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

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***Abstract*—Demand Side Management Strategies (DSMSs) can play a significant role in reducing installation and operational costs, Levelized Cost of Energy (LCOE), and enhance renewable energy utilization in Stand-Alone Microgrids (SAMGs). Despite this, there is a paucity in literature exploring how DSMS affects the planning of SAMGs. This paper presents a methodology to design an incentive-based DSMS and evaluate its impact on the planning phase of a SAMG. The DSMS offers two kinds of incentives, a discount in the flat tariff to increase the electrical energy consumption of the users, and an extra payment added to the fare to penalize it. The design of the methodology integrates the optimal energy dispatch of the energy sources, the tariff design, and its sizing. In this regard, the main contribution of this paper is the design of an incentive-based DSMS using a Disciplined Convex approach, and the evaluation of its potential impacts over the planning of SAMG. The methodology also computes how the profits of the investors are modified when the economic incentives vary. A study case shows that the designed DSMS effectively reduces the size of the energy sources, the LCOE, and the payments of the customers for the purchased energy.**

***Key words*—Stand-Alone Microgrids, Planning, Sizing, Energy Management, Demand-Side Management.**

1. Introduction

The access to affordable and high-quality electricity service is considered as one of the barriers to overcome in order to achieve sustainable economic and social development in rural areas [1]. The installation of stand-alone microgrids (SAMG), when the extension of the utility grid is not feasible, is the most common alternative for rural electrification [2]–[6]. SAMG projects are generally considered as a good solution to provide electric energy services to isolated communities [7]. However, SAMG face technical and financial challenges that need to be addressed in their planning.

The technical aspects of the planning of SAMG refer to the sizing and the design of an appropriate Energy Management Strategy (EMS). The EMS must consider the uncertainties introduced by the Renewable Energy Resources (RERs) [8, 9]. One of the ways to deal with the uncertainties is the addition of Demand Side Management Strategies (DSMSs) to the EMS. Sending a signal to the customers to increase or decrease the consumption can reduce the risk of excess and lack of energy introduced by the RERs. Additionally, DSMSs can reduce operational costs, harmful environmental emissions, and increase the reliability of the microgrid [10]–[12].

The DSMS can affect the patterns of consumption of the customers using direct or indirect strategies [13]. One of the advantages of indirect DSMS is the possibility of the customers to choose either to participate or not in the program [14]. Indirect DSMS include pricing programs, incentive programs, rebates, subsidies, and education programs. Incentive programs offer economic incentives to the customers either to reduce or to increase the electrical energy consumption [15, 16]. Adequately designed incentives can reflect electricity production costs, which can motivate the customers to shift their demand when it is more convenient to produce electricity [17]. Additionally, adequately designed incentives can lead to energy conservation, and therefore, are desired when the energy generation is limited [18].

Palma-Behnke et al. introduce a DSMS for the operation of a microgrid based on sending information to the customers about the availability of electric energy

TABLE I: Variable declaration

SAMG modeling		
t	Hour of optimization	Hours
T	Total number of hours to optimize	Hours
n	Specific customer in the microgrid	Unitless
m	Specific generator or storage system of the microgrid	Unitless
M	Total number of generators and storage systems of the microgrid	Unitless
$D_{o,t}$	Initial Electrical demand of the community	kWh
D_t	Final Electrical demand of the community	kWh
$D_{o,t}^n$	Initial Electrical demand of the n customer	kWh
D_t^n	Final Electrical demand of the n customer	kWh
e_t^n	Self-elasticity of the n customer	Unitless
I_m	Unitary initial investment of the m device	USD/kW
C_m	Installed capacity of the m device	kW, kWh
E_m	Quantity of energy delivered with the m device	kWh
$E_{B,t}$	Stored energy in the Battery at time t	kWh
λ_m	Unitary costs of generation of the m device	USD/kWh
ξ_m	Unitary maintenance costs of the m device	USD/kWh
$LPSP$	Loss of Power Supply Probability	Unitless
$EPSP$	Excess of Power Supply Probability	Unitless
CAPEX	Capital Expenditures	USD
OPEX	Operational Expenditures	USD
Financial analysis		
ζ	Total capital expenditures	USD
ϑ	Total operational expenditures	USD
φ_{ci}	Percentage of the CAPEX paid by the investor	Unitless
φ_{cg}	Percentage of the CAPEX paid by the government	Unitless
φ_{oi}	Percentage of the OPEX paid by the investor	Unitless
φ_{og}	Percentage of the OPEX paid by the government	Unitless
φ_{pr}	Percentage of the profits to pay the incentives	Unitless
R	Internal Rate of Return for the investors	Unitless
F_c	Electric energy conservation factor	Unitless
Incentive-based DSMS design		
π_t	Vector of prices of the incentive-based tariff	USD/kWh
π_{min}	Minimum value of the incentive	USD/kWh
π_{max}	Maximum value of the incentive	USD/kWh
π_{flat}	Original price of the tariff without DSMS	USD/kWh
π_f	Flat price of the tariff	USD/kWh
$\pi_{i,t}$	Price of the incentive at t hour	USD/kWh
ψ_L	Diesel price per liter	USD/liter
Γ_{inc}^n	Payments of the n customer under the designed tariff	USD
Study case		
C_{DG}	Installed capacity of diesel generator	kW
C_{PV}	Installed capacity of photovoltaic generation	kW
C_B	Installed capacity of Battery	kWh
I_{DG}	Unitary investment costs of diesel generator	USD/kW
I_{PV}	Unitary investment costs of photovoltaic generation	USD/kW
I_B	Unitary investment costs of Battery	USD/kWh
ξ_{DG}	Unitary maintenance costs of the diesel generator	USD/kWh
ξ_{PV}	Unitary maintenance costs of the photovoltaic system	USD/kW
ξ_B	Unitary maintenance costs of the battery	USD/kW
$E_{DG,t}$	Amount of energy delivered with the diesel generator	kWh
$F_{DG,t}$	Fuel consumption of the diesel generator	kWh
$E_{PV,t}$	Amount of energy delivered with the photovoltaic generation	kWh
$E_{EE,t}$	Amount of energy in excess	kWh
$E_{LE,t}$	Lack of energy to fulfill the demand	kWh
N_{PV}	Number of photovoltaic panels	Unitless
ρ_{PV}	Derating factor of the photovoltaic system	Unitless
α, β, γ	Parameters to compute fuel consumption	Unitless
P_{STC}	Output power of one PV module under standard conditions	kW
$G_{A,t}$	Global solar radiation on the surface of the PV array	W/m^2
G_{STC}	Global solar radiation at standard conditions	W/m^2
C_T	Temperature coefficient of the PV modules	$\%/^\circ C$
$T_{C,t}$	Working temperature of the PV cells	$^\circ C$
$T_{A,t}$	Ambient temperature near to the PV cells	$^\circ C$
T_{STC}	Temperature of the PV cells at standard conditions	$^\circ C$
G_{NOCT}	solar radiation at NOCT conditions	W/m^2
T_{NOCT}	Working temperature of the PV cells at NOCT conditions	$^\circ C$
$T_{a,t,NOCT}$	Ambient temperature at NOCT conditions	$^\circ C$

[19]. Lighting 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 advance. The authors did not design any economic incentive or punishment to incentivize consumers to participate.

Mazidi et al. introduce a DSMS to improve the reserve capacity of a microgrid and minimize operational costs [20]. 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 [21]. The authors formulate a DSMS to reduce the uncertainties introduced by RERs using incentive-based payments. Residential, commercial, and industrial customers can participate in the DSMS.

Chenye et al. use dynamic potential game theory to tackle the intermittent nature of wind power generation on a SAMG [22]. The authors formulate a decentralized

DSMS to reduce operational costs. Additionally, a characterization of the self-interests of the end-users helps to build the best strategies of the formulated game model. Simulation results with field data show a reduction of 38% of the operational costs compared to a benchmark where no DSMSs was applied.

References [19]–[22] 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 project. The Integrated Resource Planning (IRP) framework measures the benefits of implementing a DSMS in the planning phase of microgrids . [23, 24]. Zhu et al. use a similar approach to evaluate the impact of load control, interruptible loads, and shiftable loads over the design of a microgrid in Shanghai, China [25, 26]. The study shows that using DSMSs, it is possible to reduce the size of the facilities of the microgrid, decrease investments, and reduce social costs. Kahrobaee et al. consider dynamic tariffs in the sizing of Wind-turbine/Battery Energy Storage System (BESS) for a house [27]. The authors combine a rule-based controller, a Monte Carlo approach, and a Particle Swarm Optimization (PSO) to perform the sizing of the components. However, the combination of multiple steps of different types and the lack of an optimization formulation for energy management can lead to sub-optimal results. Erdinc et al. aim to improve these drawbacks by providing a Mixed Integer Linear Programming (MILP) formulation to design the optimal energy management strategy [28]. The work considers a Real-Time Pricing tariff scheme. However, this work did not consider how to design the DSMS itself and how different DSMSs will impact the sizing of the energy sources.

Nojavan et al. propose a Mixed-Integer Non-Linear Programming (MINLP) formulation for the sizing of a MG considering a tariff-based DSMSs [29]. However, the authors assume that 20% of the load reacts to a Time of Use (ToU) tariff ignoring the effects of the self-elasticity of the demand. Majidi et al. use Monte Carlo to determine the size of a BESS in a MG [30]. However, similarly to [29], the authors did not consider how the customers react to the DSMS; they assume that 20% of the load will react to a ToU tariff. Mehra et al. propose a work to measure the economic value of applying DSMS in the sizing of a nanogrid [31, 32]. Nevertheless, the work considers the effects of only one kind of DSMS and over a small size grid. Kumar et al. Analyze the techno-economic viability of a rural grid connected microgrid considering a demand response strategy using Homer software [33]. The study shows the feasibility of applying the demand response strategy reducing the Levelized Cost of Energy (LCOE). However, the study does not use an optimal energy dispatch strategy, neither an optimal tariff for the demand response strategy, which can lead to sub-optimal solutions.

Despite that literature has shown that applying DSMSs in microgrids planning reduces the total costs of the project, the studies found by the authors present some drawbacks that can be improved. The first drawback is that some works combine different methods to implement the EMS, DSMS, and sizing, which can lead to sub-optimal results. The second drawback is the tendency of the works to ignore the effect of the self-elasticity of the customers when the planner applies a tariff-based DSMS. A third drawback is that the authors do not focus on the design of the DSMS itself. In this regard, the present work aims to fulfill the gaps found in the literature by providing a methodology that uses one single formulation for the planning of SAMG considering the application of an incentive-based DSMS. The proposed methodology considers the self-elasticity of the customers to compute their responses to the tariffs. Additionally, the methodology designs the DSMS itself and evaluate its impact on SAMGs planning. A summary of the contributions of the methodology to the state of art proceed as follows:

- Design a methodology to obtain the optimal sizing, the optimal energy dispatch strategy, and the optimal economic incentives to guarantee the financial viability of a SAMG project using a Disciplined Convex formulation.
- Evaluate the impact of the economic incentives for the customers over the sizing, energy management, and fuel consumption of a SAMG project.
- Compare the results of the proposed method against a scenario without DSMS under a sensitive analysis that considers variations in the solar radiation, the fuel price, and the price of the storage system.

The description of the rest of the article proceeds as follows: Section 2 presents the definition of the problem and the proposed solution. Section 3 presents a study case as an example of the application of the methodology. Section 4 presents the results of the simulations. Finally, Section 5 presents the conclusions and future direction.

2. Problem formulation and proposed solution

The considered problem is the design of an economic incentive-based 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. On one side, the sizing must define the capacity of each of the energy sources of the SAMG. In this process, it is highly desirable to increase reliability while minimizing investment costs, output energy costs, or fuel consumption, among others [34, 35]. On the other side, the DSMS is in charge of doing the economic dispatch for the microgrid. The DSMS includes the monetary incentives or punishments for the customers to increase or reduce the consumption, respectively.

The methodology uses a Disciplined Convex formulation that integrates economic incentives as indirect demand response mechanisms. The methodology assumes that the planner knows historic weather variables and electrical demand data over the optimization horizon. Moreover, the methodology assumes that the planner can know the price elasticity of the demand of the customers and that the customers will change their patterns of consumption to minimize their payments. The formulation uses the initial demand D_o and final demand D_f notations to make a difference between the demand without economic incentives and the demand with economic incentives. Figure 1 shows the inputs and outputs of the proposed methodology.

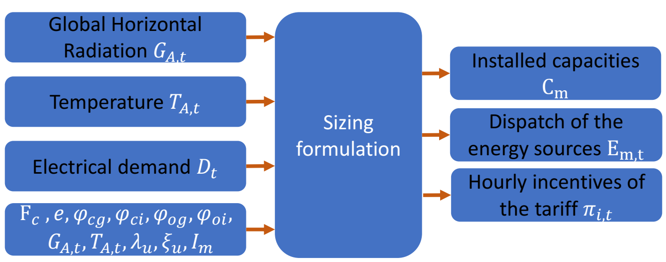


Figure 1: Flowchart for the methodology.

2.1. Proposed solution

The proposed solution considers the possibility of having public funding for the SAMG. The following equations use φ_{cg}, φ_{ci}, φ_{og} and φ_{oi} to measure the impact of the subsidies offered by the government for the Capital Expenditures and Operational Expenditures of the SAMG project according to Eqs. (1) and (2).

$$\varphi_{ci} + \varphi_{cg} = 1 \tag{1}$$

$$\varphi_{oi} + \varphi_{og} = 1 \tag{2}$$

The aim of the methodology is to minimize the Capital Expenditures (CAPEX=ζ) and the Operational Expenditures (OPEX=ϑ) that the government need to pay for the SAMG project.

$$\min \ \varphi_{cg}\zeta + \varphi_{og}\vartheta \tag{3}$$

Where ζ and ϑ are shown by Eqs. (4) and (5) respectively.

$$\zeta = \sum_{m=1}^{M} C_m I_m \tag{4}$$

$$\vartheta = \sum_{t=1}^{T}\sum_{m=1}^{M} (\lambda_{m,t} + \xi_{m,t}) E_{m,t} \tag{5}$$

The proposed formulation considers the energy prices as the only revenue stream for the investors. In this regard, they must be enough to guarantee the recovery of their investments and the expected Internal Rate of Return ($R \in (0,1)$). Eq. (6) guarantees that the investors recover their investment and the value of R for the worst-case scenario.

$$-(\varphi_{ci}\zeta + \varphi_{oi}\vartheta)(1+R) + \sum_{t=1}^{T} D_t \pi_t \geq 0 \tag{6}$$

Eq. (7) introduces an energy conservation factor $F_c \in (0, \infty)$. F_c defines how the electric energy consumption will be modified after the implementation of the incentive-based tariff π_t. If $F_c = 1$, the sum of the final demand is the same as the sum of the original demand.

$$\sum_{t=1}^{T} D_t - F_c \sum_{t=1}^{T} D_{o,t} = 0 \tag{7}$$

The designed DSMS encourages energy consumption offering a discount to the flat tariff. To discourage energy consumption, the DSMS charges an extra price to the flat tariff. To define the economic value of the incentive, the investors need to estimate how much money they can offer and how much money they can charge to the customers as an extra fare. If the incentives are paid by the investors to increase the electric energy consumption, the profit of the investors reduces. On the other side, if the incentives are paid to the investors to reduce electric energy consumption, the profit of the investors will increase. Figure 2 illustrates the two scenarios.

The design of the incentives requires two different prices π_f and π_t. π_f is a decision variable of one dimension, π_t is a decision variable of dimension T. The final tariff π_t charges the customers with the sum of π_f and π_t as described by Eq. (8).

$$\pi_t = \pi_f + \pi_{i,t} \tag{8}$$

In Eq. (9) D_t^n represents the electric energy consumption of the customer n and time t. Eq. (9) multiply the electric energy consumption with the price of the energy

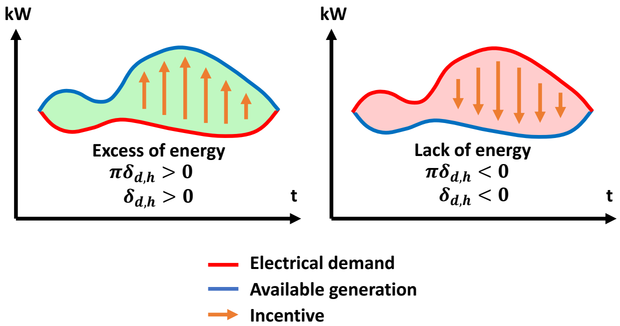


Figure 2: Possible scenarios for the economic incentive of the DSMS.

π_t, to obtain the payments of the n customer using the incentive-based tariff. Eq. (10) set a limit to the values that the planner offers as incentives.

$$\Gamma_{inc}^{n} = \sum_{t=1}^{T} D_t^n \pi_t \tag{9}$$

$$\pi_{min} \leq \pi_t \leq \pi_{max} \tag{10}$$

The planners can also define the amount of money that they want to use to pay the economic incentives. Eq. (11) defines a restriction to guarantee that the total payments of incentives do not overpass a predefined percentage (φ_{pr}) of the profits.

$$\sum_{t=1}^{T} \pi_t \leq \varphi_{pr} \left(\sum_{t=1}^{T} D_t \pi_t - (\varphi_{ci}\zeta + \varphi_{oi}\vartheta) \right) \tag{11}$$

The planners will need not only to know how much money to pay or charge, but also they will need to know 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. Considering the customers' response to the price signal and the profit of the system operator (SO), the authors maximize customers and SO utility in [36]. The research presented in [37] formulates a methodology to estimate the optimal real-time price signal, considering how the customers will respond to it. On another side, [38] 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 proposed methodology uses a concept from microeconomics that relates the price of the goods with its consumption [39]. This concept allows predicting how customers will react to different price incentives [38, 40].

$$e_t^n = \frac{\pi_t (D_t^n - D_{o,t}^n)}{D_{o,t}^n (\pi_{flat} - \pi_t)} \tag{12}$$

3. Study case

The study case aims to illustrate the capabilities and performance of the proposed methodology. To do so, the sizing and the design of an incentive-based DSMS operate over a hypothetical SAMG located at longitude $77'16'8''$ West and latitude $5'41'36''$ North (Nuquí, Colombia). The microgrid is composed of Photovoltaic panels (PV), a BESS, a Diesel Generator (DG) and a Demand Response (DR) system. Table II summarizes the unitary costs obtained from the local providers and used for the simulations. Table II describes the maintenance as the yearly costs of the installed capacities of the energy sources per kW or kWh.

TABLE II: Unitary system costs for simulations.

System	Initial Investment	Maintenance (year)	Operation
PV	1,300 USD/kW	0.02 USD/kW	0 USD
BESS	420 USD/kWh	0.01 USD/kWh	0 USD
DG	550 USD/kW	0.75 USD/kWh	Eq. 27

Due to the lack of a historical electrical demand of the community, we propose here to generate a typical community profile using the synthetic load profile generator of the Homer Pro software. The standard community profile is scaled up to make it coincide with the reported average peak in Nuquí [41]. Meteonorm database of PvSyst software provides the Global Horizontal Radiation (GHI) and temperature. Figure 3 show the daily average load profile, Figure 4 shows the daily average GHI, and Figure 5 shows daily average the temperature.

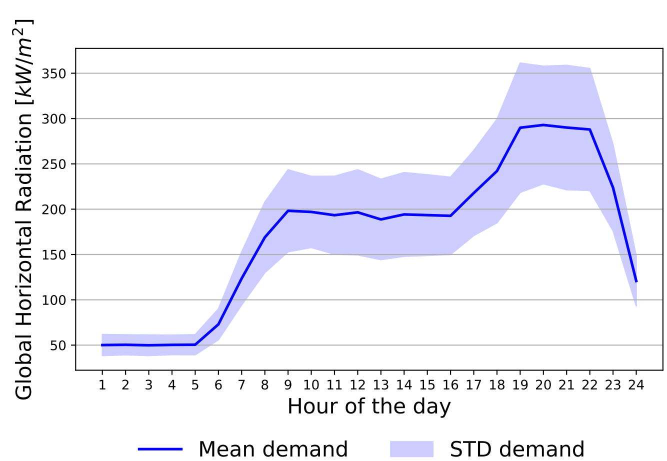


Figure 3: Daily average electrical demand

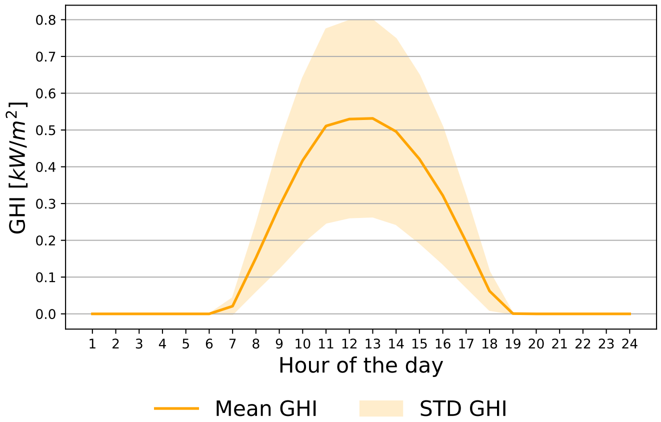


Figure 4: Daily average Global Horizontal Radiation

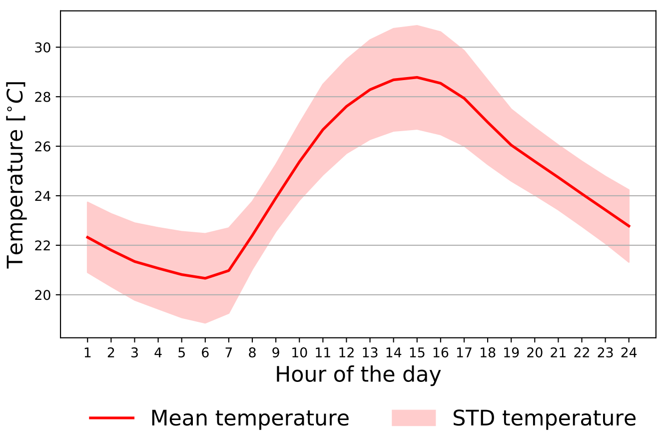


Figure 5: Daily average temperature

3.1. Application of the proposed methodology

This section aims to show how to use the proposed methodology. For all the following equations t represents the hour of simulation over an optimization horizon of one year.

3.2. Objective function

Eqs. (13), (14) and (15) are the application of Eqs. (3), (4) and (5), respectively. Eq. (14) presents the capital expenditures. C_{DG}, C_{PV} and C_B are variables of one dimension. These values, multiplied by the unitary investment costs provide the total capital expenditures. Eq. (15) presents the operational expenditures. To simplify the application of the methodology, Eq. (15) only considers the operational costs of the DG. Ψ_L represents the diesel price per liter, and α, β and γ are the parameters of the diesel generator. $E_{DG,t}$ is a variable of dimension T and represents the dispatch of the DG.

$$\min \ \varphi_{cg}\zeta + \varphi_{og}\vartheta \tag{13}$$

$$\begin{aligned}\zeta = C_{DG}I_{DG} + C_{PV}(I_{PV} + \xi_{PV}) +& \\ C_B(I_B + \xi_B)&\end{aligned} \tag{14}$$

$$\vartheta_t = \psi_L * (\alpha E_{DG,t}^2 + (\beta + \xi_{DG,t})E_{DG,t} + \gamma) \tag{15}$$

3.3. Constraints

Additionally to constraints (6), (7), (10) and (11), it is needed to define the physical constraints of the load balance, generators and storage systems. Eqs. (16) to (27) introduces the energy sources models and their respective restrictions. It is important to notice that Eqs. (21) to (27) introduce $E_{PV,t}$, $E_{B,t}$ and $E_{DG,t}$ to measure the amount of energy produced by the energy source during the time t, where the energy produced is the integral of the output power of the source over the time t.

3.3.1. Load Balance:

$$\begin{aligned}E_{B,t+1} = E_{B,t} + E_{PV,t} + E_{DG,t} + E_{LE,t} +& \\ E_{EE,t} - D_t&\end{aligned} \tag{16}$$

Where $E_{LE,t}$ and $E_{EE,t}$ are variables introduced to control the lack or the excess of energy during the optimization horizon. The desired reliability for the SAMG is guaranteed using $E_{LE,t}$ and $E_{EE,t}$ [42]. According to [43], the loss of power supply probability (LPSP) is:

$$LPSP = \frac{\sum_{t=1}^{T} E_{LE,t}}{\sum_{t=1}^{T} D_t} \tag{17}$$

Similarly, the excess of power supply probability (EPSP) is:

$$EPSP = \frac{\sum_{t=1}^{T} E_{EE,t}}{\sum_{t=1}^{T} D_t} \tag{18}$$

LPSP and EPSP are introduced in the restrictions of the problem using $E_{LE,t}$ and $E_{EE,t}$ in Eqs. (19) and (20):

$$0 \leq \sum_{t=1}^{T} E_{LE.t} \leq LPSP * \sum_{t=1}^{T} D_t \tag{19}$$

$$EPSP * \sum_{t=1}^{T} D_t \leq \sum_{t=1}^{T} E_{EE,t} \leq 0 \tag{20}$$

3.3.2. Photovoltaic system:

References [44]–[46] describe the output power $E_{PV,t}$ of a N_{PV} number of photovoltaic panels as:

$$\begin{aligned}E_{PV,t} = N_{PV}\rho_{PV}P_{STC}\frac{G_{A,t}}{G_{STC}}(1+& \\ C_T(T_{C,t} - T_{STC}))&\end{aligned} \tag{21}$$

Where $T_{C,t}$ is the working temperature of the PV cell at hour t. Reference [47] describes T_C as a function of the ambient temperature and incident solar radiation over the PV module.

$$T_{C,t} = T_{A,t} + \frac{G_{A,t}}{G_{NOCT}}(T_{NOCT} - T_{a,t,NOCT}) \quad (22)$$

Where G_{NOCT}, T_{NOCT} and $T_{a,t,NOCT}$ are the solar radiation, working temperature and ambient temperature at Nominal Operational Cell Temperature (NOCT) conditions [48, 49].

3.3.3. Battery energy storage system: Eq. (23) describes the initial residual energy of the BESS [50]. The simulations assume that the battery starts discharged (30% of its nominal capacity). Additionally, the simulation assumes that the minimum level of discharge of the battery is 30%, and that the maximum level of charge is 90% of its nominal capacity. Eq. (24) describes these limits. Moreover, the simulations consider the maximum rate of charge and discharge of the battery. The simulation assumes that the maximum rate of charge and discharge in each time slot is 30% of its nominal capacity. For all the simulations the slot of time is one hour. Eq. (25) and (26) describes the limits of charge and discharge of the battery for each time slot respectively.

$$E_{B,0} = 0.3C_B \quad (23)$$

$$0.3C_B \leq E_{B,t} \leq 0.9C_B \quad (24)$$

$$E_{B,t+1} \geq E_{B,t} - 0.3C_B \quad (25)$$

$$E_{B,t+1} \leq E_{B,t} + 0.3C_B \quad (26)$$

3.3.4. Diesel generator: The fuel consumption of a diesel generator is a function of its capacity and output power. This function uses linear or quadratic formulations [51, 52]. Reference [53] makes a quadratic fit to estimate α, β, and γ parameters as a function of the capacity of the generator using manufacturer-provided fuel consumption data. Using the same method, we make a linear fit to diesel generators ranging from 20 kW to 200 kW, considering 25%, 50%, 75% and 100% of output power. The resulting formulation expresses the diesel consumption as a function of the output power, as shown in Eq. (27).

$$F_{DG,t} = (0.000203E_{DG,t}^2 + 0.2248E_{DG,t} + 4.2272) \quad (27)$$

The maximum output power for the Diesel generator is considered to be 80% of its nominal capacity .

4. Simulations and results analysis

The simulation take as inputs the values of F_c, e, φ_{cg}, φ_{ci}, φ_{og}, φ_{oi}, R, $G_{A,t}$, $T_{A,t}$, $\lambda_{m,t}$, $\xi_{m,t}$, and I_m. The planners can define these values or perform sensitivity analysis over each one of them to know how the results vary when one of these parameters varies. Table III shows the values used for the simulations in this work.

TABLE III: Values of the input parameters for the simulations.

Input	Value	Input	Value
F_c	1	R	15%
e	0.3	$G_{A,t}$	Figure 4
φ_{cg}	0.9	$T_{A,t}$	Figure 5
φ_{ci}	0.1	$\lambda_{m,t}$	See Table II
φ_{og}	0.9	$\xi_{m,t}$	See Table II
φ_{oi}	0.1	I_m	See Table II

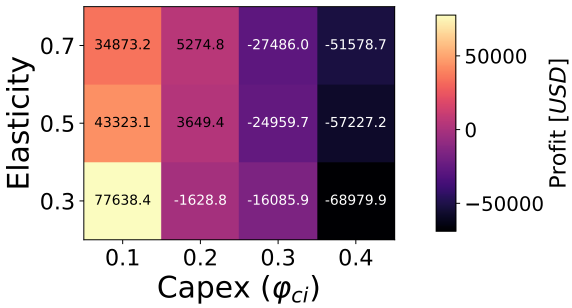
4.1. Financial analysis

The percentage of public funding for the development of the SAMG modifies the profit of the private investors. Additionally, the implementation of the incentive-based DSMS modifies the profits of the investors compared to the base case. Figure 6 shows the profits of the private investors for the two tariffs, four different percentages of private investment (φ_{ci}) and three different elasticities of the customers. Figure 6a shows the profits of the private investors using a flat tariff and Figure 6b shows the profits of the private investors using the proposed incentive-based DSMS. The negative values represent that the private investors are loosing money to run the project. Due to this, the figure only considers values of φ_{ci} until 0.4.

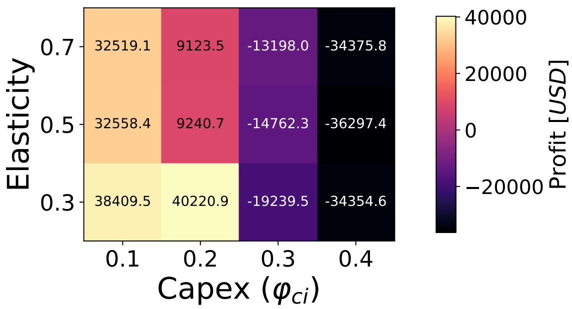
The incentive-based DSMS introduces variations in the final price of the energy. Figure 7 shows the daily prices offered to the customers. The continuous line represents the daily average and the shaded area represents the standard deviation computed over the 365 days of the optimization horizon. The variation in the final price of the energy modify the total payments of the customers.

It is interesting to notice in Figure 7 that the incentive-based DSMS allow to the investors to offer a negative final price for the energy to the customers. A negative final price means that the investor are paying to the customers to consume energy at certain hours of the day. Despite this, the formulation guarantee the reliability of the business model to the investors. Additionally, negative payments can be easily avoided by modifying the limits of the constraint presented in Equation (10).

An interesting analysis as well is how the payments of the customers change when the planner applies the



(a) Profits using flat tariff



(b) Profits using a DSMS with economic incentives

Figure 6: Profit of the private investors for different values of elasticity and different percentages of private investments for the CAPEX.

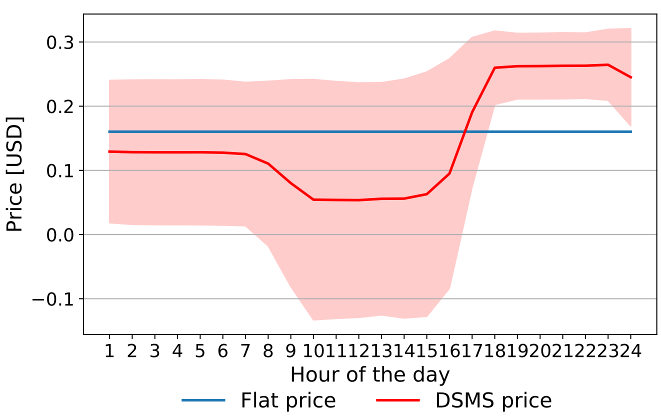
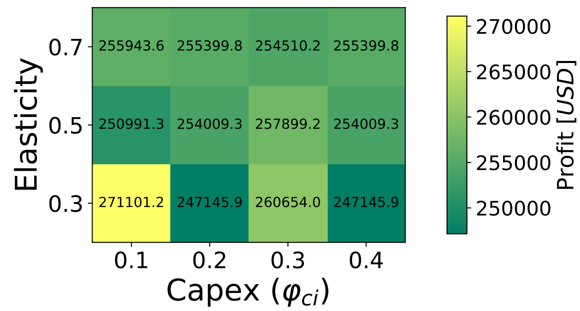


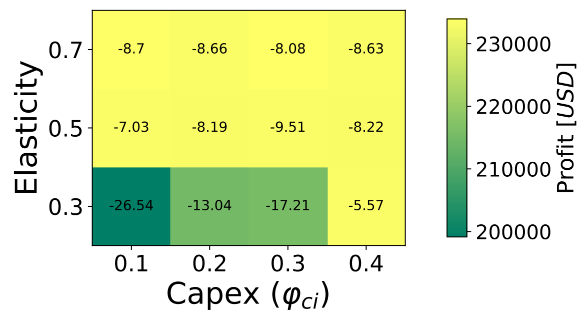
Figure 7: Final prices for the energy offered to the customers.

incentive-based DSMS. The variations in the payments of the customers depend on different aspects. Two of the aspects are the amount of private investment in the project, and the elasticity of the customers. Figure 8 shows a comparison of the customer payments for the flat and the incentive-based tariffs. Figure 8a shows the total payments of the customers when the planner applies a flat tariff. Figure 8b shows the payments of the customers when the planner applies an incentive-based tariff. However, to facilitate the comprehension of the results, Figure 8b shows the percentage variation of the payments that Eq. 28 computes.

$$\%_{var} = \frac{\sum_{n=1}^{N} \Gamma_{inc}^{n} - \sum_{n=1}^{N} \Gamma_{flat}^{n}}{\sum_{n=1}^{N} \Gamma_{flat}^{n}} \tag{28}$$



(a) Payments of the customers using flat tariff (baseline case)



(b) Percentage change in payments of the customers using a DSMS with economic incentives

Figure 8: Payments of the customers before and after of the introduction of the DSMS.

By using the results of Figure 8b is possible to compute the average reduction in the payments of the customers. The average reduction of the payments after the introduction of the DSMS is 10.8%

4.2. *Sizing and energy dispatch analysis*

The variation in the price shown in Figure 7 incentivizes the customers to modify their patterns of consumption. Figure 9 shows the variations in the demand after the application of the DSMS for an elasticity of -0.3. To make a clear visualization of the results, only the daily average and the daily standard deviation are shown in the figure. The blue and red continuous lines represent the daily average. The blue and red shaded area represent the standard deviation. The average and the standard deviation are computed over the 8760 hours of simulation.

The proposed methodology uses the tariffs of energy as a DSMS. The tariffs modify the patterns of consumption of the customers, which in the end, modify

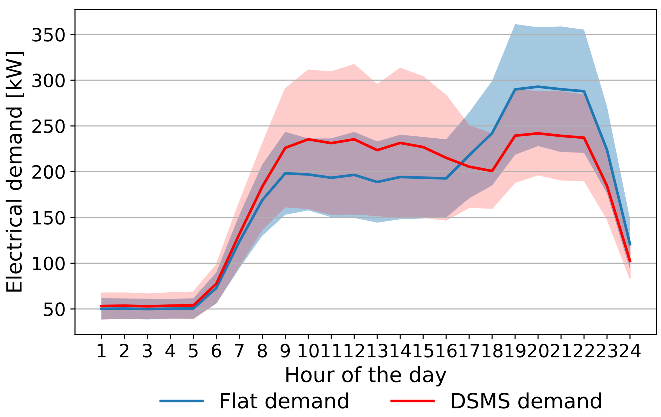


Figure 9: Comparison of the electrical demand before and after the application of the DSMS.

the installed capacities of the energy sources. However, tariffs have superior and inferior limits. The limits in the tariffs and the elasticity of the customers limit the response of the demand. In this regard, the BESS acquires relative importance in the energy dispatch of the SAMG. The BESS can store energy in periods where it is cheaper to generate electricity. The stored energy can supply the demand of the customers when it is more expensive to generate electric energy. This behavior allows the reduction of the installed capacity of the DG when the planner chooses to apply the DSMS. Figure 10 shows the daily average dispatch of the EMS with and without the application of the incentive-based DSMS.

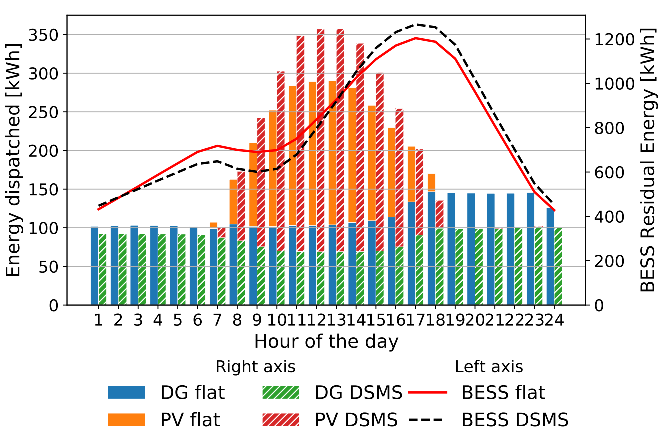


Figure 10: Daily average dispatch before and after the application of the DSMS.

4.3. Solar radiation sensitive analysis

Figure 11 shows the impacts of varying the GHI on facility size and LCOE. Figure 11 reveals the correlation between the GHI and the LCOE. When the GHI increases, the LCOE decreases. This inverse relationship is valid even when the installed photovoltaic capacity remains almost constant. Besides, Figure 11 reveals that for reductions in GHI higher than 24%, the fixed sizes of all power sources decrease considerably. Despite this, the LCOE continues to increase.

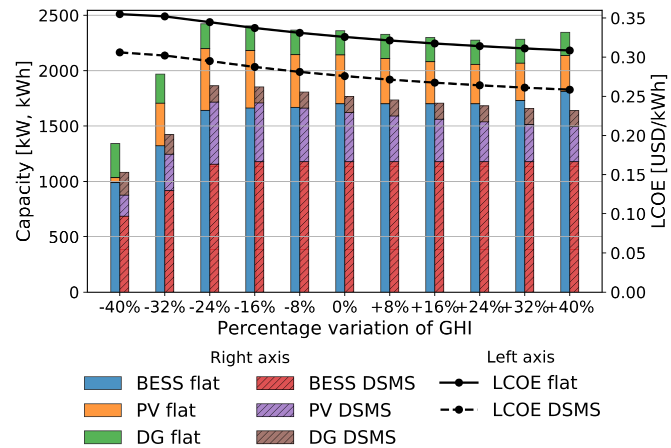


Figure 11: Comparison of the variations of the size of the energy sources before and after of the application of the DSMS when percentage variation in the GHIs are considered.

4.4. Diesel' price sensitive analysis

Figure 12 shows the variations in the sizing of the energy sources when different diesel prices are considered. On the one hand, the flexibility of the DSMS allows the size of the energy sources to be kept almost constant, even when the price of diesel increases 40%. This fact highlights the relevance of the DSMS to face variations in the price of diesel without having to increase the capacities of energy sources. On the other hand, the reduction in the price of diesel allows reducing the installed capacities of PV and BESS. This occurs because the sizing methodology chooses to increase the installed capacities of the DG. By increasing DG capacity, it is possible to supply more demand with diesel generation, taking advantage of low fuel prices.

4.5. BESS costs sensitive analysis

Figure 13 shows the impact of the BESS price on the sizing of the energy sources of the SAMG. Figure 13 shows that the installed capacities of the BESS decrease as the purchase price increases. The LCOE maintains a direct relationship with the acquisition price of BESS. Even when the BESS installed capacity decreases, the LCOE keeps to increase. Furthermore, the sizing

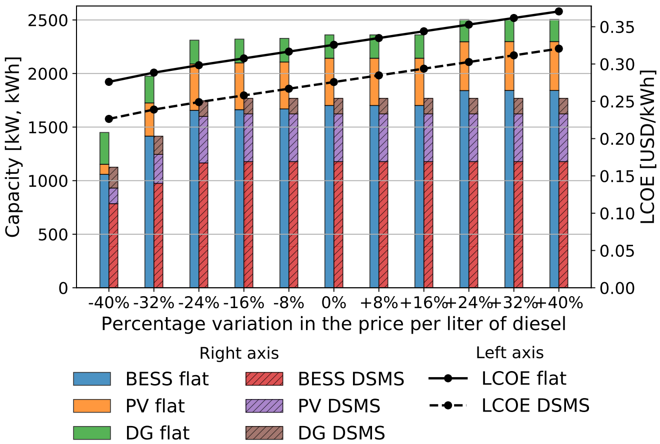


Figure 12: Comparison of the variations of the size of the energy sources before and after of the application of the DSMS when variations in the diesel price are considered.

methodology chooses to increase the DG's installed capacity when the acquisition price of BESS increases.

Another aspect worth mentioning is that the reduction in LCOE due to the introduction of DSMS remains almost constant. The average reduction in the LCOE when the GHI varies is 15.18%. The average reduction in the LCOE when the price of diesel varies is 15.45%. The average reduction in the LCOE when the BESS price varies is 15.07%. These results highlight the fact that the DSMS can keep the reduction in the LCOE stable despite the variations in GHI, the price of diesel per liter, and the acquisition price of BESS.

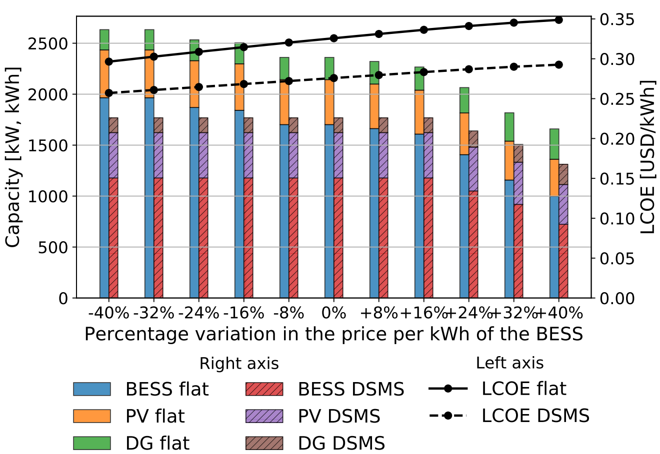


Figure 13: Comparison of the variations of the size of the energy sources before and after of the application of the DSMS when variations in the BESS price are considered.

5. Conclusions

The present study shows the design of a Demand Side Management Strategy (DSMS) using a Disciplined Convex approach for the planning of islanded micro-grids. The application of the methodology help SAMG planners to compute the sizing of the facilities considering different sources of energy and apply an optimal energy dispatch strategy for the microgrid. Moreover, the methodology allows the planners to compute the expected expenses and revenues of any SAMG project. Additionally, the methodology allows computing the required amount of subsidies from the government to make financially feasible any SAMG project.

The application of sensitivity analysis in a study case shows a reduction in the total costs of the project and the Levelized Cost of the Energy. The study case shows that the profit of the investors decreases when the elasticity of the customers' increases. In the same way, the payments of the customers reduce when the elasticity of the customers' increases. This means that the methodology is able to redistribute the excessive profits of the private investors to the customers. However, clear policies are required for SAMG projects to guarantee that the customers benefit from the application of DSMS.

Acknowledgments

The authors wish to thank the Department of Electrical, Electronics, and Telecommunications Engineering (Escuela de Ingenierías Eléctrica, Electrónica y de Telecomunicaciones); the Vice-Rectorate for Research and Extension (Vicerrectoría de Investigación y Extensión) from the Universidad Industrial de Santander (Project 8585); and the Administrative Department of Science, Technology, and Innovation (Departamento Administrativo de Ciencia, Tecnología e Innovación)-COLCIENCIAS (Contract No. 80740-191-2019, Funding source). The authors also wish to thank to the Emerging Leaders for the Americas Program (ELAP), offered by the government of Canada, to the Latino-American and Caribbean community.

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