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Design of an Incentive-based Demand Side Management Strategy using ILP for Stand-Alone Microgrids Planning

JCO Cepeda*‡, C. Duarte**, J. Solano**

*Universidad Industrial de Santander, Ph.D. student

** Universidad Industrial de Santander, Associated professor

(juan.oviedo@correo.uis.edu.co, cedagua@uis.edu.co, jesolano@uis.edu.co)

‡ Corresponding Author; First Author, Calle 9-27 Ciudad Universitaria, Bucaramanga, Colombia,

Tel: +57 316 246 6426, juan.oviedo@correo.uis.edu.co

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Abstract- The planning of Stand-Alone Microgrids (SAMG) can integrate Demand Side Management Strategies (DSMSs) using the Integrated Resource Planning Framework. Despite that DSMS demonstrate to reduce operational costs of power systems and microgrids, there is a paucity of literature exploring how DSMS can affect the planning of SAMG. In this regard, this paper presents the design of a DSMS using Integer Linear Programming (ILP) for the planning of SAMG. To evaluate the performance of the DSMS in the planning of the SAMG, the proposed methodology uses a ILP formulation for the optimal dispatch of the energy sources and the DSMS. The ILP formulation runs inside of a heuristic approximation of the gradient descent method that computes the size of the energy sources of the SAMG. Simulation results show reductions in the size of the energy sources and the Levelized Cost of Energy when the planning of the SAMG uses the designed DSMS. A sensitivity analysis demonstrates that the reductions in the size of the energy sources and the LCOE are consistent under variations in the Diesel price, Global Horizontal Irradiation and Battery Energy Storage System costs.

Keywords Stand-alone microgrids, day ahead tariffs, demand-side management, generation forecasting, demand forecasting.

1. Introduction

The access to affordable and high-quality electricity is considered one of the barriers to overcome in order to achieve sustainable economic and social development in rural areas [1]. National grids usually provide cheaper energy to the customers than isolated solutions. However, its extension to remote areas is not always the best approach. Local governments must face capital scarcity and challenging constructions due to the geographical conditions in remote areas. If the current grids cannot increase power generation, or the connection of new loads can compromise its reliability, the extension of the grid becomes unfeasible [2]–[6]. In these scenarios the installation of Stand-Alone Microgrids (SAMGs) to provide energy to isolated communities represents a better alternative [7]–[12].

The integration of Renewable Energy Resources (RERs) in SAMG projects introduces uncertainties that need to be addressed in the sizing and energy management of the microgrid [13]–[16]. One of the ways to deal with it, it is the use of Demand Side Management Strategies (DSMSs). Sending a signal to the customers to increase or decrease the consumption can reduce the risk of excess and lack of energy introduced by RERs. Additionally, DSMSs can reduce operational costs, harmful environmental emissions, and increase the reliability of the SAMG [17]–[19].

Palma-Behnke et al. introduce a DSMS based on sending information to the customer about the availability of energy in the microgrid [20]. Lighting a red, yellow, or green LEDs, they inform the customers to make a significant reduction, medium reduction or keep the current electrical consumption respectively. The signals are communicated several hours in

Cots analysis		
FC_{PV}	Fixed costs for the PV system	USD
FC_{DG}	Fixed costs for the Diesel generator	USD
FC_{B}	Fixed costs for the BESS	USD
FC_{DR}	Fixed costs of the DR	USD
C_{DG}	Installed diesel capacity	kW
C_{B}	Installed BESS capacity	kWh
C_{PV}	Installed photovoltaic system capacity	kW
C_{DR}	Installed DR system capacity	kW
II_{PV}	Unitary initial investment of the PV	USD/kW
II_{DG}	Unitary initial investment of the DG	USD/kW
II_{B}	Unitary BESS initial investment\	USD/kWh
II_{DR}	Unitary initial investment of the DLC system	USD/kW
M_{PV}	Unitary maintenance costs of the PV	USD/kW-year
M_{DG}	Unitary maintenance costs of the DG	USD/kW-year
M_{B}	Unitary maintenance cost of the storage	USD/kW-year
M_{DR}	Unitary maintenance cost of the DLC system	USD/kW-year
$TVCDG_{d,h}$	Total variable costs of the DG	USD/kWh
$TVCB_{d,h}$	Total variable costs of the BESS	USD/kWh
ψ_{L}	Fuel price per liter	USD
α	Weighting factor for the BESS costs	Unitless
r	Discount rate	Unitless
Sizing process		
T	Period of simulation	Days
d	Day of the simulation	Days
h	Hour of the simulation	Hours
k	Iteration of the simulation	Unitless
$C_{x,k}^{min}$	Minimum value of capacity x	kW, kWh
$C_{x,k}^{med}$	Medium value of capacity x	kW, kWh
$C_{x,k}^{max}$	Maximum value of capacity x	kW, kWh
$C_{DR,k}^{max}$	Maximum value of DR	kW
$\Delta C_{x,k}$	Capacity step for the search algorithm	kW, kWh
$TC_{x,k}$	Total operational costs	USD
$TC_{x,k}^{S}$	Total costs in the surroundings of the found minimum $TC_{x,k}^{p*}$.	USD
$TC_{x,k}^{*}$	Final minimum found	USD
γ_{x}	Weighting factor for the speed of convergence	Unitless
g	Defined gap to stop the search algorithm	Unitless
ILP DSMS formulation		
$TFC_{d,h}$	Total fixed costs	USD
$TVC_{d,h}$	Total variable costs	USD
$VCDG_{d,h}$	Variable costs of the DG	USD/kWh
$VFCDG_{d,h}$	Variable fixed costs of the DG	USD
$VCB_{d,h}$	Variable costs of the BESS	USD/kWh
$VFCB_{d,h}$	Variable fixed costs of the BESS	USD
$TVCDR_{d,h}$	Total variable costs of the DR	USD/kWh
$CLE_{d,h}$	Cost of lack of energy	USD/kWh
$CEE_{d,h}$	Cost of excess of energy	USD/kWh
$QDG_{d,h}$	Quantity of energy delivered by the DG	kWh
$SOC_{d,h}$	Quantity of energy stored in the BESS	kWh
$QDR_{d,h}$	Quantity of energy changed by the DR	kWh
$QLE_{d,h}$	Quantity of energy not delivered to the demand	kWh
$QEE_{d,h}$	Quantity of excess energy produced by the system	kWh
SOC_{max}	Maximum energy in the BESS	kWh
SOC_{min}	Minimum energy in the BESS	kWh
$YG_{d,h}$	Binary variable for the DG	Unitless
$YB_{d,h}$	Binary variable for the BESS	Unitless
$YC_{d,h}$	Binary variable for the BESS	Unitless
$YD_{d,h}$	Binary variable for the BESS	Unitless
$e_{d,h}$	Hourly elasticity of the customers	Unitless
$D_{d,h}^{0}$	Initial electrical demand	kWh
$D_{d,h}^{f}$	Final electrical demand	kWh
π^{0}	Initial price of the energy	USD
π^{inc}	Price of the offered incentive	USD
$max(D_{d,h}^{f})$	Maximum peak demand over the simulation horizon T	kW
β	Factor for the reliability of the microgrid	Unitless

Table 1 Variable declaration

advance. Any economic incentive or punishment is designed to incentive consumers to participate.

Mazidi et al. introduce a DSMS to improve the reserve capacity of a microgrid and minimize operational costs [21]. Using responsive loads and distributed generation units, they create the reserve requirement for compensating renewable forecast errors. Residential, commercial, and industrial customers can participate in the program either to reduce energy consumption or to schedule reserve capacity. Agbayani et al. propose a stochastic programming model to minimize operating costs and emissions in a smart microgrid with renewable sources [22]. A DSMS is formulated to reduce the uncertainties introduced by RERs using incentive-based payments as price offer packages. Residential, commercial, and industrial customers can participate in the DSMS.

Chenye et al. use dynamic potential game theory to tackle the intermittency in wind power generation in a SAMG [23]. A decentralized DSMS is formulated to reduce operational costs.Self-interests of end users were characterized to know the best strategies of the formulated game model. Simulation results with field data shown a reduction of 38% of the operational costs compared to a benchmark where no DSMSs was applied. Kumar et al. design a voltage drop controller that is capable to curtail the demand in order to regulate the voltage variability of a SAMG [24], [25]. Results show that the proposed drop controller can curtail 19% of the demand ton maintain the voltage in the desired limits.

Majid et al. use Integer Linear Programming (ILP) to design a Home Energy Management Controller (HEMC) to apply a DSMS [26]. Zhu et al. make a similar work using a ILP-Game Theory based approach [27], [28]. Results shows that the HEMC effectively reschedule power-shiftable appliances and time-shiftable appliances to reduce the peak load. Other works using ILP as [29] and [30] show the effectiveness of ILP models. References [20]- [30] show the benefits of using DSMSs in the operational phase of a microgrid. However, they do not consider the potential effect of applying a DSMS in the planning phase of a microgrid or a SAMG project.

The Integrated Resource Planning (IRP) framework allows microgrid planners to measure the effects of applying DSMS in the planning phase [31], [32]. By using this framework, Zhu et al. evaluate the impact of load control, interruptible loads, and shiftable loads over the design of a microgrid in Shanghai, China [33], [34]. The study shows that using DSMSs it is possible to reduce the size of the facilities of the microgrid, decrease investments, and increase social benefits.

Despite that Zhu et al. proves that applying a DSMS in the planning phase of the microgrid reduces the total costs of the project, the two studies do not focus on the design of the DSMS [33], [34]. In this regard, the present work aims to design a DSMS and evaluate the impact over the total costs of a SAMG in the planning phase. To do so, it is proposed a methodology that executes the sizing of the microgrid on one side and simulates the operation of the microgrid with the DSMS on the other side. The sizing is carried out using a heuristic algorithm that mimics the behavior of the gradient descent method. The simulation of the operation of the microgrid is carried out using power and energy balances. The DSMS is formulated using ILP, considering that the load and weather forecasts are known one day in advance. Economic incentives and penalizations for the customers are designed to increase or decrease electrical consumption. The DSMS is formulated as a function of the installed capacities, allowing the sizing methodology and the simulation model work together. The cooperative work of the two formulations enables the proposed method to find the size of the microgrid and the optimal dispatch strategy. A sensitive analysis is included considering variations in the solar radiation, the fuel price, and the price of the storage system. The study case shows a comparison between the proposed method and a scenario without DSMS.

Considering the above, the main contribution of this work to the state-of-the-art proceeds as follows:

- Design of a methodology that can compute the size of the energy sources using a heuristic approach and the optimal energy dispatch of the energy sources using an Integer Linear Programming formulation.
- Design of an incentive based DSMS using an Integer Linear Programming formulation to be applied on the planning phase of SAMGs.
- A sensitivity analysis to evaluate the impacts in the planning of SAMG of variations in the Global Horizontal Radiation, the price of fuel and the costs of installing a Battery Energy Storage Systems.

The description of the rest of the document proceeds as follows: section 2 presents the formulation of the problem, the cost evaluation, and, the proposed solution. Section 3 describes briefly the proposed iterative search heuristic algorithm used for the sizing of the SAMG. Section 4 introduces the formulation of the DSMS using the Integer Linear Programming formulation. The analysis of the results, the sensitivity analysis, and comparisons of the proposed methodology with a baseline case are presented in section 5. Finally; section 6 presents the conclusions and remarks of the work.

2. Problem formulation and proposed solution

The considered problem is the design of a DSMS and the evaluation of their potential impact over the sizing of a SAMG. In this matter, solving two problems is required: sizing and energy management. In one side, the sizing refers to the process of determining the size of each of the generators and storage systems that will feed the demand of the microgrid. In this process, it is highly desirable to increase reliability while minimizing investment costs, output energy costs, or fuel consumption, among others [35], [36]. On the other side, the DSMS performs the economic dispatch of the SAMG. The operational points of each of the technologies are set considering weather and demand forecasts. The DSMS includes the monetary incentives or penalizations for the customers to increase or reduce the consumption, respectively.

Formulate the sizing and the DSMS requires to know the installation and operational costs of each of the technologies. To achieve the solution of both formulations simultaneously, we formulate the ILP as a function of the installed capacities, and the costs on a unitary basis [37], [38]. Section2.1 introduces the proposed solution for the problem, and section 2.2 presents the cost models of the energy sources.

2.1. Proposed solution

The proposed methodology must be able to solve the sizing and the optimal dispatch for the DSMS simultaneously. To achieve this, it is proposed a nested simulation model inside of the sizing process of the SAMG. The nested simulation model finds the optimal dispatch strategy considering the proposed DSMS and finds the total costs of installation and operation of the microgrid. The total costs are stored and compared to the total costs of other combinations of capacities proposed by the sizing algorithm. This process is repeated until the sizing algorithm finds the less expensive combination of capacities that can feed the electrical demand. Figure 1 illustrates the proposed methodology.

2.2. Cost models of the energy sources for the DSMS

This section introduces the costs models of the energy sources for the objective function. The costs of the photovoltaic system are presented in section 2.2.1. The costs of the Diesel generator in section 2.2.2. The costs of the BESS in section 2.2.3. Finally, section 2.2.4 presents the costs of the DR mechanism.

2.2.1. Photovoltaic system costs:

The photovoltaic system costs are related to the initial investment and the maintenance of the system:

$$FC_{PV} = C_{PV}II_{PV} + C_{PV}M_{PV} \tag{1}$$

The variable costs of the photovoltaic system are assumed to be zero after installation.

2.2.2. Diesel generator system costs:

The diesel generator fixed costs are related to the initial investment and the maintenance of the system:

$$FC_{DG} = C_{DG}II_{DG} + C_{DG}M_{DG} \tag{2}$$

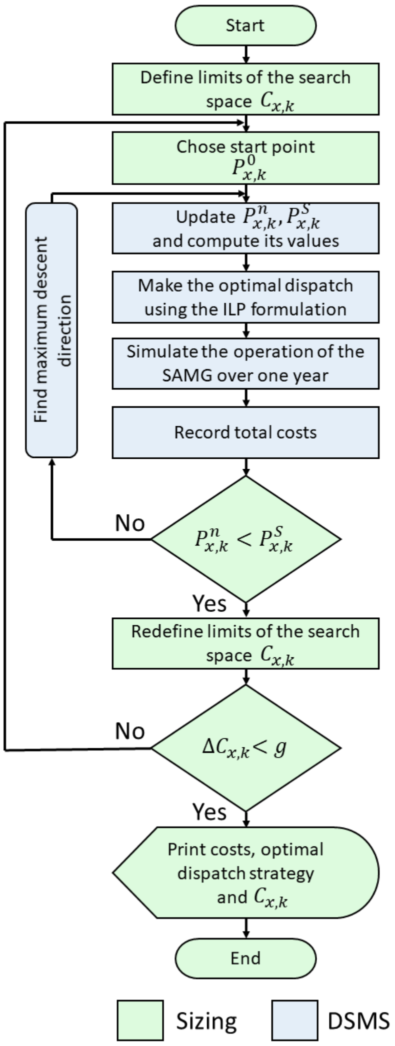

Figure 1 Algorithm for the proposed methodology.

The variable costs of the diesel generator are related to its fuel consumption. The fuel consumption is a function of the generator capacity and the output power. This function can be expressed using linear or quadratic formulations [39], [40]. In here, different data sheets of commercial generators were consulted to know the capacities and their respective diesel consumption at a different output power to create a linear regression. The linear regression takes the diesel consumption of generators from 100 kW till 1.000 kW considering 25%, 50%, 75% and 100% of output power. The resulting formulation express the diesel consumption as a function of the installed capacity and the output power, as shown in equation (3) and depicted in Figure 2.

$$TVCDG_{d,h} = \psi_L C_{DG}\left(\frac{0.24QDG_{d,h}}{C_{DG}} + 0.031\right) \quad (3)$$

2.2.3. Battery energy storage system costs:

Battery fixed costs are related to its installation and maintenance:

$$FC_B = C_B II_B + C_B M_B \quad (4)$$

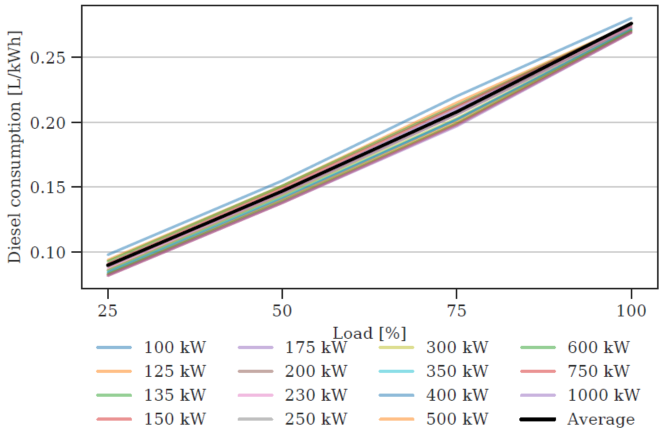

Figure 2 Diesel consumption for different generators and percentages of load.

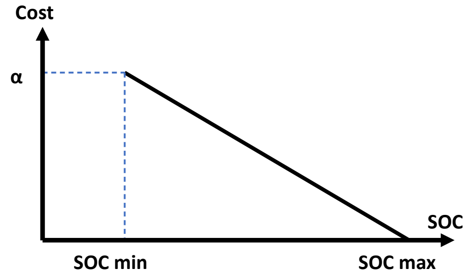

Figure 3 Variable costs of the BESS as a function of the SOC.

To avoid dispatching the battery when the *SOC* is low, we propose in here to define the variable costs as a function of its state of charge as depicted in Figure 3 and expressed in equation (5) and (6):

$$TVCB_{d,h} = -\frac{\alpha\left(SOC_{d,h} - SOC_{\max}\right)}{\Delta SOC} \quad (5)$$

$$\Delta SOC = SOC_{max} - SOC_{min} \quad (6)$$

Where α is a parameter used to define the cost difference of the two states of the battery: charged and discharged. Parameter α can be tuned to guarantee that the costs associated with the operation of the battery at the end of the lifetime are recovered through the tariffs to rebuy the system.

2.2.4. Demand response system costs:

The demand response fixed costs are related to the initial investment to acquire the technology and its maintenance.

$$FC_{DR} = C_{DR} II_{DR} + C_{DR} M_{DR} \quad (7)$$

Variable costs are related to the operation of the DSMS. The designed DSMS uses two different incentives, one to increase energy consumption and another to reduce it. To encourage energy consumption, the DSMS offer a discount to the regular tariff. To discourage energy consumption, the DSMS charges an extra price to the regular tariff. Figure 4 illustrates the two scenarios.

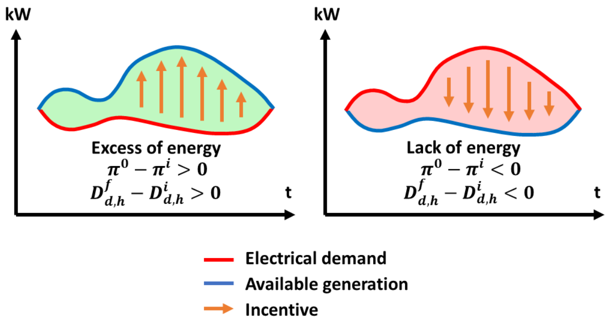

Figure 4 Possible scenarios for the economic incentive.

To define the economic value of the incentive, the microgrid operator needs to estimate how much money he can offer and how much the customers will modify their patterns of consumption in the presence of the stimulus. Different approaches are being considered by researchers to solve this problem. In [41] it is maximized the utility of the customers and the utility of the system operator (SO) considering the customer response to the price signal and the profit of the SO. The research presented in [42] formulates a methodology to estimate the optimal real-time price signal, considering how the customers will respond to it. On another side, [43] proposes to use self-elasticity and cross elasticity of each user to estimate how customers will react to an Emergency Demand Response Program and a Time of Use tariff. Here, the concept that relates the price of the goods with its consumption originally introduced by microeconomics is used [44]. This concept allows to predict how customers will react to different price incentives [43], [45].

$$e_{d,h} = \frac{(D^f_{d,h} - D^0_{d,h})\pi^0}{(\pi^{inc} - \pi^0)D^0_{d,h}} \tag{8}$$

3. Sizing process

To perform the sizing of the microgrid, it is proposed a heuristic iterative search algorithm that mimics the behavior of the gradient descent method. The algorithm executes three different steps to find the size of the microgrid. Section 3.1 explains the creation of the search space. Section 3.2 explains the search process. Finally, section 3.3 explains the process of redefining the limits of the search space and the stops criteria.

3.1 Creation of the search space

At first, the algorithm creates the search space using initial and final points, and a predefined step for each of the technologies, as described in equations (9) to (14).

$$C^{min}_{x,k} \geq 0 \tag{9}$$

$$\Delta C_{x,k} \geq 0 \tag{10}$$

$$C^{med}_{x,k} = C^{min}_{x,k} + \Delta C_{x,k} \tag{11}$$

$$C^{max}_{x,k} = C^{med}_{x,k} + \Delta C_{x,k} \tag{12}$$

$$C^{max}_{DR,k} \leq 0.1 \max(D^f_{d,h}) \tag{13}$$

$$x = C_{PV}, C_{DG}, C_B, C_{DR} \tag{14}$$

The simulation model computes the sum of the fixed and variable costs of the operation of the microgrid over a horizon of T days. For the simulations it is assumed to be known one day ahead perfect forecasts of the electrical demand and the solar radiation.

$$TC_{x,k} = \sum_{d=1}^{T}\sum_{h=1}^{24} TFC_{d,h} + TVC_{d,h} \tag{15}$$

$$\mathrm{TFC}_{\mathrm{d,h}} = (FC_{PV} + FC_{DG} + FC_B + FC_{DR})(1+r)^{-\frac{T}{365}} \tag{16}$$

Variable $TC_{x,k}$ represents the total costs obtained at iteration k using the capacities C_{DR}, C_{GD}, C_{PV}, and C_B. Variable $TVC_{d,h}$ represents the total variable costs of operating the microgrid (Explained in section 4).

3.2 Search process

To avoid computing all the possible combinations inside of the search space and reduce the computational time of the problem, a search methodology that mimics the behavior of the gradient descent method it is proposed in here. Using a preset configuration of the capacities $C^{min}_{x,k}$, $C^{med}_{x,k}$, and $C^{max}_{x,k}$ as an initial point $TC^0_{x,k}$, the simulation frame computes the costs of operating the microgrid over a horizon of T days. Afterward, the algorithm evaluates the surroundings of the initial point. To find the value of the capacities of the surroundings $TC^*_{x,k}$, a $\Delta C_{x,k}$ is added to the initial point. A comparison of all the computed costs is used to find the maximum descent direction. This process repeats until the algorithm finds a minimum point $TC^*_{x,k}$where the costs of all the surroundings $TC^S_{x,k}$ are higher.

3.3 Redefining the limits of the search space

The limits of the search space are tightened around the found minimum combination. This process reduces the space search and allows to find a new minimum point $TC^*_{x,k}$ in the next k iteration. The rules of redefining the search space are based on two possible scenarios; either if the minimum is in the limits of the search space or if is inside.

If the localization of the minimum is at the limits of the search space, the space search moves in the same direction of the found limit. Equations (17) and (18) redefine the limits using positive sign if the minimum is in a superior limit $C^{max}_{x,k}$, or negative sign if the minimum is in an inferior limit $C^{min}_{x,k}$:

$$C^{min}_{x,k} = C^{min}_{x,k-1} - \Delta C_{x,k} \tag{17}$$

$$C^{max}_{x,k} = C^{max}_{x,k-1} + \Delta C_{x,k} \tag{18}$$

If the localization of the minimum is inside of the matrix CM, the space search tights around the minimum point. γ_x factor is introduced to control the speed of convergence of the proposed search algorithm. Equations (19)-(21) describe the actualization process:

$$C^{min}_{x,k} = C^{min}_{x,k-1} \pm \gamma_x \Delta C_{x,k} \tag{19}$$

$$\Delta C_{x,k} = (1-\gamma_x)\Delta C_{x,k-1} \tag{20}$$

$$0 < \gamma_x < 1 \tag{21}$$

Finally, the algorithm stops to iterate when the difference between the minimum cost $TC^*_{x,k}$ and the cost in the surroundings TC^S_x is less than a predefined gap.

$$TC^*_x - TC^S_x < g \tag{22}$$

4. ILP formulation of the DSMS

The DSMS is formulated as a centralized energy management scheme in which is desired to minimize initial investment, system operation and maintenance costs of the islanded microgrid [46]. To achieve this an ILP formulation was made. Equation (23) describes the objective function of the DSMS.

$$TVC_{d,h} = \sum_{d=1}^{T}\sum_{h=1}^{24} VCDG_{d,h}QDG_{d,h} + VFCDG_{d,h} + VCB_{d,h}SOC_{d,h} + VFCB_{d,h} + TVCDR_{d,h}QDR_{d,h} + CLE \cdot QLE_{d,h} + CEE \cdot QEE_{d,h} \tag{23}$$

The ILP formulation uses different restrictions and binary variables. Sections 4.1 to 4.4 explain each of the terms introduced by equation (23) and all the restrictions. Equation (24) presents the first restriction designed to balance generation and demand. As defined by [47], a battery is an element strongly coupled in time. However, the lack of energy in one hour or the excess of power in another hour can be demanded or stored in the battery. In this regard, the battery is a deposit to store something temporarily. This problem was modeled before by the operations research, and it is well known as the inventory problem [48]. Using this formulation, it is not only possible to balance the demand and the generation, but also to consider the energy saved from one period to another in the BESS.

$$SOC_{d,h-1} + QDG_{d,h} + QDR_{d,h} + QLE_{d,h} + QEE_{d,h} = D^f_{d,h} + SOC_{d,h} \tag{24}$$

4.1 Diesel generator model

The operational costs of the Diesel generator introduced by section 2.2.2 with equation (3) have two parts: variable and fixed costs. Equations (26) and (27) express this using standard ILP notation.

$$VCDG_{d,h} = 0.24\psi_L \tag{26}$$

$$VFCDG_{d,h} = 0{,}031\psi_L C_{DG} \tag{27}$$

Additionally, the capacity limits of the generator are defined using the binary variable $YG_{d,h}$:

$$0.3C_{DG}YG_{d,h} - QDG_{d,h} \leq 0 \tag{28}$$

$$QDG_{d,h} - 0.8C_{DG}YG_{d,h} \leq 0 \tag{29}$$

4.2 Battery energy storage model

Operational costs of the battery stated by equation (4) have variable and fixed costs, which can be expressed in standard ILP notation using the binary variable YB.

$$VCB_{d,h} = -\frac{\alpha SOC_{d,h}}{\Delta SOC} \tag{30}$$

$$VFCB_{d,h} = \frac{\alpha SOC_{max}YB_{d,h}}{\Delta SOC} \tag{31}$$

Equations (32) to (34) model the restrictions of the rate of charge and discharge of the battery. Binary variables $YC_{d,h}$ and $YD_{d,h}$ are introduced to avoid non-physical solutions and restrict the model to charge and discharge the battery at the same time.

$$SOC_{d,h} - SOC_{d,h-1} - 0.3C_BYC_{d,h} \leq 0 \tag{32}$$

$$SOC_{d,h-1} - SOC_{d,h} - 0.3C_BYD_{d,h} \leq 0 \tag{33}$$

$$YC_{d,h} + YD_{d,h} \leq 1 \tag{34}$$

Equations (37) and (38) presents upper and lower limits of the SoC:

$$-SOC_{d,h} \leq 0.3C_B \tag{35}$$

$$SOC_{d,h} - 0.9C_BYB_{d,h} \leq 0 \tag{36}$$

4.3 Demand response model

As described by section 2.2.4 and equation (8), the response of the customers to an economic stimulus can be estimated if the demand, the incentive, and the elasticity of the customers are known. However, to model the incentive as a function of the desired response, non-linear functions must be introduced in the objective function; which is not allowed by the present ILP formulation. To face this restriction, the economic value of the offered incentive must be determined alternatively. Therefore, to compute the incentive it is assumed that only 10% of the customers will react to the stimulus. If only 10% of the customers react, the value of the incentive can be computed for the worst-case scenario, which will be paying enough money to reduce 10% of the demand. Equation (37) and (38) show the calculation of the offered incentive $\pi\delta_{d,h}$.

$$-0.1\max\left(D^f_{d,h}\right) < DR_{d,h} < 0.1\max\left(D^f_{d,h}\right) \tag{37}$$

$$\pi^i_{d,h} = \frac{0.1\pi^0 D^0_{d,h}}{e_{d,h}} \tag{38}$$

Equation 38 computes the value of the incentive, assuming that it is possible to know the cost of generating *D* units of energy at day *d* and hour *h*. Additionally, it is assumed that the elasticity of the customers is known for every hour of simulation.

4.4 Excess and lack of energy model

A cost CEE is introduced to weight the energy that the generation facilities provide, but it is not possible to consume by the demand. A cost CLE is proposed to weight the power that customers require, but the generation facilities are not able to produce. The definition of both costs is:

$$CEE = \beta FC_{PV} \tag{39}$$

$$CLE = \beta FC_{PV} \tag{40}$$

$$\beta > 1 \tag{41}$$

Equations (42) and (43) are introduced to guarantee that the ILP formulation always will find a solution for any of the capacities that the algorithm of the sizing can use.

$$0 < QLE < \infty \quad (42)$$

$$-\infty < QEE < 0 \quad (43)$$

5. Simulation results and analysis

This section provides numerical examples to illustrate the performance of the proposed method. The study case is a hypothetical microgrid located at longitude 77′16′8″ West and latitude 5′41′36″ North (Nuquí, Colombia). The microgrid is composed of Photovoltaic panels (PV), a Battery Energy Storage System (BESS), a Diesel Generator (DG) and a Demand Response (DR) system. The maximum load of the considered microgrid is 460 *kW*. Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM), a Colombian institute in charge of monitoring the weather across the country, provides meteorological data for the simulations. The average Global Horizontal Irradiance (GHI) in Nuquí is 3,5 kWh/m^2. The cost of Diesel used for the simulations is 0.79 *USD/liter*. The lifetime of the PV is 25 years, BESS 8 years, DG 15 years and DR 25 years. The planning horizon for the microgrid is 25 years. However, simulations of operation were carried out only for one month due to the lack of seasons, lack of significant monthly variations in the GHI during the year, and the tropical conditions of the study case. Table II summarizes the unitary costs obtained from the local providers and used for the simulations.

System	Initial Investment	Maintenance	Operation
PV	1300 USD/kW	0.02 USD/kW	0 USD
BESS	420 USD/kWh	0.01 USD/kWh	Equation 5
DG	550 USD/kW	0.75 USD/kWh	Equation 3
DR	50 USD/kW	0 USD/kW	Equation 8

Table 2 Costs for the simulations.

Different simulations were carried out (Section5.1) to evaluate the performance and the capabilities of the designed DSMS to handle variations in the load and weather forecasts. Additionally, the simulations are used to estimate the impact of the DSMS over the sizing of the microgrid considering changes in the solar radiation (Section 5.2), diesel price (Section 5.3), and BESS price (Section 5.4).

5.1 Performance of the designed DSMS

To measure the performance of the DSMS, we compare simulation results with a baseline case without DSMS. Baseline case was designed using ILP. To guarantee a fair comparison, both scenarios use the same load and weather forecasts over the simulation time. Figure 5 presents the comparison of both scenarios considering the output power of an average day of simulation.

Figure 5 shows that the application of the DSMS incentive the customers to increase their consumption at noon hours. This leads to an average reduction of the excess of energy. On the other side, the DSMS also incentive the customers to reduce their consumption at peak hours. The reduction in peak hours allow the algorithm to reduce the size of the installed BESS.

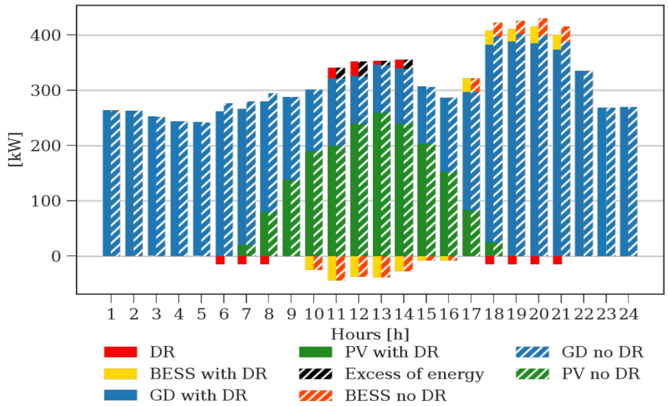

Figure 5 Average day output power from the generators.

Figure 6 presents the output power of both scenarios and the total dispatch costs of a period of ten days. The input/output power from the BESS is not included in the graph because the battery is sized to be fully charged and discharged in one day. The proposed algorithm of DSMS and sizing give this result because of the predefined horizon of planning for the ILP formulation. If load and weather forecasts are supposed to be known for more than one day in advance, the BESS will deal better with solar radiation variations. However, increasing the horizon of planning also increases the uncertainties in the forecasts [15]. The study of the impact on the sizing of expanding the load and weather forecasts horizon is left out for further research.

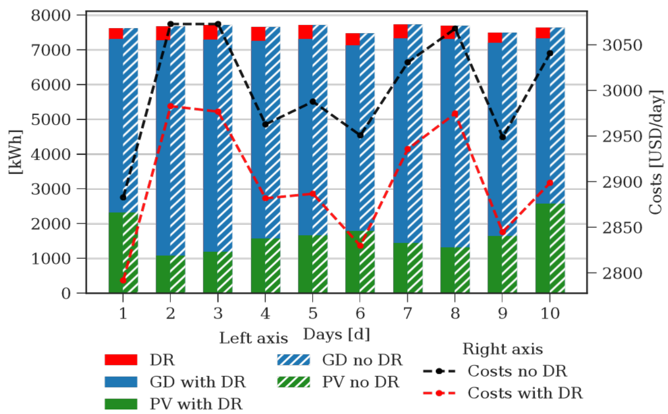

Figure 6 Output power over ten days of simulations.

Figure 5 shows that the daily average dispatch of the microgrid is modified by the DSMS. The changes in the patterns of consumption of the customers leads to variations in the price of operating the SAMG as shown by Figure 6. At the end, the variations in the operational costs and the installed capacities will lead to reductions in the LCOE, as shown by the sensitivity analysis.

5.2 Solar radiation analysis

A simulation is carried out to estimate the differences in the sizing of the PV and BESS system, considering deviations in the GHI of ± 30% from the standard case. Figure 7 shows the impact that the GHI has on the sizing of the facilities.

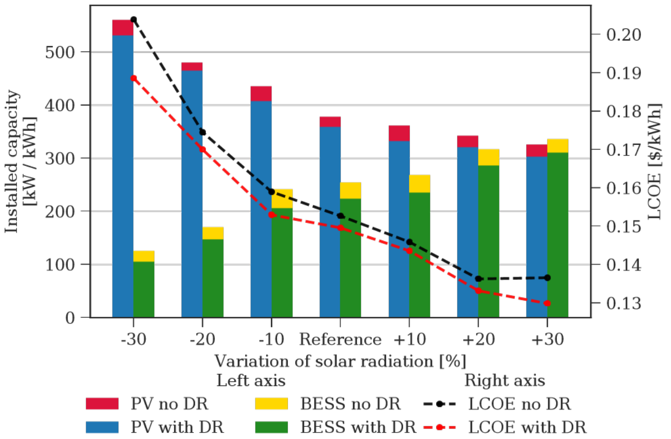

Figure 7 PV and BESS variation considering different GHIs.

Figure 7 shows that the proposed DSMS reduce the installed capacities of the PV system in 3.3% on average compared to the base case when different GHIs are considered. The BESS is reduced 8.2% compared to the base case. The LCOE of the SAMG is reduced 2.6% on average after the application of the DSMS.

5.3 Diesel price sensitivity analysis

A simulation is performed to study the impact of the variations of the diesel price over the sizing of the microgrid [13]. The simulation considers differences of ±30% of the diesel cost from the standard case. From the obtained results shown in Figure 8, it is possible to see a reduction in the diesel generator installed capacity when the price of the diesel increases. The opposite effect occurs for the BESS, if the cost of the diesel increases, the size of the BESS increases too.

Figure 8 shows a direct relation between the LCOE and the Diesel price. This relation makes sense since the SAMG is relies on Diesel generation. However, Figure 8 shows that the application of the DSMS makes a slower growth for the LCOE compared to the baseline case, which is more notorious for the highest prices of the diesel.

5.4 BESS costs sensitivity analysis

Considering variations of ±30% in the price of the BESS simulations were carried out. Figure 9 shows the impact of the BESS price on the sizing of the microgrid.

Figure 9 shows that the variations in the LCOE due to changes in the acquisition price of the BESS are less than the changes produced by GHI or diesel price variations. However, the reduction in the PV system reach 3.2%. On the other side, the variations in the BESS system present variations of 24.1%, its highest variations in all the simulations carried out.

6. Conclusions

The present study shows the design of a DSMS using an ILP approach for the planning of SAMG. The study uses a nested model that simulates the operation of the DSMS in the lower level and computes the sizing of the SAMG in the upper level. This approach allows to compute the effects of the DSMS in the size of the energy sources of the SAMG. This approach can be useful to microgrid planners to evaluate the technical and economic impacts of applying DSMS in the planning phase of a SAMG. A good selection of the DSMS

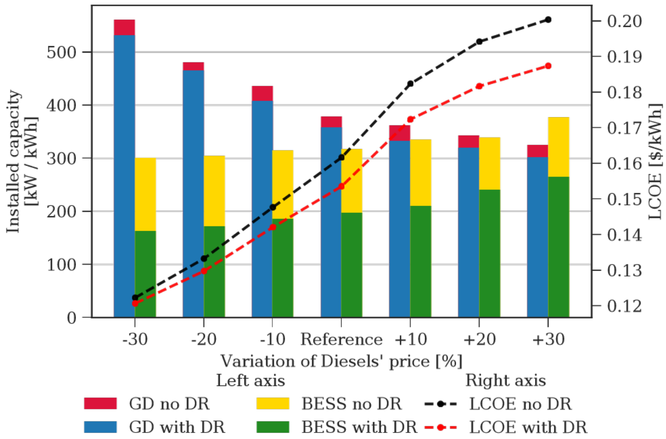

Figure 8 GD and BESS variations considering different Diesel price.

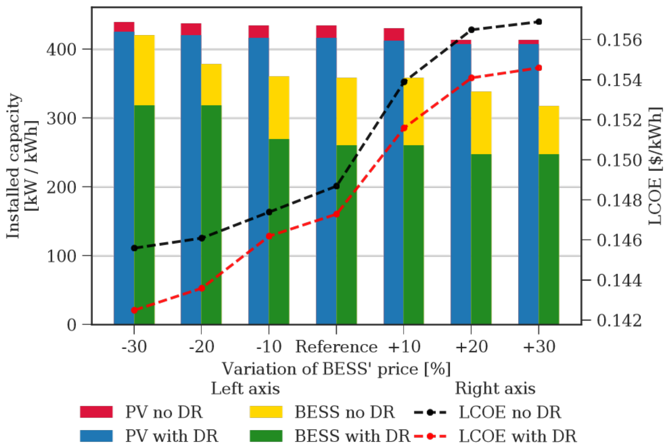

Figure 9 PV and BESS variations considering different BESS acquisitions price.

can help them to reduce the initial investment costs and operational costs. Even more, the proposed approach can be useful to governments or policymakers to evaluate the effects of policies regarding the application of DSMSs for SAMG.

The application of a sensitivity analysis in a study case of the proposed approach show a reduction in the installation and operational costs, and the LCOE. This can lead to a reduction in the payments of the customers. Additionally, the study case shows a reduction in the capacities of the energy sources. However, more studies are needed in this regard. Governments can partially fund SAMG projects, private capital, or a combination of both. The presence of public capital will reduce the amount of money that private investors need to recover using tariffs. This will modify the payments of the customers and the profits of the private investors. Further research in this aspect is required. Another aspect worth it to evaluate is the impact of the elasticity over the designed DSMS. This work assumes an average elasticity for the customers. However, real-life applications need more sophisticated models for the elasticity of the customers. Finally, the simulation of this work assumes a perfect day ahead forecast for the electric demand and the weather variables. However, it is needed to further works to evaluate the impact of uncertainties in the forecasts. Even more, it is needed to evaluate the impact of considering different forecast horizons.

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