System components
Garcia-Torres et al., (2019)	Mixed-Integer Quadratic Programming (MIQP)	TOMLAB /CPLEX	Wind Turbine, PV System, Supercapacitor, battery Hydrogen, Lead-acid battery, load.
Liu et al., (2016)	Particle Swarm Optimization (PSO)	MATLAB	Wind Turbine, PV System, Diesel generator, Supercapacitor, Li-ion battery, Lead-acid battery, Load.
Chong et al., (2016)	PSO	MATLAB	PV System, Supercapacitor, battery, Load.
Jing et al., (2018)	PSO, genetic algorithm, simulated annealing	MATLAB	Li-ion battery, supercapacitor, PV System, Load.
Roy et al., (2019)	linearized step rules algorithm, and a fuzzy interference system	MATLAB	PV,Li-ion battery, Supercapacitor, PV System, Power Grid.
Abdelkader et al., (2018)	Geneticalgorithm	MATLAB	battery, Supercapacitor, PV System, Wind System.
Chia et al., (2015)	Support Vector Machine (SVM)	MATLAB	Lead-acid battery, Supercapacitor, PV System, Load.
Jing et al.,(2017)	Convex function	MATLAB	Lead-acid battery, Supercapacitor, PV System, Load.
Jing et al., (2019)	Convex function	MATLAB	PV System, Li-ion battery, Supercapacitor, Load,
Akram & Khalid, (2017)	frequency regulation control strategy		PV System, Wind System, battery, Supercapacitor, Load
Semassou et al.,	NLP	MATLAB	PV System, battery, Supercapacitor, Load

(2020)			
Bai et al., (2020)	Algorithm for Power Control	MATLAB	PV System, Diesel, battery, Supercapacitor, Load, Power Grid
Krishan & Suhag, (2020)	Control strategy	MATLAB	Nickel-Cadmium, Supercapacitor, PV System, Wind System, Load
Akram et al., (2017)	Control strategy	MATLAB	sodium-sulfur (NAS) battery, Supercapacitor, PV System, Wind System, Power Grid, Load
Ren et al., (2016)	Control strategy	PSCAD/EMTDC	PV System, baterry, Supercapacitor, Load.

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I.I Colombian electricity system problem

The problem that affects electric power in Colombia is that its infrastructure does not cover the entire Colombian territory. The installed capacity corresponds mainly to water resources that are affected each year by variations in precipitation as a consequence of climate change, such as the phenomenon called the child (Gaona et al., 2015).

In (La Crisis de la Electrificadora del Caribe S.A., 2017) carried out a diagnosis in the northern region of Colombia, where it found the most significant number of electrical interruptions in the country. It emphasizes the terrible quality and inefficiency of the energy supply, which is an essential service. This region of the country "has been subject to constant blackouts that are repeated daily in hospitals, hotels, and restaurants, causing premature outages due to voltage fluctuations that damage equipment and appliances."

The Colombian government, intending to reduce the effect of greenhouse gases caused by thermal plants that burn fossil fuel, encourages the installation of small and large-scale self-generators of so-called alternative renewable energy technologies (FNCE) in the interconnected area: photovoltaic, wind, little hydroelectric, geothermal and biomass solar energy. The consumer is authorized to sell its surplus electrical energy to the local energy company. Concerning photovoltaic solar energy, it is expected to reach 1.6GW in 2030 (Aroca, 2019).

II. METHODOLOGY

Next, the methodology for the design of the microgrid connected to the local grid with HESS is presented. The first is to acquire the forecast data of the energy resources of the area where the microgrid will be installed. Second, the mathematical model proposal with its restrictions on storage units and the photovoltaic panel was selected. The MINLP optimization problem is implemented in PYOMO with the different solvers (MINLP-BB, BONMIN, FILMINT, KNITRO). In the following subsections, each step is rewritten in detail.

Pyomo-Neos

Pyomo is an open-source tool for mathematical models and complex optimization applications, and it is integrated into Python. It was developed by the Sandia National Laboratories research center (Hart et al., 2017). Pyomo supports a variety of optimization issues, including Mixed-Integer Nonlinear Programming (MINLP), and can connect to the NEOS server for remote troubleshooting (Czyzyk, J. Mesnier, M. Moré, 1998).

Table 2 shows the solvers used with this tool that combine various techniques to improve its performance, such as Branch and bound (BB) that was first used to solve mixed-integer linear programming (MILP) problems (Land & Doig, 1960). A BB solves an MINLP problem by relaxing the integer constraints and solving continuous (convex) relaxations of NLP (Kronqvist et al., 2019).

Table 2.The solver used by Pyomo.

Solver	License type	Algorithm Type	Classification Solvers	Ref.
BONMIN	Open-source	BONMIN-BB	BB-based	Bonami et al., (2008)
		BONMIN-OA	MILP based	
		BONMIN-Hyb	BB-based	
FILMINT	Open-source	FilMINT v0.1	BB-based	Abhishek et al., (2010)
		Filmint-SBC	BB-based	
KNITRO	Commercial	KNITRO-QG	MILP based	Byrd et al., (2006)
		KNITRO-BB	BB-based	
MINLP_BB	Open-source	-------------	BB-based	Leyffer, (1999)

Residential PV microgrid problem formulation

The studied system is shown in Fig.1 the main components are photovoltaic panels, hybrid storage that includes a lead-acid battery and a supercapacitor, electronic converters, a home charger, a bi-directional meter, and a low-voltage grid. The controller collects a variety of information, such as voltage values, battery and Supercapacitor charge status, charge profiles, weather conditions, and solar radiation.

The proposed MINLP algorithm is solved with PYOMO software. It aims not only to maintain the system stability and power quality but also to optimize the loading and unloading of hybrid storage. The Supercapacitor is designed to produce transient energy, to face disturbances in balanced and unbalanced conditions. Because the Supercapacitor is a high-power density device with less power capacity than the lead-acid battery, it cannot be used as a long-term power source (Li et al., 2016). In the Hybrid Energy Storage System (HESS) topology, the battery is parallel to the Supercapacitor and is isolated from the AC bus by bidirectional DC / AC converters. With this topology, performance, battery life, and AC bus stability can be improved by an optimization strategy.

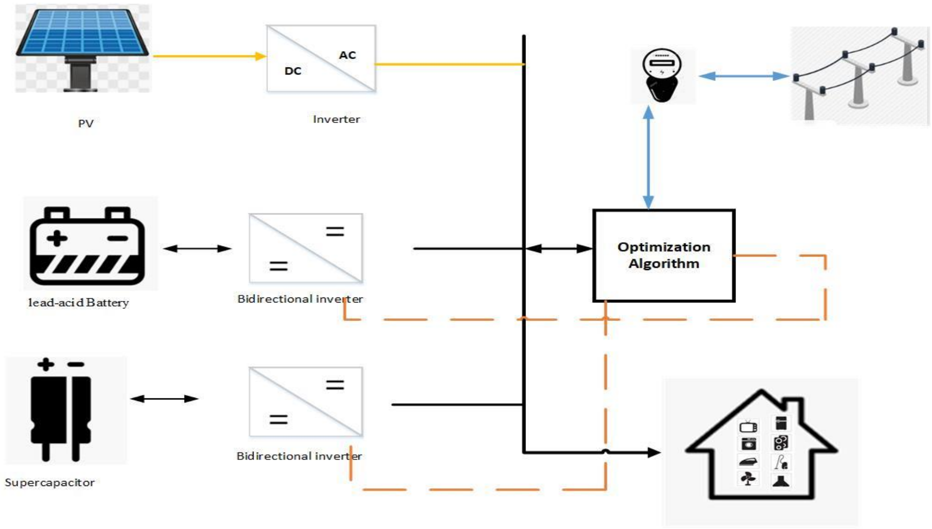

Figure 1. Hybrid storage configuration for a grid-connected PV system

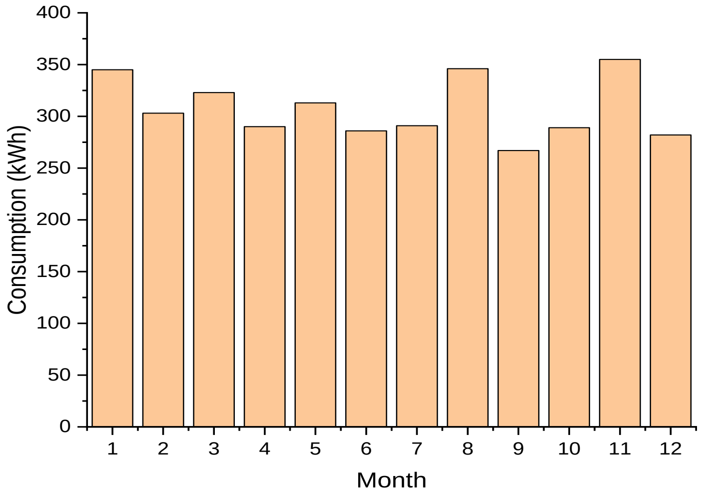

Figure 2. Electricity consumption of a residential user

The photovoltaic panels and the inverter are the heart of the grid-connected photovoltaic system. Zilles et al. 2012 (Zilles et al., 2012) indicate the calculations used to calculate the panels and the output power of the inverter. Additionally, the energy storage system will play an essential role in reliable and economic performance with specific amounts of renewable energy. The lead-acid battery is the oldest technology and has been applied for different operations of the power system. The advantage of this model is its low cost compared to other types, simplicity, and easy parameter extraction (Rezvani et al., 2016). Bechouat et al.2015 (Bechouat et al., 2015) describe the lead-acidbatterymodel. Finally, the bank of supercapacitors is modeled as a first-order RC circuit, and the detailed model proposed by (Barrade, 2003) is adopted. Table 3has defined the characteristics and operational parameters.

Figure 2 shows the monthly consumption of a residential user. The load profiles (refrigerators, televisions, fans, lighting, and others) were taken from the energy bill. Using the System Advisor Model (SAM)software, a daily load profile was modeled for each month, taking into account business days and weekends.

Table 3. Technical characteristics of the equipment

Photovoltaic panel	**ISF-230**
Nominal Maximum Power P_{max}	230 W
Open circuit voltage V_{oc}	35,6 V
Short circuit current I_{sc}	8.63A
Optimum operating voltage Vmp	29.7V
Optimum operating current Imp	7.75A
Number panels series Ns	2
Number panels parallel Np	5
lead-acid battery UP-SP070	
C_{100}	70 Ah
V_{banco}	24V
V_{batt}	12V
Number battery series N_{BS}	2
Number battery parallel N_{PS}	6
Supercapacitor BCAP 3000 MAXWELL	
Wscu	478.8 J
Co	2600 F
Rs	0.00031 Ohmio
Uc	2.7 V
d	75%
UscM	24 V
Uscm	12 V
Ns	6
Np	1
CT	3.8 F
RsT	2.5 m Ohmio
PD	58.06 kW

Mathematical formulation.

The Energy and Gas Regulation Commission (CREG) decreed resolution 30 of 2018 in Colombia. It establishes the equation for delivery of surplus to the local concessionaire (trading company) that receives energy from a small-scale autogenerator (Spanish: AGPE) is responsible for settlement and billing, incorporating detailed information on consumption, exports, charges, among others.

The proposed objective function for the model is.

$$\min(J_{rede} + J_{bat} + J_{sc}) \quad (1)$$

Where
J_{rede}represents the function cost of the electrical grid.
$J_{bat}$is the lead-acid battery cost function.
$J_{sc}$is the Supercapacitor cost function.

Function cost the electrical grid.

In (030, 2018) indicates the equation so that a residential or commercial user through a photovoltaic system can take advantage of the sun's energy to generate electricity for consumption, connect to the public grid and sell their surplus in Colombia. The problem has been formulated, representing a discrete-time (tk), where Exp_1 (tk) and Exp_2 (tk) are the powers injected into the grid. Imp (tk) is the power absorbed from the electrical grid. The cost is represented by CU_m, marketing cost Cv_m, and the value of the hourly average monthly bag price PB_m. The subscript m represents the month in which equation 2 is calculated.

$$J_{rede} = \sum_{t=1}^{tk} \left(Exp_1(tk) - Imp(tk)\right) * CU_m - (Exp_1(tk) * Cv_m) + Exp_2(tk) * PB_m \quad (2)$$

Cost function of the lead-acid battery.

One of the problems identified in the lead-acid battery (bat) is the formation of oxides during charging. For this reason, the shorter the discharge, the battery will have a longer life. Equation 3 represents the objective function of the battery and is included to store the excess energy, where $D_{bat}(tk)$is the state of charge of the battery (equation 4) and C_{bat} is the battery cost (equation 5), which is ten times less CU_m is a battery penalty cost, defined in(Luna, Diaz, Graells, et al., 2017).

$$J_{bat} = \sum_{t=1}^{tk} D_{bat} * Cbat \quad (3)$$

$$D_{bat}(tk) = Soc_{bat}^{max} - Soc_{bat}(tk) (4)$$

$$C_{bat} = CU_m * \left(0.1 \left(\$ \frac{US}{KWh}\right)\right) \quad (5)$$

Cost function of the Supercapacitor.

Equation 6 represents the objective function of the Supercapacitor (sc), J_{sc}has a quadratic term defined in (Garcia & Bordons, 2013). Equation 7 defines the cost C_{sc}.

$$J_{sc} = \sum_{t=1}^{tk} \left(Soc_{sc}(tk) - Soc_{sc}^{ref}\right)^2 * C_{sc} \quad (6)$$

$$C_{sc} = \frac{1}{Soc_{sc}^{max^2}} \quad (7)$$

Where,

Soc_{sc}^{max}Is the upper limit of the state of charge of the Supercapacitor.

Soc_{sc}^{ref}Is the initial value of supercapacitor charge status.

The following restrictions are set for the optimization problem.

$$Soc_{bat,sc}^{min} \leq Soc_{bat,sc}(tk) \leq Soc_{bat,sc}^{max} \quad (8)$$

$$0 \leq P_{bat,sc}^{d}(tk) \leq -P_{bat,sc}^{min}(tk) * \delta_{bat,sc}^{d}(tk) \quad (9)$$

$$0 \leq P_{bat,sc}^{c}(tk) \leq P_{bat,sc}^{max}(tk) * \delta_{bat,sc}^{c}(tk) \quad (10)$$

$$Soc_{bat,suc}(tk) = Soc_{bat,sc}(tk-1) + P^{c}_{bat,sc}(tk) * \frac{\eta^{c}_{bat,sc}}{C_{bat,sc}} - P^{d}_{bat,sc}(tk)/(\eta^{d}_{bat,sc})C_{bat,sc} \quad (11)$$

$$\left(1-\delta^{c}_{bat}(tk)\right) + \left(1-\delta^{d}_{bat}(tk)\right) = 1 \quad (12)$$

$$\left(1-\delta^{c}_{sc}(tk)\right) + \left(1-\delta^{d}_{sc}(tk)\right) = 1 \quad (13)$$

$$0 \leq Imp(tk) \leq P_{load}(tk) \quad (14)$$

$$0 \leq Exp_{t}(tk) \leq P_{pv}(tk) \quad (15)$$

$$Exp_{t} = Exp_{1}(tk) + Exp_{2}(tk) \quad (16)$$

$$0 \leq Exp_{1}(tk) \leq Imp(tk) \quad (17)$$

$$P_{res}(tk) = P_{pv}(tk) - P_{load} \quad (1P_{grid}(tk) = Exp_{t}(tk) + Imp(tk) \quad (19)$$

$$P_{res}(tk) = P_{grid}(tk) + P^{c}_{bat}(tk) - P^{d}_{bat}(tk) + P^{c}_{sc}(tk) - P^{d}_{sc}(tk) \quad (20)$$

Equations 8 establish the lower limit ($Soc^{min}_{bat,sc}$) and upper bound ($Soc^{max}_{bat,sc}$)) of the state of charge of the battery and the Supercapacitor. $P^{c}_{bat,sc}(tk)$and $P^{c}_{bat,sc}(tk)$are the charge and discharge power defined by equation 9 and equation 10. Limits $P^{max}_{bat,sc}(tk)$ and $P^{min}_{bat,sc}(tk)$to avoid rapid degradation.

The state of charge of the battery and the Supercapacitor is represented by equation 11. Where $C_{bat,sc}$is the nominal capacity in kWh.$\eta^{c}_{bat,sc}$Efficiency during charging and $\eta^{c}_{bat,sc}$Efficiency during discharge. The logical variables $\delta^{d}_{bat,sc}$and $\delta^{c}_{bat,sc}$ indicatethe state of charge (1) and discharge (0) of the battery at time tk for the HESS control (equation 12 y equation 13).

Equation 14 represents energy import (Imp (tk)); the lower limit is set to zero, and the upper limit cannot exceed the house load demand (P_{load}). Equation 15 represents Total export ($Exp_{t}(tk)$) the lower limit is set to zero and the upper limit cannot exceed the output power generated by the photovoltaic panels (P_{pv} (tk))). Also $Exp_{t}(tk)$, it is formed by the sum of two variables $Exp_{1}(tk)$ and $Exp_{2}(tk)$ (equation 16). The variable $Exp_{1}(tk)$ is represented by equation 17 cannot exceed the value of the variable $Imp(tk)$. Equation 18 defines the residual power variable $P_{res}(tk)$, which is the difference of the photovoltaic power $P_{pv}(tk)$and the load power of the house P_{load}. The power of the grid $P_{grid}(tk)$is the difference of the powers injected into the grid $Exp_{t}(tk)$ and the absorbed power of the grid $Imp(tk)$of equation 19. The optimization problem is restricted to feasible solutions, and the energy balance of equation 20 is considered.

Price of electrical energy.

Electricity pricing is regulated and generally higher for residential and small commercial consumers (see Table 3). For the industry, prices are not regulated, and they can negotiate lower rates. The CREG resolution 119 of 2007, determines the electrical energy consumed by a residential user based on the unit cost of the service.

$$CU_n = G_m + T_m + D_m + Cv_m + PR_m + R_m \quad (21)$$

Where:
CU_m Kilowatt hour cost ($USD /kWh).
G_m The cost of producing energy through the use of different sources of water, gas, diesel, carbon, photovoltaic.
T_m The cost of transporting electricity from generation plants to large consumption centers (entry to regions, cities or large consumers
D_m The cost of distributing energy from the entry sites to the areas to the address of the end-user.
Cv_m The cost of buying and selling electricity and includes billing costs, meter reading, and user attention, among others.
PR_m The cost of energy losses incurred to reach end-use.
R_m The costs that are generated by network conditions, which limit the capacity to transport energy.

m: month for which the unit cost is calculated.

Table 4. Electricity costs US$.

Month	G	T	PR	R	D	C	CU ($US/ KwH)
January	0,0462	0,0078	0,0089	0,0085	0,0344	0,0183	0,1241
February	0,0383	0,0061	0,0072	0,0084	0,0331	0,0170	0,1101
March	0,0379	0,0087	0,0076	0,0091	0,0347	0,0167	0,1148
April	0,0466	0,0091	0,0091	0,0063	0,0347	0,0173	0,1231
May	0,0437	0,0089	0,0085	0,0063	0,0354	0,0190	0,1220
June	0,0407	0,0070	0,0079	0,0087	0,0337	0,0180	0,1159
July	0,0384	0,0061	0,0072	0,0084	0,0334	0,0170	0,1104
August	0,0386	0,0083	0,0077	0,0084	0,0338	0,0166	0,1134
September	0,0453	0,0075	0,0086	0,0082	0,0341	0,0171	0,1210
October	0,0475	0,0088	0,0092	0,0068	0,0331	0,0177	0,1232
November	0,0474	0,0087	0,0092	0,0068	0,0331	0,0177	0,1229

III SIMULATION AND DISCUSSION OF RESULTS

The methodology information corresponds to the municipality of Sincelejo and is located in the department of Sucre (DANE, 2018). It has a dry tropical climate. The annual average temperature is close to 27 ° C, with minimum temperatures of 19.7 ° C and maximum temperatures of 37.3 ° C.The most radiant period of the year lasts for 2.9 months, from January 8 to April 4, with a daily average of shortwave energy per square meter above 5.6

kWh. The brightest day of the year is March 1, with an average of 6.1 kWh. The darkest period of the year lasts for 3.3 months, from August 10 to November 19, with a daily average of shortwave energy per square meter below 4.0 kWh. The darkest day of the year is September 29, with an average of 3.5 kWh. Figure 3 shows the solar insolation data from the municipality of Sincelejo, which were obtained from (Benavides Ballesteros et al., 2017).

The input variables were defined for the MINLP model, which are the output power of the photovoltaic panels (P_{pv}), the load of the residential user (Pl_{oad}), the cost of the variables of the electrical energy defined in Table 4. Figure 3 shows the average monthly photovoltaic power of the area.

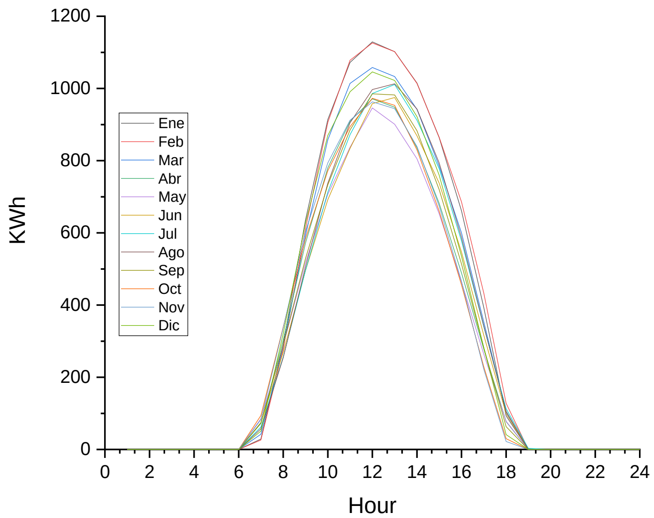

Figure 1. Photovoltaic power.

independent optimizations are carried out for each month and with the different solvers (MINLP-BB, BONMIN, FILMINT, KNITRO). The algorithm is encoded in PYOMO, which is based on PYTHON. The results are presented in the operation of the microgrid, simulation time, and standard deviation. The data is analyzed in terms of months, and the average is made for 24 hours. Table 5 shows the values used for the simulation of the microgrid.

Table 5. Reference values of the microgrid

Microgrid Components	Reference values
Power grid	$P_{grid}^{Max} = 1100W, P_{grid}^{Min} = -1100W$
Supercapacitor	$P_{Sup}^{Max} = 478W, P_{Sup}^{Min} = -478W$ $SOC_{Sup}^{Max} = 478W,$ $SOC_{Sup}^{Min} = 0.2 * 478W$ $SOC_{Sup}^{ref} = 0.5 * 478W$
	$P_{bat}^{Max} = 3420W, P_{bat}^{Min} =$

lead-acid battery	$-3420W$ $SOC_{bat}^{Max} = 3420W$ $SOC_{bat}^{Min} = 0.2 * 3420W$ $SOC_{bat}^{ref} = 0.5 * 3420W$

Table 6 compares the standard deviation for February with the particular characteristic of having the highest solar irradiance in the year, where little variation is observed in the result with the analyzed solver.

Table 6. Standard deviation result

Variables	MINLP	KNITRO	FILMINT	BONMIN
Soc_{bat}	1194,64519	1194,6452	1194,64519	1194,6452
Soc_{sc}	3,69166119	3,69166149	3,69166119	3,69166147
Imp	264,819584	264,819584	264,819584	264,819583
Exp	331,933496	331,933496	331,933496	331,933492

Figure 4 and Figure 5 show the state of charge of the lead-acid battery and the Supercapacitor in the 24 hours, obtained with each solver. It indicates that the behavior of the Soc_{bat} and Soc_{sc} load state is identical. Both HESS is programmed not to exceed the established upper and lower limits. During the hours of the highest solar irradiance, excess photovoltaic power is produced, used to export to the local electrical grid, and the HESS is even charged.

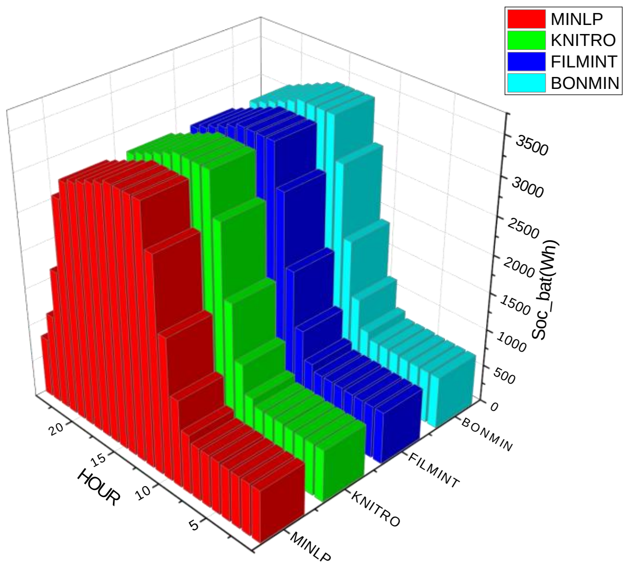

Figure 2. State of Charge Lead Acid Battery.

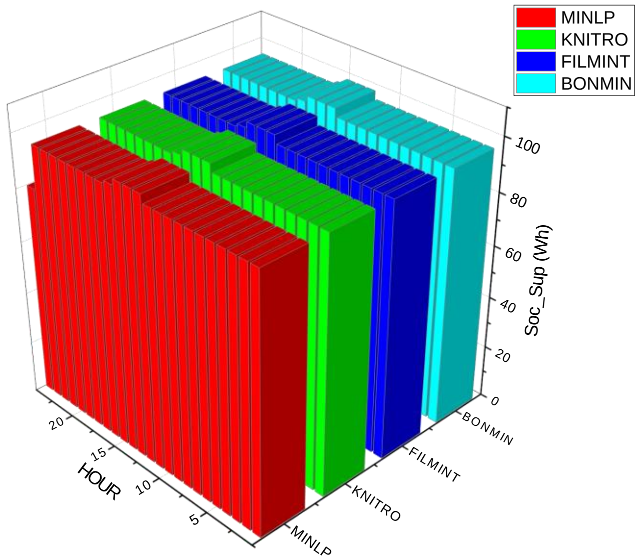

Figure 3. Supercapacitor charging status.

With PYOMO-NEOS, the cumulative solution time per month was obtained for each solver in seconds (table 7). In Fig. 6, the order in which each solver takes to solve the MINLP problem in the shortest possible time can be seen. First, we have FILMINT, second MINLP, third KNITRO, and fourth BONMIN.

Table 7.Simulation time (second)

Mouth	MINLP	KNITRO	FILMINT	BONMIN
Jan	42,9	195,2	12,2	379,1
Feb	22,4	415,6	28,1	239,7
Mar	23,6	324,7	21,7	575,8
Apr	36,8	515,3	35,4	477,5
May	35,2	143,8	33,8	195,4
Jun	19,2	135,1	19,9	499,9
Jul	29,9	225,7	32,8	478,8
Ago	23,1	216,8	20,1	317,6
Sep	20,3	95,7	32	353,6
Oct	27,9	178,3	33,5	418,6
Nov	21,1	282,6	20,4	336,6
Dic	31,6	459,8	10,4	543,8

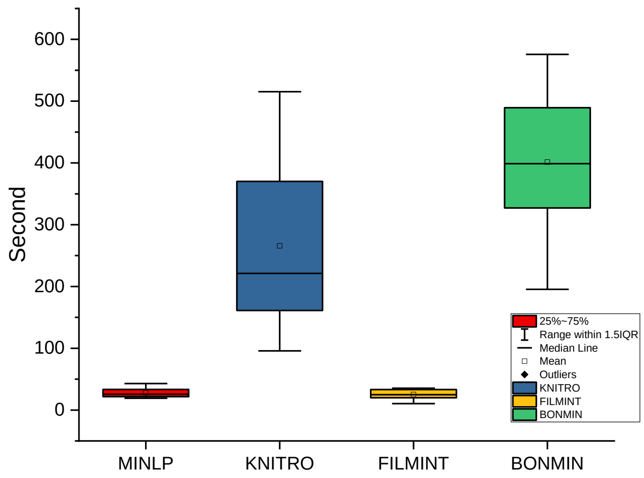

Figure 6. Simulation time diagram.

Analysis of the hybrid microgrid

Figure 7 shows the surplus of electrical energy exported to the local network between 1100h to 1700h. This surplus is the average result obtained for each month with the optimization algorithm.

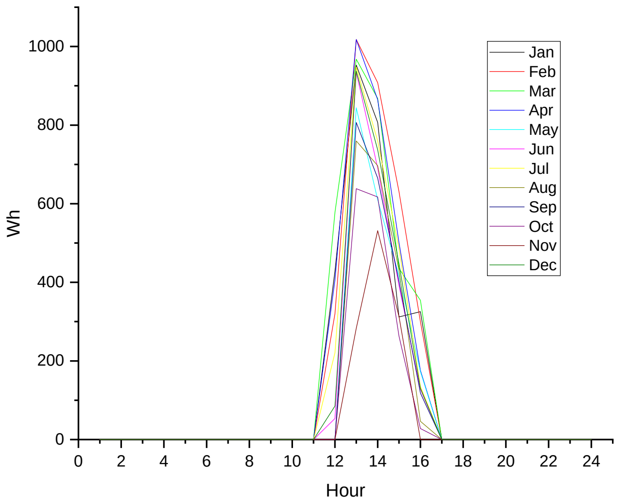

Figure 4. Electric power surplus

Since the HESS's electrical energy storage capacity is limited, and the consumer's energy demand must be met, the optimization algorithm must also import electrical energy, as shown in Figure 8.

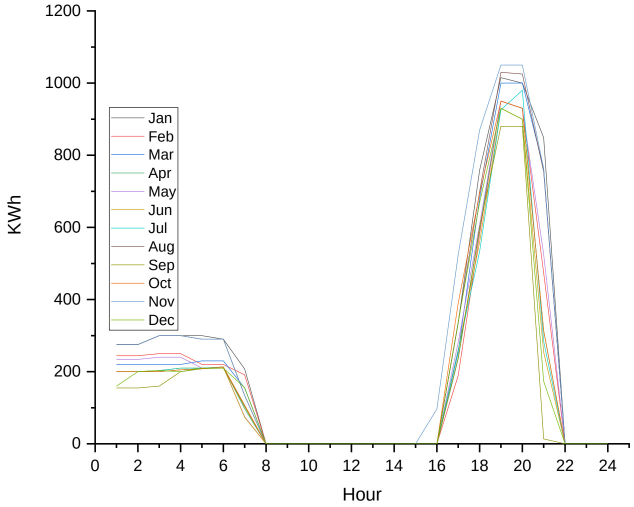

Figure 5. Electrical energy imported.

Figure 9 and Figure 10 indicate the state of charge of the HESS. The surplus of electrical energy generated between the hours of highest solar radiation is stored in HESS and later used to supply consumer demand at night.

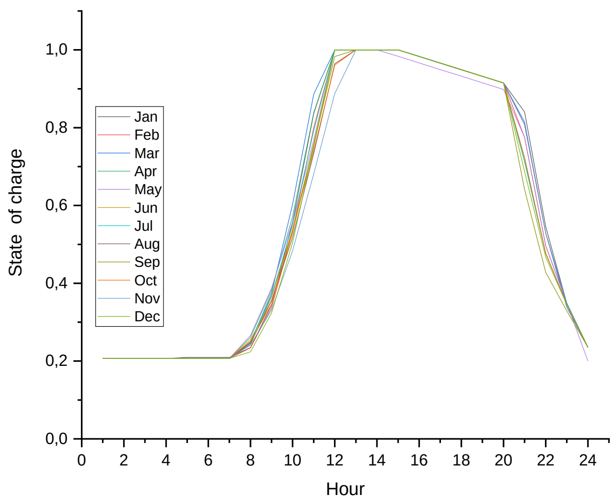

Figure 6. State of charge lead-acid battery

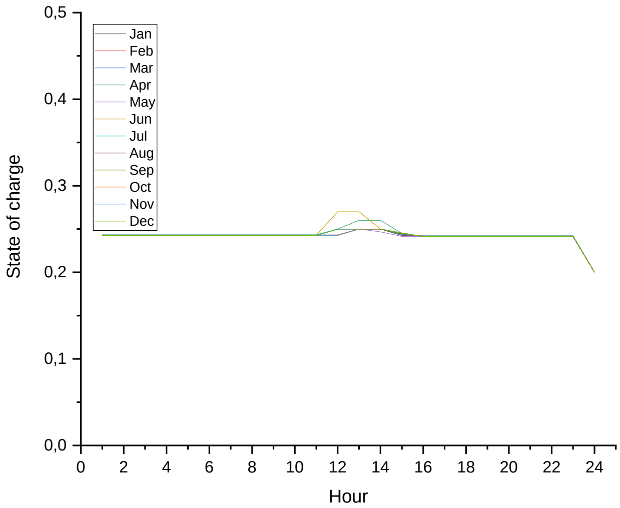

Figure 7. State of charge Supercapacitor

The results of the export, import, and cost function variables obtained for each month are shown in Table 8. A cost function with a negative value indicates the value that the user pays to the local electric power company, and the positive value is the balancein favor. In conclusion, the proposed optimization problem decreases the amount that the prosumer pays for electrical energy consumption.

Table 8. Result with the MINLP

Mouth	Pload (kWh)	Exp (kWh)	Imp (Kwh)	CostfunctionHESS	Costfunctionwithout PV
Jan	344	84,77	177,141061	$ -4,88	$ -37,35
Feb	303	95,30	142,320751	$ -0,46	$ -29,20
Mar	323	96,09	155,758051	$ -2,19	$ -32,44
Apr	290	88,94	130,385453	$ 0,57	$ -31,23
May	313	61,32	142,214892	$ -2,27	$ -33,40
Jun	286	65,95	126,404172	$ 0,04	$ -29,01
Jul	291	76,49	129,71334	$ -0,01	$ -28,12
Ago	346	58,02	171,251482	$ -4,81	$ -35,35
Sep	267	59,77	114,098422	$ 1,44	$ -28,26

Oct	289	46,40	138,318739	$ -1,75	$ -31,17
Nov	355	33,83	186,506789	$ -7,37	$ -38,18
Dec	282	70,13	130,458216	$ 0,17	$ -30,33
Total	3689	837,009263	1744,57137	-21,5226105	-384,0369425

Future work

Currently, the implementation of a photovoltaic microgrid with energy storage and the meteorological unit is being carried out at the University of Sucre (Fig. 11) within the framework of the call "Strategy for the transformation of the Colombian energy sector in the 2030 horizon" Code 58667. The objective of this program is to develop strategies for the transformation of the electricity sector in Colombia, aimed at its reliability and social, economic, and environmental sustainability in the 2030 horizon. With this microgrid, tests will be carried out with the proposed optimization algorithm and adjusted If necessary. It is also essential to study other optimization models, such as heuristics, to know their performance.

Figure 8. Photovoltaic installation at the University of Sucre.

This work focused only on the interconnected national zone. However, it is open to study the non-interconnected zones that are 51% of the national territory that comprises 70 municipalities, and 218,401 subscribers(IPSE, 2017), where the main supply of electrical energy is through diesel generators.

IV CONCLUSIONS

Pyomo allows the formulation of optimization problems with a full set of libraries, commercial solvers, and open-source solvers. The numerical results obtained for the HESS photovoltaic microgrid demonstrate the potential of the Python-based solver. FILMINT was the fastest to fix the optimization problem. Also, Pyomo solvers are general and could apply to more complex engineering problems, but computational cost is always a concern.

Hybrid storage technology is of vital importance for the northern region of Colombia, which suffers from a lack of 24-hour power supply due to the lack of investment and maintenance of the electrical grid. A difficulty for implementation in residential users is related to the economic stratification scheme is distorted and does not reflect current household conditions. Many wealthy households in sectors economic stratification medium and medium-high refuse to pay higher rates.Also, a substantial increase in private photovoltaic systems in the most affluent households could generate a deficit in the subsidy of the most impoverished population, because they would stop paying the electric energy surcharge tax (López et al., 2020). Thus, it is essential to seek a balance on the sustainability of the energy market in Colombia.

Another problem is the variation of the local currency concerning the dollar, increasing the costs of installing photovoltaic systems and hybrid storage technology. It is proposed to generate subsidies according to the socioeconomic level and the energy needs of the users.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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