Dimensionamiento óptimo de microrredes aisladas considerando el costo total de inversión y los beneficios tributarios en Colombia

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DIMENSIONAMIENTO ÓPTIMO DE MICRORREDES AISLADAS CONSIDERANDO EL COSTO TOTAL DE INVERSIÓN Y LOS BENEFICIOS TRIBUTARIOS EN COLOMBIA

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1. Agradecimientos

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Optimal Sizing of Islanded Microgrids Considering Total Investment Cost and Tax Benefits in Colombia

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2. Abstract

This paper deals with the optimal sizing of islanded microgrids (MGs) which use diesel generators for supplying energy in off grid areas. The MG under study integrates PV (PV) and diesel generation, a Battery Energy Storage System (BESS), and an inverter for the connection between AC and DC voltage buses. Levelised Cost of Energy (LCOE) and Annual System Cost (ASC) are considered as economic indicators; while Loss of Power Supply Probability (LPSP) is used as a reliability indicator. Fiscal incentives such as tax benefits and accelerated depreciation applied in Colombia are considered for optimizing the sizing of each microgrid element. The mathematical model of each element of the MG is presented. Solar measurements were taken at a weather station located in the main campus of Universidad de Antioquia in Medellín, Colombia at latitude 6.10 and longitude -75.38. The objective function is the minimization of the total energy delivered from the power sources that successfully meets the load. The model was implemented in python programming language considering several scenarios. Two cases were evaluated: the first one considers PV panels, a BESS and a diesel generator, while the second one only considers PV panels and a BESS. This methodology was applied in Colombia; however, it can be easily adaptable for other developing countries with similar tax incentives.

Keywords: Optimization, sizing, renewable energies, islanded microgrids, Non-Interconnected Zones.

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Facultad de ingeniería
Departamento de ingeniería eléctrica
Maestría en ingeniería

Wilmer Ropero Castaño

3. Resumén

Este trabajo trata sobre el dimensionamiento óptimo de microrredes (MGs) que utilizan generadores diésel para suministrar energía en zonas no interconectadas (ZNI). La MG en estudio integra generación fotovoltaica (PV) y diésel, un Sistema de Almacenamiento de Energía de Batería (BESS), y un inversor para la conexión entre los buses de tensión AC y DC. El Costo Nivelado de la Energía (LCOE) y el Costo Anual del Sistema (ASC) se consideran indicadores económicos; mientras que la Probabilidad de Pérdida de Carga (LPSP) se utiliza como un indicador de confiabilidad. Se consideran incentivos fiscales como los beneficios tributarios y la depreciación acelerada aplicados en Colombia para optimizar el dimensionamiento de cada elemento de la microred. Se presenta el modelo matemático de cada elemento de la MG. Las mediciones solares se realizaron en una estación meteorológica ubicada en el campus principal de la Universidad de Antioquia en Medellín, Colombia, a latitud 6.10 y longitud -75.38. La función objetivo busca minimizar el costo total del despacho de energía eléctrica a la carga. El modelo fue implementado en lenguaje de programación python considerando varios escenarios. Se evaluaron dos casos: el primero considera paneles fotovoltaicos, un BESS y un generador diésel, mientras que el segundo solo considera paneles fotovoltaicos y un BESS. Esta metodología se aplicó en Colombia; sin embargo, puede adaptarse fácilmente a otros países en desarrollo con incentivos fiscales similares.

Palabras clave: Optimización, dimensionamiento, energías renovables, Microrredes aisladas, Zonas No Interconectadas.

4. Planteamiento del problema

El gobierno colombiano ha avanzado en la regulación para promover la penetración de las Fuentes No Convencionales de Energía Renovable (FNCER) en la matriz energética del país. Un ejemplo de ello es que el país comenzó a reglamentar la penetración de autogeneración a pequeña escala en el sistema interconectado nacional (SIN),mediante la resolución CREG 030 de 2018, donde los usuarios podrán generar su propia energía electrica provenientes de fuentes no renovables y renovables. Además, El 9 de abril de 2018 se publicó la resolución CREG 038 de 2018 por la cual se regula la actividad de autogeneración en las Zonas No Interconectadas y se dictan algunas disposiciones sobre la generación distribuida [1]. La resolución CREG 174 de 2021 actualizo las reglas en aspectos operativos y comerciales de autogeneración a pequeña escala y generación distribuida garantizando así mayor transparencia en al asignación de conexiones al SIN [2]. Además, En 2021, el gobierno colombiano promulgó la Ley 2099 que tiene como objetivo modernizar la legislación existente. Esta ley hizo enmiendas y adiciones a la Ley 1715 de 2014, donde el gobierno colombiano otorga beneficios fiscales para promover el desarrollo y uso de fuentes de energía no convencionales, en particular las de naturaleza renovable. Con el avance regulatorio el gobierno demuestra el interés en promover el uso de las FNCER. Entonces, Colombia es partícipe de la incuestionable necesidad que tienen los países de un acceso sostenible a la energía eléctrica. En países en vía de desarrollo, todavía hay lugares sin suministro de energía eléctrica. Por ejemplo, en Colombia la entidad encargada de los lugares sin suministro es el Instituto de Planificación y Promoción de Soluciones Energéticas para las Zonas No Interconectadas – IPSE, el cual atiende las necesidades energéticas de los habitantes que no cuentan con este servicio en las Zonas no Interconectadas- ZNI [3]. En el informe de gestión para el año 2019, según el IPSE, en Colombia hay 431.137 viviendas sin servicio a nivel nacional, de las cuales 172.662 (40 %) corresponden a viviendas sin servicio de energía eléctrica ubicadas ZNI (Zonas No Interconectadas) al SIN (Sistema de Transmisión Nacional) [4].

Por otra parte, el gobierno Colombiano mediante el Plan Nacional de Electrificación Rural – PNER para ZNI y SIN demuestra el interés en cubrir las necesidades del los usuarios en ZNI, ejemplo de ello es que según el documento se está trabajando en el diseño e implementación de un programa de electrificación rural que promueva la competencia y viabilice la entrada en operación de proyectos de energización con vinculación de capital privado. Lo anterior se suma a mecanismos como lo es el Fondo de Apoyo Financiero para la Energización de las Zonas No Interconectadas – FAZNI de que trata el artículo 82 de la Ley 633 de 2000, el cual tendrá vigencia hasta el 31 de diciembre de 2030 [9].

Entonces, de acuerdo en el Plan Indicativo de Expansión de Cobertura de Energía Eléctrica (PIEC) 2013-2017 las microrredes de distribución local han sido utilizadas durante muchos años en todo el mundo en zonas donde la demanda total no justifica económicamente la extensión de la red eléctrica nacional. En Colombia en el 17.74 % de viviendas en las ZNI es preferible tener soluciones de generación del tipo off-grid o aislado. Estas soluciones son microrredes que utilizan generación diésel, aunque en algunos casos se han integrado con sistemas fotovoltaicos [5].

Sin embargo, estas soluciones suelen ser costosas en su operación, estos costos son asociados al uso del combustible fósil y su transporte. No obstante, esta situación ha ido cambiando gracias al desarrollo de alternativas de generación con Fuentes No Convencionales de Energía Renovable que han superado barreras regulatorias, económicas, técnicas y tecnológicas que permiten una opción con un beneficio costo-eficiencia e impacto ambiental mínimo comparado con la generación diésel [6]

Si bien es cierto que el costo de inversión en unidades de generación diésel suelen ser bajos comparado con las otras tecnologías, los costos de mantenimiento suelen ser superiores. En general puede decirse que las desventajas encontradas en el uso de la tecnología diésel, son los altos costos de mantenimiento, las emisiones, principalmente de NOx y en ocasiones resulta ser un problema de contaminación auditiva [7].

Por lo cual, el Plan Indicativo de Expansión de Cobertura de Energía Eléctrica - PIEC 2019-2023 para Colombia, analiza las siguientes alternativas: interconexión al SIN, generación aislada con solución individual solar fotovoltaica y soluciones aisladas híbridas para microredes. Este informe menciona que La utilización de microredes se justifica en agrupaciones de al menos 25 viviendas en un radio de 1 kilómetro, con una demanda potencial de energía eléctrica unitaria superior al consumo mínimo residencial de los sistemas solares individuales.Por otro lado, los sistemas solares individuales pueden estar dimensionados para ofrecer un servicio de menor nivel. Finalmente, se aclara que en el diseño de la microrred se debe tener en cuenta el tipo de carga a conectar y la necesidad de usar un convertidor de corriente alterna [10].

Entonces, Las microrredes y los sistemas solares individuales se han convertido en una solución para satisfacer la necesidad de energía eléctrica de los usuarios de zonas alejadas. El dimensionamiento es importante porque los componentes deben hacerse según la demanda de energía del usuario y la ubicación de la microrred [5], Entonces, para abastecer la demanda de carga de manera eficiente, económica y limpia, debe optimizarse el dimensionamiento. Además, el dimensionamiento óptimo de una microrred aparece como un problema desafiante debido a la naturaleza estocástica de las FNCER, relacionado con variables como el recurso solar, la temperatura y la demanda de la carga [6].

Las técnicas de optimización siempre dependerán de la función objetivo seleccionada, la cual puede ser orientada a minimizar los costos económicos, maximizar la confiabilidad, reducir el impacto ambiental, entre otros objetivos según la estrategia de optimización seleccionada [8]. Diferentes métodos metaheurísticos y lineales han sido empleados, estos son: optimización lineal entera mixta (MILP), optimización multiobjetivo, optimización por enjambre de partículas (PSO), algoritmos genéticos (GA), optimización evolutiva (OE), optimización por búsqueda gravitacional (GSA) y optimización por colonia artificial de abejas (ABC), entre otros. Para el dimensionamiento de la microrred es importante considerar la incertidumbre de los recursos meteorológicos y la variación de la demanda, propias de cada zona. Además, los incentivos tributarios, depreciación de equipos, costos de operación y mantenimiento, deben ser considerados en el modelo desarrollado. Usualmente en la literatura se resuelve el problema sobre el dimensionamiento de microrredes teniendo en cuenta las condiciones geográficas y tributarias de cada país o la zona considerada en la investigación. Por lo tanto, se presenta como una oportunidad desarrollar metodologías para el dimensionamiento de microrredes en las ZNI teniendo en cuenta el contexto colombiano, considerando la geografía y los beneficios tributarios disponibles para minimizar el costo, asegurando la confiabilidad en el suministro de energía por parte de la microrred a los usuarios.

5. Objetivo general

Proponer una metodología de optimización, para el dimensionamiento de microrredes aisladas, considerando los beneficios tributarios y las Zonas No Interconectadas en Colombia, minimizando el costo de inversión y garantizando la confiabilidad del sistema.

5.1. Objetivos específicos

1. Seleccionar metodologías existentes para procesar la información recolectada en la Universidad de Antioquía de irradiancia solar considerando paneles fotovoltaicos y demanda flexible. Información necesaria para los modelos de producción de energía de las tecnologías consideradas en la microrred.

2. Proponer una metodología de optimización para el dimensionamiento de una microrred aislada.

3. Integrar el modelo de optimización desarrollados con los beneficios tributarios y los modelos de producción de energía y demanda.

4. Implementar la metodología propuesta para un usuario de las Zonas no Interconectadas, considerando su demanda para un año. Se comparará con la solución entregada por el software HOMER.

6. Cumplimiento de objetivo general y específicos

Esta tesis de maestría se ha estructurado como la compilación de dos artículos (congreso y en revisión) producto del trabajo de investigación realizado. Estos artículos cumplen con el objetivo general (5). Los articulos se encuentran anexos al final de este documento. El articulo 1, denominado: *Optimal Sizing of Islanded Microgrids Considering Total Investment Cost and Tax Benefits in Colombia*, muestra los resultados de procesar la información de demanda de energía, radiación solar y temperatura, cumpliendo así con el objetivo 1. Estos datos fueron tomados por mediciones en la universidad de Antioquía. Este articulo también cumple con el objetivo 2 al presentar un modelo de optimización determinista de programación lineal entera Mixta (MILP). El modelo de optimización considera el dimensionamiento y la con-fiabilidad. El problema multi-objetivo se resolvió como problema mono-objetivo al tratar el indicador de confiabilidad, LPSP, como una restricción. El objetivo 3 y 4 se consideran cubiertos al implementar la metodología propuesta en un caso de estudió real. Se asume que la microrred a instalar en la universidad de Antioquía funcionaria de manera aislada. Además, El articulo 2, denominado: *Open Source Tool for Sizing Hybrid Islanded Microgrids in Colombia*, muestra el desarrollo e implementación de la metodología en una herramienta de libre acceso y producto de este trabajo de investigación, aportando de igual manera al objetivo 3 y 4. EL articulo 2 fue presentado en el congreso: *X SICEL 2021 - Transición Energética en la Cuarta Revolución Industrial*, llevado a cabo de manera virtual.

7. Resultado HOMER

El software de microrredes de HOMER Energy es el estándar mundial para optimizar el diseño de microrredes en todos los sectores, desde pequeñas comunidades y zonas aisladas, hasta los campus conectados a la red y bases militares. Esta herramienta puede modelar diferentes tipos de sistemas energéticos híbridos que integran fuentes de energía renovable como la solar, la eólica, hidroeléctrica y biomasa. Además, su costo puede superar los 2000 $USD/year$.

HOMER ofrece evaluación de las combinaciones posibles de los tipos de sistemas en una sola ejecución, realizar análisis de sensibilidad sobre variables seleccionadas; evaluación plurianual para considerar cambios en el perfil de carga; costo del combustible o costo de la energía; 9 módulos que permiten simular microrred que incluye diferentes fuentes de energía como eólica, hidráulica, biomasa, energía térmica, hidrógeno, almacenamiento de energía, entre otros.

La comparación entre el software comercial HOMER y la metodolgía propuesta se realiza considerando lo siguiente:

- Se simulará la opción PV-DG-BAT en el software HOMER y se comparara con la misma solución dada por la metodología propuesta.
- La información meteorológica y de demanda sera la misma en las dos simulaciones.
- Los parámetros técnicos de las tecnologías empleadas serán las mismas en las dos simulaciones.
- En cada solución se deja fijo una capacidad de generador diésel.

- La Figura 1 muestra la configuración de la microrred simulada en HOMER.

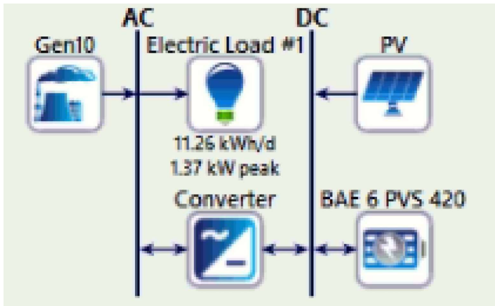

Figura 1: Esquema microrred

En las siguientes tablas se puede observar la solución de las simulaciones de la metodología propuesta dada por el software HOMER.

	HOMER		**METODOLOGIA**	
Equipo	**Cantidad**	**Capacidad (kW)**	**Cantidad**	**Capacidad (kW)**
Generador diesel	1	10	1	10
Arreglo PV	35	10,3	190	57
BESS	34	27,3	48	40,32
Inversor	1	2,08	–	–

En la anterior tabla podemos observar que en la metodología propuesta la capacidad del arreglo fotovoltaico y el banco de baterías es mucho mayor, 57 y 40.32 kW, comparado con la solución dada por el software HOMER, qué 10.3 y 27.3 kW respectivamente. Cómo se puede observar HOMER entrega la capacidad del Inversor utilizado en la solución a diferencia de la metodología propuesta, donde no se obtiene la capacidad del mismo.

	RESULTADO	
Indicador	***HOMER***	***METODOLOGIA***
NPC HOMER (USD)/ ASC (USD/year)	13,824	17016,74
Capital Inicial (USD)	10,818	111737,24
O&M (USD/año)	259,63	4974,51
LCOE (USD/kWh)	0,291	0,54

En la anterior tabla se observa que HOMER usa el indicador NPC como principal criterio para la evaluación económica de la solución, teniendo un valor de 13824 USD, mientras que en la metodología propuesta se utiliza el indicador ASC alcanzando un valor de 17016.74 USD/-year. Además, el capital inicial requerido por la metodología propuesta es altamente elevado comparado con la solución entregada con HOMER, esto se debe a que el costo se ve altamente influenciado por el modelo usado para la estimación OM, como se puede observar en la comparación donde el costo de OM es mucho menor en la solución dada por HOMER, lo cual se debe al tamaño y cantidad de componentes entregados. Finalmente, se observa que la solución de la metodología propuesta obtiene un LCOE mayor, hasta el doble del obtenido por HOMER.

Adicionalmente es importante considerar que el software HOMER utiliza información promedio por hora y por mes, mientras que la metodología propuesta utiliza en detalle información horaria en cada día del año analizado. Los valores mas altos en la solución propuesta se deben a que considera múltiples restricciones que requieren aumentar la cantidad de elementos a utilizar en la microrred.

La principal diferencia de los dos modelos se da en la estrategia de despacho, puesto que la metodología propuesta prioriza el consumo de la energía renovable sobre el generador diésel. Además, notese que HOMER utiliza el valor presente Neto (NPC) como indicador. Por otro lado, el programa HOMER utiliza menos recursos para cumplir con el suministro de la carga, por lo tanto, el LCOE es bajo.

8. Trabajos futuros

- Considerar la microrred conectada y agregar la red eléctrica como recurso en el modelo de optimización.
- Implementar modelos de optimización híbridos para la solución del problema.
- Agregar a la aplicación desarrollada la capacidad de procesar e imputar datos recolectados de mediciones reales.
- agregar la opción de usar información calculada para cada recurso e implementarlo en la aplicación propuesta.
- Considerar indicadores de impacto ambiental en la metodología propuesta.
- Agregar el recurso eólico al modelo de optimización y al análisis.
- Ampliar los modelos de OM que permitan mejorar la toma de decisiones y disminuir el alto impacto que estos generarían en la toma de decisión.

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ANEXO 1

ARTICULO:

Optimal Sizing of Islanded Microgrids Considering Total Investment Cost and Tax Benefits in Colombia

Article

Optimal Sizing of Islanded Microgrids Considering Total Investment Cost and Tax Benefits in Colombia

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Abstract: This paper deals with the optimal sizing of islanded microgrids (MGs) which use diesel generators for supplying energy in off grid areas. The MG under study integrates PV (PV) and diesel generation, a Battery Energy Storage System (BESS), and an inverter for the connection between AC and DC voltage buses. Levelised Cost of Energy (LCOE) and Annual System Cost (ASC) are considered as economic indicators; while Loss of Power Supply Probability (LPSP) is used as a reliability indicator. Fiscal incentives such as tax benefits and accelerated depreciation applied in Colombia are considered for optimizing the sizing of each microgrid element. The mathematical model of each element of the MG is presented. Solar measurements were taken at a weather station located in the main campus of Universidad de Antioquia in Medellín, Colombia at latitude 6.10 and longitude -75.38. The objective function is the minimization of the total energy delivered from the power sources that successfully meets the load. The model was implemented in python programming language considering several scenarios. Two cases were evaluated: the first one considers PV panels, a BESS and a diesel generator, while the second one only considers PV panels and a BESS. This methodology was applied in Colombia; however, it can be easily adaptable for other developing countries with similar tax incentives.

Keywords: Optimization; sizing; renewable energies; islanded microgrids; off grid areas.

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1. Introduction

Islanded microgrids (MGs) are one of the most promissory proposals for supplying electricity in off grid areas when the cost of energy production is high or when power supply problems occur [1]. Usually, off grid areas use diesel generators in developing countries for electricity supply; however, the use of diesel generators has negative environmental impacts while their supply and maintenance are costly [2]. For overcoming the dependence on diesel generators, hybrid systems that involve distributed energy resources (DER) such as battery energy storage systems (BESS) as well as PV (PV) and wind generators have become a convenient option. Nonetheless, DER working alone can not continuously supply power to the loads [2]; in consequence, diesel generators and BESS must meet the load when DER present intermittence.

Several researchers have reported the use of hybrid systems in islanded MGs. In [3–5], the authors propose configurations of PV generators, wind turbines, fuel cells and backup battery systems. In [6–11], wind turbine and a battery-backed PV generator were only considered, while in [12–22] a diesel generator is added as backup. Other generation sources such as biomass, thermal systems, flywheel and the utility grid are considered in [23–28]. However, the optimal sizing of generators in islanded MGs is still a topic under research.

MGs planning must guarantee the reliability of the system at minimum cost, satisfying the needs of users. MGs planning is usually divided into sizing and operation. This is done because of the multi-level mature of the problem. Also, optimization problems regarding MGs planning are often non-convex and NP-Hard [21]. Single and multi-objective optimization methodologies have been proposed in the technical literature for successfully performing MG planning.

Researchers have used different optimization techniques for sizing MGs. These techniques can be classified into exact and approximate methods. For example, in [20], an iterative method and dynamic programming (DP) approach are used to sizing BEES considering the energy management system of a MG. In [22], the authors propose an optimal scheduling approach of a hybrid MG using dynamic programming, that incorporates BESS, conventional generation (e.g. diesel generator), and PV solar generators. The main objective is to ensure the maximum utilization of the renewable energy resources and minimum operational cost of the conventional resources. In [25], a methodology based on PV power forecasting and the evolution of load curve is proposed for the optimization of an isolated MG. The proposed method aims to determine the size of PV panels and batteries at minimal cost, keeping the system reliability. In [12], the authors present a multi-objective optimization method to jointly optimize the planning and operation of a grid-tied MG with various DG sources such as wind turbine and PV arrays with the assistance of demand side management. To solve the multi-objective optimization problem, a fuzzy method is adopted to convert the original problem into a single objective optimization problem and a mixed integer linear programming algorithm is then used to solve it. In [29], the authors propose a Mixed Integer Linear Programming (MILP) problem that allows to determine the optimal size of Distributed Energy Resources (DER) in a DC MG. In [24], a MILP algorithm is used for the optimal sizing of a grid-connected MG, minimizing the total cost. In [26], Dynamic Programming and a MILP algorithm was implemented to sizing a small MG with storage. In [11,15,30], the authors use the HOMER tool which is a widely used software for the sizing of MGs.

Several metaheuristic techniques have been implemented for the planning of MGs in recent years. In [4], a Multiobjective Particle Swarm Optimization (MOPSO) algorithm was carried out to minimize Loss of Load Expected (LOLE) and Loss Of Energy Expected (LOEE) costs of hybrid wind–solar generating MG systems. In [5], a Gray Wolf Optimization (GWO) algorithm was used for the optimal sizing of BESS to minimize the operation cost of MGs. In [6], an Improved Fruit Fly Optimization Algorithm (IFOA) was used to sizing islanded MGs with real data collected from Dongao Island. In [7], an Ant Colony Optimization (ACO) approach was employed for minimizing the total capital cost and total maintenance cost in a hybrid PV–wind energy system. In [31], an Artificial Bee Colony (ABC) algorithm was implemented for sizing a grid-connected MG with solar PV plants, wind turbines and energy storage systems. The goal is the maximization of energy savings benefits for the community being served. In [8], a Genetic Algorithm (GA) is used for multi-objective design of hybrid energy systems. The authors aim at minimizing the Life Cycle Cost, greenhouse emissions and dump energy in remote residential buildings. In [9], the authors tested four different algorithms, namely ABC, PSO, GA and Gravitational Search Algorithm (GSA), for solving the optimal sizing of grid connected MG components. In [10], a PSO algorithm is developed to determine the optimal configuration of a MG while ensuring the minimum cost and satisfying the desired loss of power supply probability. In [14], Whale Optimization Algorithm (WOA), Water Cycle Algorithm (WCA), Moth-Flame Optimizer (MFO), and Hybrid particle swarm-gravitational search algorithm (PSOGSA) were applied for the optimal sizing of PV/wind/diesel hybrid MG systems with BESS while minimizing the cost of energy

(COE) supplied by the system and increasing the reliability and efficiency of the system. In [16], the ABC optimization algorithm was used for sizing and performance analysis of standalone hybrid energy system. In [18], the authros compare the performance of PSO and Invasive Weed Optimization (IWO) algorithms for the optimal sizing for hybrid microgrids based on PV, wind, diesel and BESS. In this case, the BESS is considered in summer and winter to determine daily storage. In [17], a GA approach minimizes the total annual cost over the number of solar panels and micro-turbines, battery capacity, and diesel generator size, with a constraint on renewable energy penetration. In [19], A double layer optimization strategy is implemented to determine the optimal size of a BESS considering the energy management system of a MG. The authors in [21] propose a bi-level optimization model to solve the problem of planning and operation of MG projects, inspired by the System of System (SoS) concept. In [23], an optimization technique based on a Multiobjective Genetic Algorithm (MOGA) which uses high temporal resolution is implemented for sizing a MG. The proposed MOGA employs a techno-economic approach to determine the microgrid system design optimized by considering multiple criteria including size, cost, and availability. In [27], the optimal sizing of a standalone PV/Wind/Biomass hybrid energy system is carried out using GA and PSO optimization techniques.

In the technical literature, some researchers have also analyzed fiscal incentives for implementing MGs. In [32], the authors conducted a Feasibility analysis of solar generation in local communities in Libya. The study was carried out using the Net Present Value (NPV) and the payback time indicators to determine the impacts of Feed-in Tariff (FiT) rates, financial incentives, electricity tariff, and inflation rate on the economic viability of the PV grid system. In [33], the authors provide a comprehensive evaluation of the technical and financial feasibility of a campus MG based on a techno-economic analysis. Such analysis captures all the benefits of financial incentives for MG projects in California, U.S. The authors in [34] investigate the effect and cost-efficiency of different renewable energy incentives and potential for hydrogen energy storage to the perceived viability of a MG project from the perspective of different stakeholders, i.e., government, energy hub operators and consumers in Ontario province, Canada. The aforementioned research papers focus on the analysis of financial incentives that each government provides to projects that include renewable energy sources; however, the research does not provide a sizing methodology of the MG. Also, the analysis is always focused on each studied area and the tax benefits vary with respect to the respective country. The main contribution of this paper is the development of a methodology for the optimal sizing of islanded MGs considering tax benefits in Colombia while meeting the needs of users. This methodology can be used by other developing countries modifying the tax benefit rules.

The Colombian government aims to promote the development and implementation of Non-Conventional Energy Sources (NCES), primarily those of a renewable nature. These energy sources are meant to be integrated into the electricity market, allowing the reduction of greenhouse gas emissions and providing a more varied energy basket. Projects that implement NCES have the possibility of saving 50% of the total investment made from their annual income tax over a no more than 15-year period, they also may apply accelerated depreciation of up to 20%, exclusion of Value Added Tax (VAT) goods and services and exemption from customs duties. Then, the 50% income deduction tax and the accelerated depreciation was included in the methodology. The proposed approach was implemented in an open source software (Python programming language), envisaged to be an available tool for other researchers. Several researchers have developed methodologies for optimal sizing of MGs; nonetheless to the best of the authors' knowledge, open source tools such as the one presented in this paper have not yet been implemented and published. Furthermore, the data used in the results of this paper can be found in a GitHub repository.

This paper is organized as follows: Section 2 describes the economic and reliability indicators implemented in the proposed methodology. Section 3 presents the proposed model as well as the mathematical representation of assets within the MG. Section 5 shows the case study application. Finally, Section 7 presents the conclusions.

2. Indicators and fiscal incentives

This section describes the economic and reliability indicators used to evaluate the sizing of islanded MGs considered in this work. This section also includes the Colombian fiscal incentives that were taking into account during the elaboration of this work.

2.1. Economic indicators

Several economic parameters can be implemented when sizing MGs [1], [35]. These include: Net Present Cost (NPC), Life Cycle Cost (LCC), Annual System Cost (ASC) and Levelised Cost of Energy (LCOE). In this paper, LCOE and ASC are selected.

The LCOE can be expressed as the ratio between the total cost and total energy consumed by the load in the project lifetime. The economic model assumes that the yearly load served is constant during the lifetime of the project as in [35]. This can be calculated by Equation (1). Where T is the horizon time to evaluate, $Eload_t$ is the energy required by the load at time t and $PENS_t$ indicates the energy not supplied to the load at time t. In this case, ASC is the summation of capital, replacement, operation and maintenance cost, as indicated by Equation (2).

$$LCOE = \frac{ASC}{\sum\limits_{t \in T} (Eload_t - PENS_t)} \tag{1}$$

$$ASC = \sum_{i \in Nc} (CC_i + RC_i) \cdot CRF(i_r, R) + O\&M_i \tag{2}$$

Where, CC_i and RC_i are the capital and replacement cost, respectively; i_r is the annual interest rate, R is the lifetime of the project and CRF is the capital recovery factor. N_c is the set of system components and $O\&M_i$ is the operation and maintenance cost given by Equations (3), (4) and (5).

$$O\&M_{pv} = CC_{pv} \cdot \rho_{pv} \tag{3}$$

$$O\&M_{bat} = CC_{bat} \cdot \rho_{bat} \tag{4}$$

$$O\&M_{dg} = cf + cl + ac \tag{5}$$

In this case, $O\&M_{pv}$, $O\&M_{bat}$ and $O\&M_{dg}$ are the operation and maintenance cost for PV array, BESS and diesel generator, respectively. CC_{pv} and CC_{bat} are the investment cost of the PV array and BESS, respectively. ρ_{pv} and ρ_{bat} are a percentage of the investment cost of the PV array and BESS, respectively. cf is the average cost of fuel given by Equation (6), cl is the average cost of lubricant given by Equation (7), and ac is the average administrative costs given by Equation (8).

$$cf = CEC \cdot E \cdot (PA + Tr + Cal) \tag{6}$$

$$cl = CEL \cdot (Tr + P\lim) \cdot E \tag{7}$$

$$ac = 0.1 \cdot (cf + cl) \tag{8}$$

Where, CEC is the specific consumption of fuel per kWh for a diesel generator, E is the energy delivered to the load and BESS. In this case, PA is the average fuel price of a gallon from the nearest supplier plant, Tr is the cost of transportation of fuel, and Cal is the fuel storage cost. CEL is the specific consumption of lubricant per kWh for a diesel generator, and $P\lim$ is the average lubricant price of gallon. Administrative costs are considered as 10% of the total cost of fuel and lubricant consumption.

The capital recovery factor ($CRF(ir, R)$) is given by Equation (9), where R is the project lifetime in years and ir is the annual interest rate.

$$CRF(ir, R) = \frac{ir(1+ir)^R}{(1+ir)^R - 1} \tag{9}$$

The investment cost for each system component considered in this work is given by Equation (10).

$$CC_i = cki_i \cdot N_i \cdot P_i \tag{10}$$

Where, cki_i is the cost per kWh installed for each system component. This cost is associated with electronic power equipment, battery cells, PV panels and diesel generation units. N_i is the number of units for each system component, and P_i is the rated power of each unit for each system component considered.

The replacement cost is only considered for the BESS and diesel generator, since the life cycle of the PV panels is greater than the projects lifetime. This is given by Equation (11).

$$RC_i = \lambda_i \cdot CC_i \cdot K_i(i_r, L_i, y_i) \tag{11}$$

In this case, λ_i is a factor used to consider a percentage of the initial investment cost for each system component, and k_i is the single payment present worth, given by Equation (12) [36].

$$K_i(i_r, L_i, y_i) = \sum_{n=1}^{y_i} \frac{1}{(1+i_r)^{n \cdot L_i}} \tag{12}$$

Where, y_i is the number of replacements during the useful lifetime of the project given by Equation (13). In this case, L_i is the useful lifetime of each component and R is the life time of the project.

$$y_i = \frac{R}{L_i} \tag{13}$$

2.2. Reliability indicator

The loss of power supply probability ($LPSP$) is given by Equation (14). The parameter is used to estimate the reliability of the microgrid. It is the ratio between the total energy not supplied to the load ($PENS_t$) and the total energy required by the load ($P_{Load,t}$).

$$LPSP = \frac{\sum_{t \in T} P_{ENS,t}}{\sum_{t \in T} P_{load,t}} \tag{14}$$

2.3. Fiscal incentives

In 2021, the Colombian government issued the Law 2099 which aims to modernizing the existing legislation. This law made amendments and additions to Law 1715 of 2014 where the Colombian government gives tax benefits to promote the development and use of non-conventional energy sources, in particular those of a renewable nature. The projects can deduct from their annual income tax, in a period not exceeding 15 years up to 50% of the total investment made. The annual income tax can be calculated using Equation (15).

$$i = 0.5/T1 \tag{15}$$

Where, $T1$ corresponds to the years in which the tax benefit is applied, that does not exceed 15. The accelerated depreciation is equally distributed according the project requirements as shown in Equation (16).

$$d = 1/T2 \tag{16}$$

Where, $T2$ corresponds to the years in which the accelerated depreciation is applied. The tax deduction factor (ω) applied in the project can be calculated by Equation (17) where τ is the effective corporate tax income rate of the project.

$$\omega = \frac{1}{(1-\tau)} \cdot \left[1 - \tau \cdot \left(\begin{array}{c} \sum_{j=1}^{T1} \frac{i}{(1+ir)^j} + \\ \sum_{j=1}^{T2} \frac{d}{(1+ir)^j} \end{array} \right) \right] \tag{17}$$

3. Proposed Methodology

The configuration of the MG to be optimized is shown in Figure 1. It is composed of a DC bus and an AC bus connected through an inverter. The PV array, load controller and BESS are connected to the DC bus, while the load and the diesel generator are connected to the AC bus. The main goal of the energy sources is to supply power to the load.

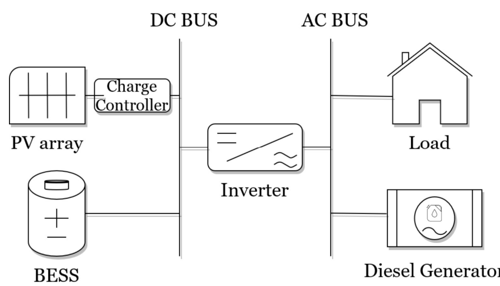

Figure 1. Islanded microgrid

The schematic diagram of the proposed methodology is illustrated in Figure 2.

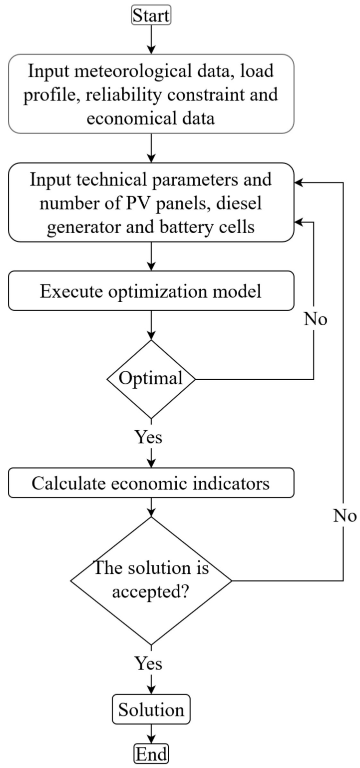

Figure 2. Schematic diagram of the proposed methodology

3.1. PV array model

An hourly power model was adopted for the PV array (Epv_t) which is calculated using Equation (18). A more in dept description of this model is presented in [35].

$$Epv_t = Npv \cdot P_{pv_{stc}} \cdot \frac{G(\beta, \alpha)}{Gstc} \cdot T_{pv} \cdot fpv \quad (18)$$

Where N_{pv} is the number of PV modules, $P_{pv_{stc}}$ is the rated power of the solar panel in standard test condition, $G(\beta, \alpha)$ is the global irradiance on the plane of the PV array, T_{pv} is the cell temperature in Celsius calculated by Equation (19), f_{pv} is a derating factor that includes the losses due to dust, shading and wiring; also, this factor considers the mismatching and natural degradation of solar modules. $Gstc$ is the global irradiance in standard test condition of the PV cell.

$$T_{pv} = \left(1 + \frac{\alpha_p}{100} \cdot (Tcell_t - T_{stc})\right) \quad (19)$$

In equation (19), α_p is the temperature coefficient of maximum power $\%/C$, T_{stc} is the temperature in standard test conditions and T_{cell} is calculated by Equation (20) [35].

$$Tcell_t = T_{amb} + G(\beta, \alpha)_t \cdot \left(\frac{NOCT - 20}{800}\right) \quad (20)$$

Where, $NOCT$ is the rated operation cell temperature which can be consulted in the module datasheet while T_{amb} corresponds to the average ambient temperature measured each month.

3.2. BESS model

The BESS model is based on the time estimation of State of Charge (SoC) (SoC_t) that is defined in Equation (21)

$$SoC_t = (1-\sigma)\cdot SoC_{t-1} + Ebat_t^+ \cdot \eta_c - Ebat_t^- / \eta_{inv} \tag{21}$$

Where, σ is the self-discharge rate per hour, $Ebat_t^+$ is the power delivered to the BESS, η_c is the BESS load efficiency, $Ebat_t^-$ is the power of BESS delivered to the load, η_{inv} is the inverter efficiency. $Ebatn$ is the rated capacity of BESS given by Equation (22).

$$Ebatn = Nbat \cdot Ebat_{cell} \tag{22}$$

Where, $Ebat_{cell}$ is the rated power of the battery cell and $Nbat$ is the number of batteries and can be calculated by Equation (23).

$$N_{bat} = Nb_p \cdot Nb_s \tag{23}$$

Where, Nb_p is the number of batteries cell in parallel and Nbs is the number of batteries in series and can be calculated by Equation (24), where, Vdc_{sist} is the DC system voltage and Vdc_{bc} is the battery voltage.

$$N_{bs} = \frac{Vdc_{sist}}{Vdc_{bc}} \tag{24}$$

In this case, $SoC^{\max}$ is the maximum SoC of the BESS considering the maximum capacity defined by Equation (25); on the other hand, $SoC^{\min}$ is the minimum SoC of the BESS according the maximum depth of discharge defined by Equation (26), where DOD^{max} is the maximum depth of discharge that determines the fraction of power that can be withdrawn from the BESS expressed as a percentage of maximum capacity.

$$SoC^{\max} = Ebatn \tag{25}$$

$$SoC^{\min} = Ebatn \cdot (1 - DOD^{\max}) \tag{26}$$

The maximum flow of energy to avoid overheating when charging or discharging the BESS, labeled as $E_{\max}$ is defined by Equation (27), where C_{rate} is the capacity rate in hours [35].

$$E_{max} = \frac{Ebatn}{C_{rate}} \tag{27}$$

The number of charging/discharging cycles of the battery can be calculated using Equation (28):

$$B_{cycles} = \frac{\sum_{t\in T} Ebat_t^-}{Ebatn} \tag{28}$$

3.3. Diesel generator

The power model of the diesel generators (Pdg) is calculated using Equation (29).

$$Pdg = \eta_{dg} \cdot Pdg^{rate} \cdot N_{dg} \tag{29}$$

Where η_{dg} is the efficiency of the generator, Pdg^{rate} is the rated power and N_{dg} is the number of diesel generator units. The total fuel consumption for a diesel generator measured in litres per hour (L/h) is calculated using Equation (30):

$$Fdg_i = \sum_{i=1}^{N} a_i + b_i \cdot Pdg_i + c_i \cdot Pdg_i{}^2 \tag{30}$$

Where, N is the number of diesel generators, a_i, b_i y c_i are coefficients of the fuel consumption of the generator while Pdg_i with $i = 1, 2, ..., N$ is the power output measured in kWh from diesel generators.

4. Proposed Optimization Model

In this work, a deterministic cost model is proposed. The main goal is to minimize the total cost of dispatching energy from energy resources that successfully meet the load. The objective function given by Equation (31) minimizes the cost of energy dispatched for the time horizon T. cpv, cdg, $cbat$ and $cens$ are the cost per kilowatt ($\$/kWh$) of the PV array, diesel generator, BESS and energy not served, respectively. Epv is the delivered energy of the PV array, $Ebat_t^{pv}$ is the load power to the BESS from the PV array, Edg is the power delivered by the diesel generator, $Ebat_t^{dg}$ is the load power to the BESS from the diesel generator, $Ebat_t^-$ is the energy delivered from the BESS to the load and $PENS$ is the energy not served to the load.

$$Min \sum_{t \in T} \begin{array}{c} cpv \cdot (Epv_t + Ebat_t^{pv}) + \\ cdg \cdot (Edg_t + Ebat_t^{dg}) + \\ cbat \cdot Ebat_t^- + cens \cdot PENS_t \end{array} \tag{31}$$

4.1. Energy balance constraint

The constraint given by Equation (32) represents the energy supplied to the load.

$$Epv_t + Edg_t + Ebat_t^- + PENS_t = Eload \ \forall t \in T \tag{32}$$

4.2. Reliability constraint:

The constraint given by Equation (33) ensures that the loss of power supply probability ($LPSP$) does not exceed its maximum limit.

$$LPSP \leq LPSP^{\max} \tag{33}$$

4.3. PV constraint

Expression (34) ensures that the energy delivered from the PV array to the load (Epv_t) and the energy delivered from the PV array to charge the BESS ($Ebat_t^{pv}$) does not exceed the maximum PV energy available ($Epv_t^{\max}$), at time t. Equation (35) ensures positive values in the energy delivered. The constraint given by Equation (36) ensures that the energy delivered from the PV array to charge the BESS is only available after supplying the load.

$$Epv_t + Ebat_t^{pv} \leq Epv_t^{\max} \tag{34}$$

$$Epv_t + Ebat_t^{pv} \geq Epv_t^{\min} \tag{35}$$

$$Ebat_t^{pv} \leq Epv_t^{\max} - Epv_t \tag{36}$$

4.4. Diesel generator constraint:

Equation (37) ensures that the power delivered from the diesel generator to the load (Edg_t) and the power delivered to charge the BESS from the diesel generator ($Ebat_t^{dg}$) does not exceed the maximum capacity of the generator (Pdg^{rate}); otherwise, the binary variable Bdg_t will be zero. The constraint given by Equation (38) ensures that the diesel generator does not supply power below its technical (Pdg^{min}); otherwise, the binary variable Bdg_t will be zero. Equation (39) ensures that the energy delivered from the diesel generator to charge the battery is only available after supplying the load.

$$Edg_t + Ebat_t^{dg} \leq Pdg^{rate} \cdot Bdg_t \quad (37)$$

$$Edg_t + Ebat_t^{dg} \geq Pdg^{\min} \cdot Bdg_t \quad (38)$$

$$Ebat_t^{dg} \leq Pdg^{rate} - Edg_t \quad (39)$$

4.5. BESS charge and discharge constraints:

Equation (40) ensures that the BESS State of Charge SoC_t is within its minimum and maximum values, labeled as SoC^{min} and SoC^{max}, respectively.

$$SoC^{\min} \leq SoC_t \leq SoC^{\max} \quad (40)$$

Equation (41) ensures that the power to charge the battery is delivered from the PV array ($Ebat_t^{pv}$) and the diesel generator ($Ebat_t^{dg}$). The energy delivered from the diesel generator to the BESS is multiplied by the efficiency of the inverter (η_{inv}). Equations (42) and (43) prevent the BESS from overheating in the charging and discharging process, respectively. In this case, E_{max} is the maximum energy for loading and unloading. Bc and Bd are binary variables that determines if the BEES is charging and discharging respectively. Mb is a positive battery constant to ensure the constraint. Equations (44) and (45) ensure that the charge ($Ebat_t^{+}$) and discharge ($Ebat_t^{-}$) energy does not violate the maximum and minimum state of charge limits of the BESS. The constraint given by (46) ensures that the maximum BESS charge and discharge cycles ($cycles^{max}$) are not exceeded by the total cycles result of the BESS (B_{cycles}).

$$Ebat_t^{+} = Ebat_t^{pv} + Ebat_t^{dg} \cdot \eta_{inv} \quad (41)$$

$$Mb \cdot Bc_t \leq Ebat_t^{+} \leq E\max \cdot Bc_t \quad (42)$$

$$Mb \cdot Bd_t \leq Ebat_t^{-} \leq E\max \cdot Bd_t \quad (43)$$

$$Ebat_t^{-} \leq SoC_t - SoC^{\min} \quad (44)$$

$$Ebat_t^{+} \leq SoC^{\max} - SoC_t \quad (45)$$

$$B_{cycles} \leq cycles^{\max} \quad (46)$$

5. Tests and Results

The tests of the proposed methodology were carried out at the east headquarters of Universidad de Antioquía, in Colombia at latitude 6.10 and longitude -75.38. The experimental data was collected in 2019 by measures at the University building and weather station. All data as well as the complete methodology is available in an open-source repository in [37].

5.1. Load Profile

The electrical demand to be met at the building is shown in Figures 3 and 4. Figure 3 corresponds to the daily average load profile for one year while Figure 4 is the monthly load profile for one year. Note that there is a consumption peak around office hours at the University. Also, the months with the highest energy consumption were October, November and December.

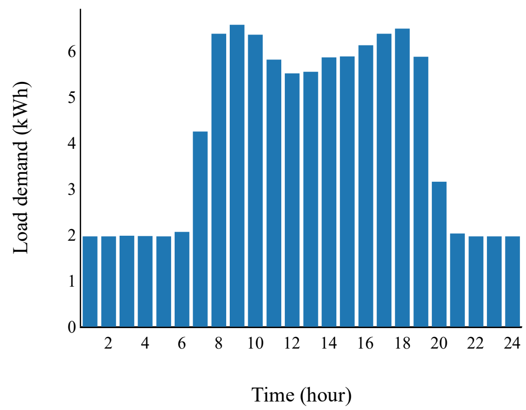

Figure 3. Daily average load profile for one year

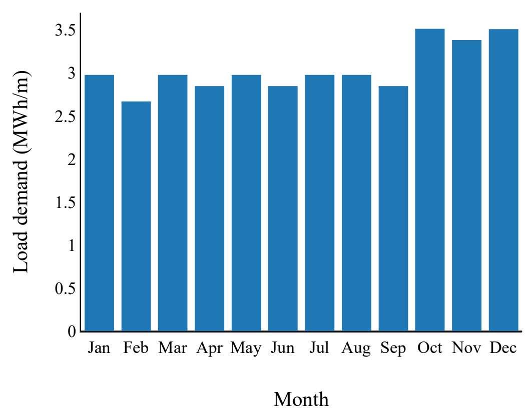

Figure 4. Monthly load profile for one year

318 *5.2. Solar radiation and temperature*

319 Figure 5 shows the daily average solar radiation for one year by month. The solar radiation is around 700 Wh/m^2 in average daily while the radiation is more than 770 Wh/m^2 in June, July an August.

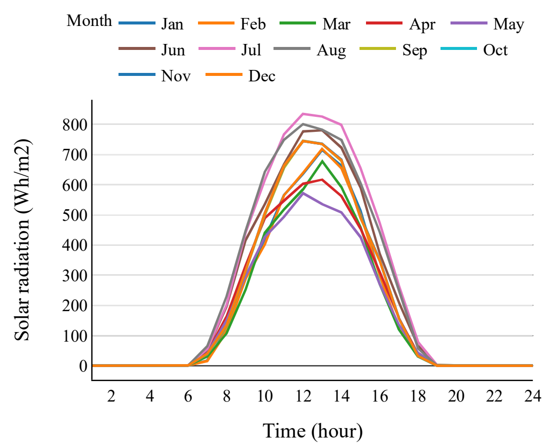

Figure 5. Daily average solar radiation for one year by month

322 Figure 6 corresponds to the montly solar radiation for one year. As it is shown, the
323 total summation of solar radiation by month is also highest in in June, July an August.

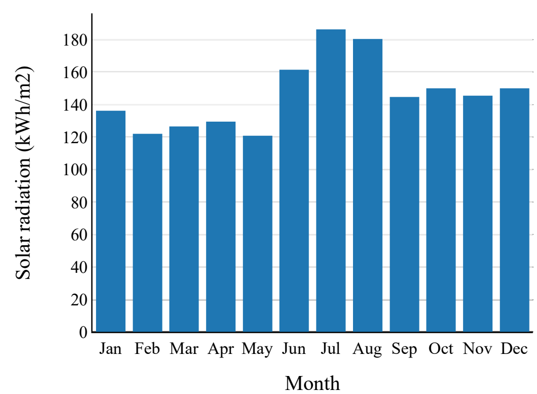

Figure 6. Monthly solar radiation for one year

324 Figure 7 is the daily average temperature for one year for month. The average
325 temperature at noon is around 23 °C. The month with the highest temperature is
326 August.

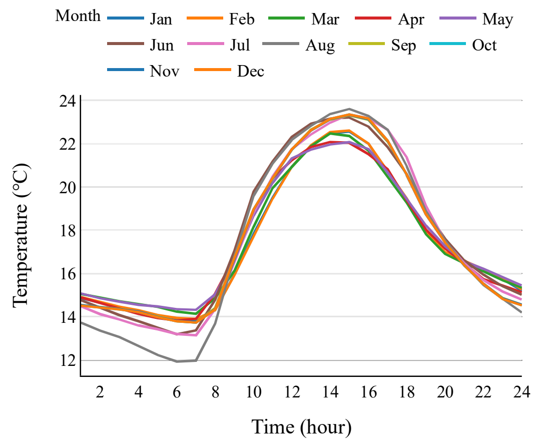

Figure 7. Daily average temperature for one year by month

5.3. Input Parameters

The systems input parameters and benefits are shown in Table 1, which were selected under the Colombian Law. The real interest rate was taken from [38] while the tax reduction factor was calculated in section 2.3. The cost of energy not supplied in Colombia (*cens*) and *LPSP* were taken from [39]. The variable labeled as *cens* in Colombia corresponds to the marginal economic cost of rationing the energy demand in off grid areas; it is a value defined by the Colombian regulation and updated by mining and energy planning unit (UPME, Spanish acronyms) according to the percentage of demand to be rationed [40].

Table 1: Input parameters of the project

Input	**Symbol**	**Value**
Lifetime of the project $(years)$	R	20
Loss of power supply probability $(\%)$	$LPSP^{max}$	5
Real interest rate $(\%)$	ir	8.08
Cost of energy not supplied (USD/kWh)	$cens$	0.7434
Tax reduction factor $(\%)$	ω	91.47
Years income tax $(years)$	$T1$	15
Years accelerated depreciation $(years)$	$T2$	10
Corporate tax income rate$(\%)$	τ	33

Table 2 presents the technical and economic parameters of the PV module. The data were selected from a commercial mono crystalline PV module of 300wp from the company JINKO SOLAR.

Table 2: Input parameters of the PV module

Input	**Symbol**	**Value**
Maximum Power Wp	Epv_{stc}	300
Module Efficiency $(\%)$	η_{pv}	18.33
$NOCT(\circ_C)$	$NOCT$	45
Price per kWh generated (USD/kWh)	cpv	0.003
PV derating factor $(\%)$	fpv	85
$O\&M$ factor initial investment $(\%)$	ρ_{pv}	1
Price per kW installed (USD/kW)	cki_{pv}	1.5
Power Temperature Coefficient $(\%/\circ_C)$	α_p	-0.39

Table 3 presents the technical and economic parameters of the BESS. The data was selected from commercial Vented lead-acid batteries with reference sun power V LSeries OPzS/OPzS bloc special to cyclic applications from HOPPECKE company. The data sheet recommend a maximum depth of discharge of 50% to obtain 3000 life cycles.

Table 3: Input parameters of the BESS

Input	**Symbol**	**Value**
Positive battery constant	Mb	0.01
Self-Discharge rate	σ	0.2
Capacity Rate (h)	$Crate$	5
Maximum depth of Discharge (%)	DOD^{max}	50
Maximum number of cycles	$cycles^{max}$	3000
Price per kWh generated (USD/kWh)	$cbat$	0.12
Battery cell capacity (kW)	$Ebat_{cell}$	0.84
DC system voltage (V)	Vdc_{sist}	48
Battery Voltage (V)	Vdc_{bc}	2
Inverter efficiency (%)	η_{inv}	95
$O\&M$ factor initial investment (%)	ρ_{bat}	2
Factor initial capital cost invested (%)	λ_{bat}	70
Lifecycle $(years)$	Lc_{bat}	10
Price per kWh installed (USD/kW)	cki_{bat}	144.5
Discharge efficiency (%)	η_d	100
load efficiency (%)	η_c	90
Number of batteries in parallel	Nb_p	2

Table 4 summarizes the technical and economic parameters of the diesel generator. The average price of fuel and lubricant was selected from the companies of the region.

Table 4: Input parameters of the Diesel generator

Input	**Symbol**	**Value**
DG Power (kW)	Pdg^{rate}	10
Price per kWh installed (USD/kW)	cki_{dg}	2041
Minimum ratio allowed	Pdg^{min}	0.9
Diesel efficiency (%)	η_{dg}	100
Price per kWh generated (USD/kWh)	cdg	0.22
Factor of the initial capital cost invested (%)	λ_{dg}	70
Specific consumption of fuel (gal/kWh)	CEC	0.0974
Specific consumption of oil (gal/kWh)	CEL	0.0005
Lifecycle $(years)$	Lc_{dg}	10
Average price of oil (USD/gal)	alc	21.4
Average price of fuel (USD/gal)	afc	2.4

The cost per kW installed in each technology, the factor of the initial capital cost invested and life cycle of each technology considered in this work were taken from [35].

6. Results and Discussion

This section shows the results of 159 tests that were carried out on the case study with a personal computer equipped with an Intel Core i7-8550U 1.8 GHz processor with 8 CPUs and 8 GB of RAM memory. The proposed optimization model was implemented in the Pyomo Python-based open-source software package. The solver used in Pyomo was a Gurobi Optimizer version 9.0.3 with an academic license.

Since the model formulated is linear, it is possible to use an open-source solver. However, due to the size of the problem, it is not recommended because the performance is lower than a solver such as GUROBI, as can be seen in Figure 8. Note that GUROBI achieves a solution between 0-5% of GAP around 20 minutes, meanwhile CBC achieves the same solution in about 70 minutes with a higher GAP.

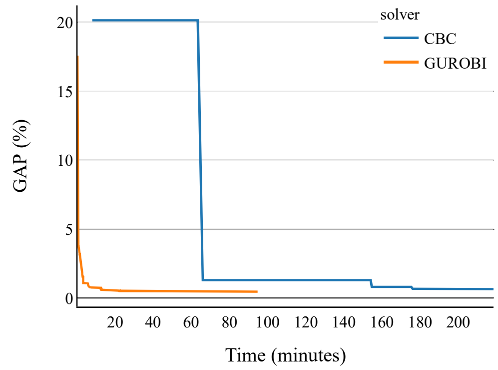

Figure 8. Time solution with different GAP in CBC and GUROBI solvers

A matrix that correlates the energy supplied with the load and the ASC and LCOE indicators is shown in Figure 9. Note that diesel energy and ASC have a negative and strong correlation. This means that if the diesel energy increases, the ASC decreases. This behavior is due the load profile, because if the model uses more PV modules and batteries to satisfy the load; then, the capital, replacement, operation, and maintenance cost increase. On the other hand, the LCOE has a negative and medium correlation with the PV energy and BESS. This is due to the energy that is supplied to the load; in other words, if the PV modules and batteries increase, the load can be fully covered. In this case, the energy supplied by the diesel generator is not decisive in the LCOE due to operational constraints, if the load to be supply is lower than the minimum capacity that is able to dispatch the diesel generator, the load could not be dispatched.

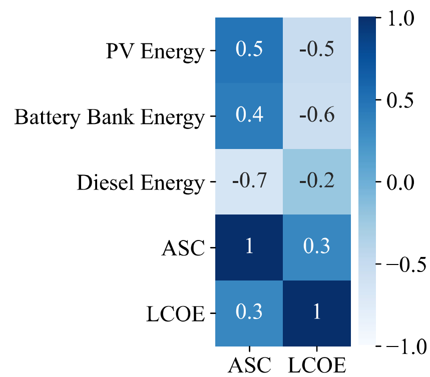

Figure 9. Energy correlating with ASC and LCOE

Figure 10 shows that the use of renewable resources yields a lower LCOE; however it is increased the ASC due the load profile and the amount of installed capacity. It also shows the relationship between the energy delivered to the load by the MG and the *ASC* and *LCOE* indicators. The size of the circles indicates the amount of energy delivered to the load during a year by technology. The bigger the circle, the more emery is delivered by the corresponding resource. Figure 10 also shows that when ASC is greater than 15k the energy delivered by the PV array is higher. This shows that increasing the installed capacity of the PV array increases the $O\&M_{pv}$ costs. Also, it is shown that the LCOE is lower in the cases where the energy delivered by the PV array is higher with respect to the other resources. Therefore, the simulations that obtained an LCOE below 0.3 were the ones with the highest installed capacity of the PV array and BESS.

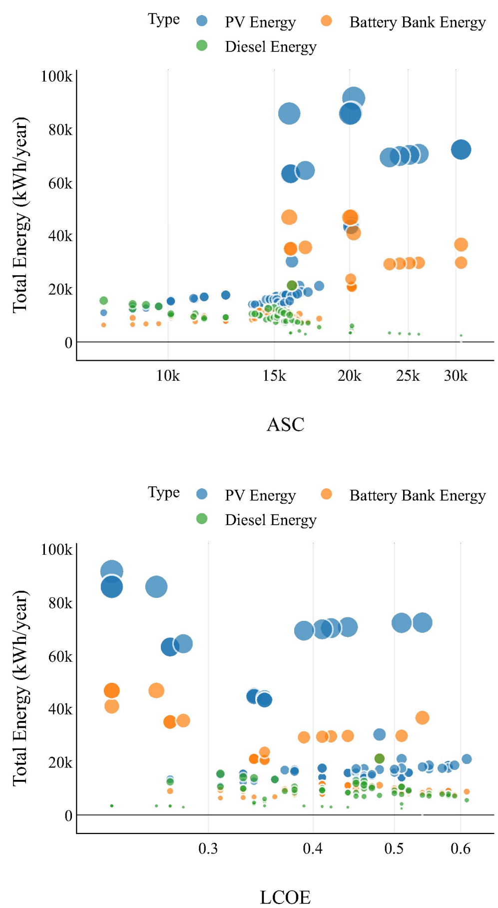

Figure 10. Energy vs ASC and Energy vs LCOE

The diesel generator is not decisive in the LCOE because it is a backup resource. In addition, it has technical restrictions of minimum dispatch of its capacity. In other words, in the simulations the constraint is that the diesel generator is only dispatched if the energy to be covered is at least 90 % of its capacity.

Figure 11 shows the fulfillment of the $LPSP^{max}$ allowed which was considered as the objective. It is observed that the resulting $LPSP$ is always lower than the maximum value and varies according to the input parameters. In general terms, if more power generation is available, the resulting $LPSP$ is lower.

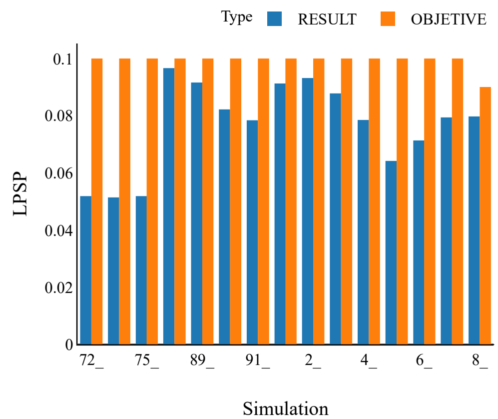

Figure 11. LPSP objetive vs LPSP result for some simulations

388 Table 5 presents the results of the solution of the planning problem for two configurations of the MG. The first case considers PV panels, BESS, and a diesel generator; while the second case only considers PV panels and BESS.

391 According to IPSE (Institute for Planning and Promotion of Energy Solutions for Non-Interconnected Zones), there are 106, 566 users in off grid areas in Colombia that typically have between 5 to 10 hours of daily electrical service [41]. If this type of MG was installed in a non-interconnected area with similar characteristics, the two solutions found in this paper would improve electricity supply in these off grid areas with 19 and 21 hours respectively. In these hours the load was fully supplied ($PENS = 0$). This may vary according to the $LPSP$ selected at the beginning of the projects and the criteria of the user for selecting the sizing methodology. Furthermore, the results show that the best cost is obtained in the first option with a $LCOE$ of 0.51$\$/kWh$, wichi is 0.27$\$/kWh$ lower than the second option with 0.78$\$/kWh$. This result is due to the load profile, in which, during the hours of lower solar radiation there is a high energy demand, so; for the second option, more PV and BESS units are required for satisfying the energy demand.

Table 5: Result of the study case

Parameter	Unit	PV-BAT-DG	PV-BAT
Npv	Units	190.00	405.00
$Nbat$	Units	48.00	120.00
$Nbat_p$	Units	2.00	5.00
$Ebatn$	kW	40.32	100.80
LC	$Number$	229.00	116.30
Pdg	kW	10.00	-
$CCpv$	USD	85,500.00	182,250.00
$CCbat$	USD	5,826.24	14,565.60
$CCdg$	USD	20,411.00	-
$O\&Mpv$	$USD/year$	855.00	1,822.50
$O\&Mbat$	$USD/year$	116.52	291.31
$O\&Mdg$	$USD/year$	4,002.99	-
$RCbat$	USD	2,737.40	6,843.50
$RCdg$	USD	9,589.90	-
$LPSP$	%	5.00	4.99
CRF	%	10.00	10.00
$PENS$	$kWh/year$	1823.30	1821.20
$Cost_{ENS}$	$USD/year$	1,355.44	1,353.93
ASC	$USD/year$	17,016.74	22,479.72
$LCOE$	USD/kWh	0.54	0.84
δASC	$USD/year$	16,237.73	20,800.89
$\delta LCOE$	USD/kWh	0.51	0.78
$AvgTimeW_{PENS}$	$Hours$	19	21

Figures 12 and 13 shows that for first and second cases, the energy provided from renewable resources is prioritized over the energy provided by the diesel generator, which is in accordance with the proposed optimization model. Then, in the PV-BAT-DG solution, the energy delivered by the PV array to the load corresponds to 48.3%, the energy delivered by the BESS to the load corresponds to 25.3%, and the energy delivered by the diesel generator to the load was 21.3%. Finally, the non-served energy was 5%. For the PV-BAT solution, the energy delivered by the PV array to the load corresponds to 62.9% while the energy delivered by the BESS was 32.1%. Finally, the non-served energy was 4.99%.

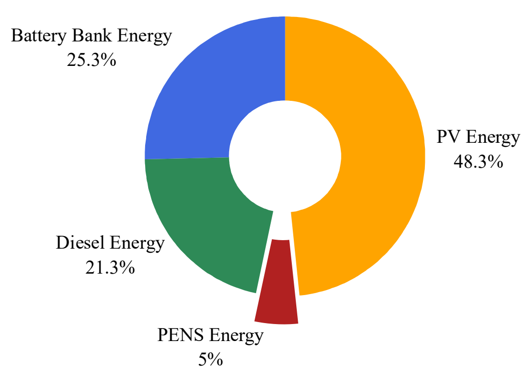

Figure 12. Energy supplied to the load in a year from PV-BAT-DG

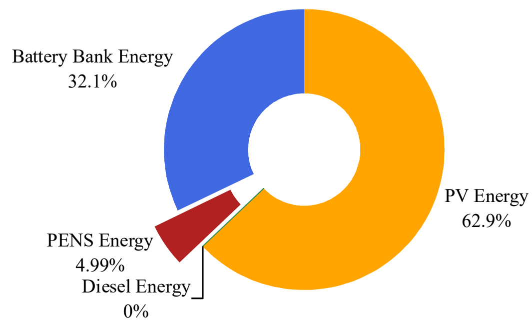

Figure 13. Energy supplied to the load in a year from PV-BAT

Figures 14 and 15 show that the diesel generator and BESS are only used when the PV Energy is not available or is insufficient, being the diesel generator the last option to supply the load and charge the BESS. Figure 14 shows that there is presented energy not supplied for some hours, this is due to $SoC(t)$ of the BESS is below the allowable limits or due to the technical restriction for the diesel generator that is in the minimum ratio allowed. For the PV-BAT-DG solution, it is shown that in hours 17 and 18 the diesel generator was used as backup due to the shortage of energy from the PV array and BESS. In hours 5, 6, 7, 8, and 9; there was no power supplied for the day under analysis. In the evening hours, power was mainly supplied from the BESS. In the PV-BAT solution, between 6 and 17 hours, energy was mainly used from the PV array while in the evening hours the BESS was used for supplying the energy.

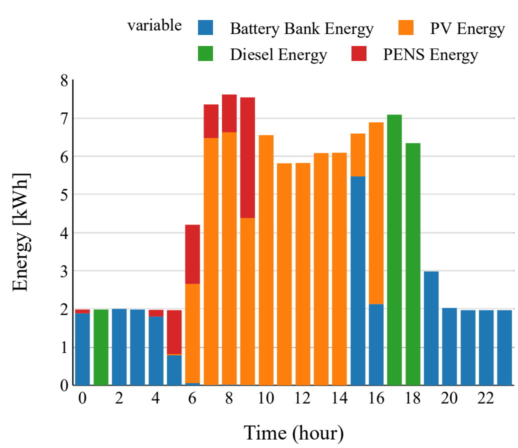

Figure 14. Energy supplied to the load in a day from PV-BAT-DG

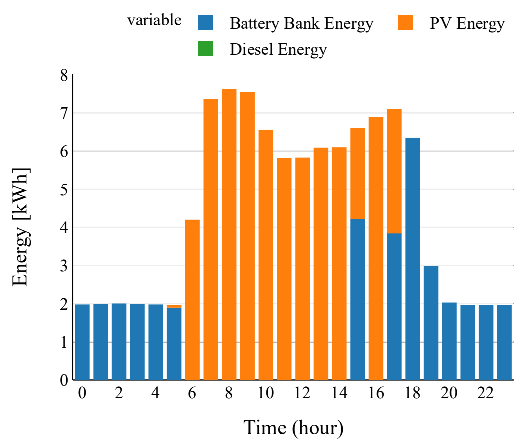

Figure 15. Energy supplied to load in a day from PV-BAT

Figure 16 shows that the optimization model proposed prioritizes the PV energy for charging the BESS and only uses the energy from the diesel generator when PV energy is not available. The model prioritizes the BESS load according to the cheapest resource, in this case PV energy. Then, between 6 am and 5 pm the BESS is charged with the energy left over from the PV array after supplying the load. Between 2 and 4 pm, there the highest use of the diesel generator is presented to charge the battery, this is because during these hours the *SoC* of the BESS is at its lowest levels.

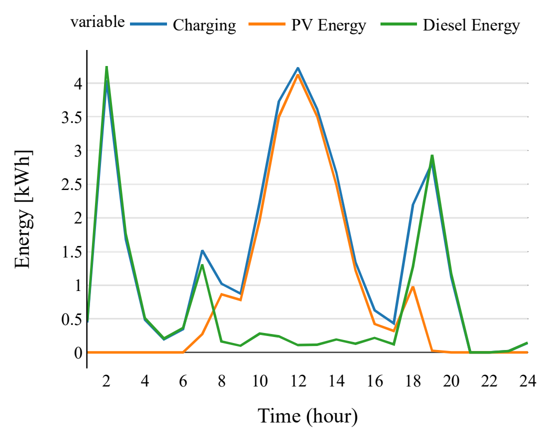

Figure 16. Average energy to charge the BESS for PV-BAT-DG

Figure 17 shows the SoC average of the BESS. In the first option, the process is started when there is energy available from the diesel generator and PV Array. Meanwhile, Figure 18 shows that the BESS is only loaded when there is energy available from the PV array. Figures 17 and 18 show the average SoC of the BESS. For the two given solutions it is shown that the battery charging process occurs mainly between 7 am and 5 pm. This is due to the availability of the solar resource for charging. Also, green and orange lines show that the charging and discharging processes do not occur simultaneously.

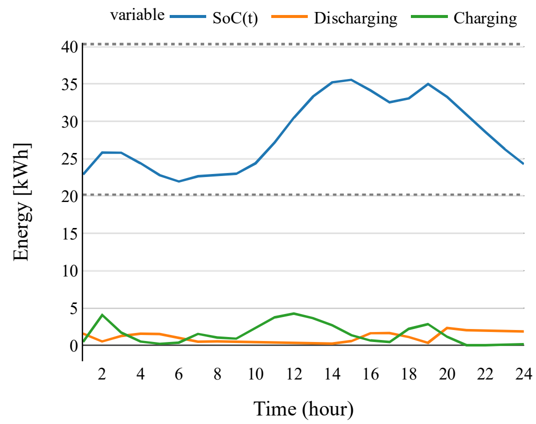

Figure 17. Average State Of Charge of BESS for PV-BAT-DG

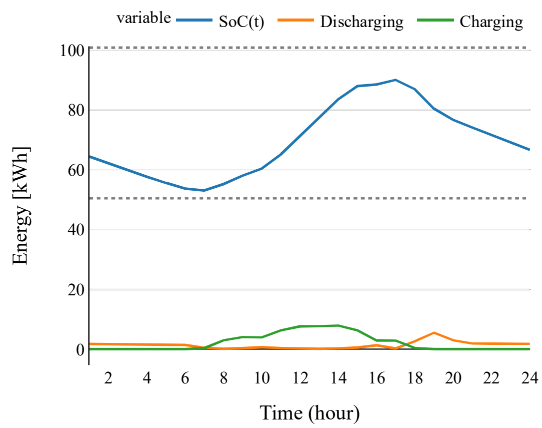

Figure 18. Average SoC of the BESS for PV-BAT

Figures 19 and 20 show that in both options the optimization model ensures that the process of charging and discharging the BESS does not occur at the same time. For the PV-BAT-DG solution, it is observed that in hours 11, 12, and 13; a charging process was initiated, therefore, the battery did not supply energy to the user (discharge process). In hours 14 and 15, the opposite happened when a discharge process is initiated. The same behavior is observed in the PV-BAT solution.

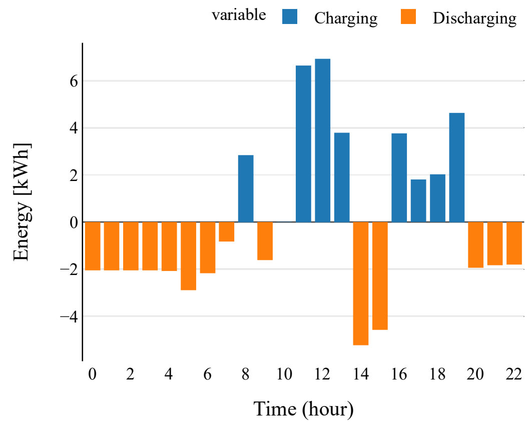

Figure 19. Charging and Discharging Process of the BESS in a day for PV-BAT-DG

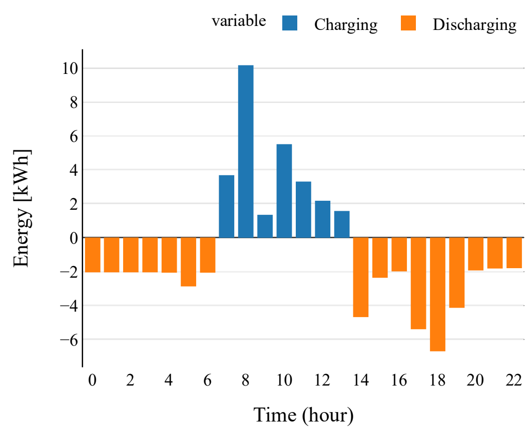

Figure 20. Charging and Discharging Process of the BESS in a day PV-BAT

7. Conclusions

This paper presented a methodology for sizing islanded MGs in Colombia This methodology considers a deterministic optimization model and the tax benefits that the Colombian government gives new projects that include renewable energy. The optimization model considers the technical constraint of battery as maximum cycles allowed of charging and discharging.

The reliability of the system was included as a constraint on the optimization model and the energy no supplied to the load was treated as a variable with a high cost in the objective function.

Several cases were evaluated due the possibility of running multiple times the model through the implementation in python programming language. This approach improves the decision making. Then two cases were selected as a result of the study cases: The first case considers PV panels, a BESS and a diesel generator while the second case only considers PV panels and a BESS without diesel generator. The second case presents the highest cost due to the load profile of the study case. Results showed that the service of the user can be improved using the methodology.

The total energy by source was related with ASC and LCOE. It can be seen that the energy delivered by the PV array is higher with respect other resources

In fact, the selected solutions give 19 and 21 hours respectively without having energy not served to the load. It was found that the LCOE was lower when considering the tax benefits. The meteorological data and the load profile are decisive in the sizing process of each case. This methodology can be used for sizing an islanded microgrid when available: the hourly load profile of the users, meteorological data, technical data of the system assets and validating and update the tax-benefits rules.

8. Nomenclature

This section presents the nomenclature used in the paper for parameters and variables of the proposed optimization model.

8.1. Parameters

- G, Sets of systems Components
- T, Time horizon to evaluate the Study Case
- cpv, Price per kW installed of PV Eenrgy in (USD/kW)
- cdg, Price per kW installed of Diesel Energy in (USD/kW)
- $cbat$, Price per kW installed of BESS Energy in (USD/kW)
- $cens$, Cost of energy not supplied in (USD/kWh)
- $LPSP^{max}$, Maximum Loss of power supply probability allowed in (%)
- $Eload$, Load to meet at time t in kWh
- Epv^{max}, Maximum energy available from PV array at time t in kWh
- Epv^{min}, Minimum energy available from PV array at time t in kWh
- Pdg^{min}, Minimum energy available from Diesel generator taking in account the minimum ratio constraint, in kWh
- Pdg^{rate}, Is the rated power of diesel generator in kWh
- Mb, Positive BESS constant
- SoC^{max}, Maximum state Of Charge of the BESS considering the maximum capacity in kW
- SoC^{min}, Minimum state Of Charge of the BESS according the maximum depth of Discharge in kW
- $cycles^{max}$ Maximum number of charging/discharging cycles of the BESS allowed
- $Emax$, Maximum flow of energy to avoid overheating in charging/discharging of the Battery Bank

8.2. variables

- Epv, Energy supplied to load from PV Array in kWh
- Pdg, Energy supplied to load from Diesel Generator in kWh
- $Ebat^{-}$, Energy supplied to load from BESS in kWh
- $Ebat^{+}$, Energy supplied to BESS from PV Array and Diesel Generator in kWh
- $Ebat^{pv}$, Energy supplied to BESS from PV Array in kWh
- $Ebat^{dg}$, Energy supplied to BESS from Diesel Generator in kWh
- $PENS$, Energy not supplied to load in kWh
- SoC, Estate Of Charge of BESS at time in t in kWh
- Bdg, Binary variable that determines if the Diesel Generator is Used
- Bc, Binary variable that determines if the BESS is charging
- Bd, Binary variable that determines if the BESS is discharging
- $Bcycles$, Number of charging/discharging cycles of the BESS

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L, E.F.C.-B. and P.A.M.-D.; Visualization, W.R.-C.; Writing—original draft, W.R.-C. and N.M-G.; Writing—review and editing, W.R.-C., N.M-G., J.M.L.-L, E.F.C.-B. and P.A.M.-D.

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ANEXO 2

ARTICULO:

Open Source Tool for Sizing Hybrid Islanded Microgrids in Colombia

Open Source Tool for Sizing Hybrid Islanded Microgrids in Colombia

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***Abstract*—This paper introduces an open-source tool for sizing islanded microgrids (MGs) which was developed in programming language python. This tool can be used to sizing islanded MGs. Several researchers have developed methodologies for sizing microgrids, however no open-source available tools have still been implemented for the use of these methodologies, also commercial tools are usually expensive. The proposed tool allows the user to change different parameters of the MG such as solar, diesel and battery parameters; the user can also ingress weather variables and load data. The user can use the free tool to make decisions on the sizing of islanded MGs.**

Keywords—open-source, microgrids, optimization, islanded MGs.

I. Introduction

Islanded Microgrid (MG) is considered an option for providing power in off-grid areas when there are high costs of conventional power production or when there are power supply problems. Normally, off-grid areas in Colombia use diesel gensets to supply electricity. Diesel gensets could have a negative effect on climate change; however, the main drawback is that diesel gensets are very expensive and operating costs could be higher depending of access roads or social conditions. To face the problems associated with diesel gensets, hybrid systems involving photovoltaic and wind generators (denominated as distributed energy resources (DERs)), battery energy storage systems (BESS), and diesel gensets, are a desirable option. DERs are becoming more economical and environmentally friendly options; nonetheless, due to their inherent intermittence, DERs themselves are not able to continuously supply power to the MG load; therefore, diesel gensets and battery energy storage systems (BESSs) can support the load when DERs are interrupted. Particularly, in Colombia, there are many off-grid areas that uses diesel gensets as power source; however, these areas tend to be very poor, extremely far from major cities, which makes diesel difficult to transport and increases costs. Therefore, we recommend the installation of hybrid systems with DERs to reduce diesel consumption, in consequence, it could be reached lower operating costs.

Researchers around the world have applied hybrid technologies in islanded MGs. In [4]-[6], it is proposed configurations of photovoltaic array generators, wind turbines, fuel cell and the battery back-up systems. In [7]-[13], the wind turbine and PV array with battery back-up were only taken into consideration, while in [13]- [24] a diesel genset is included as back-up. Other power generation sources, including biomass, thermal systems, a flywheel, and the utility grid, have been studied in [27]-[32].

Microgrid planning must ensure system reliability with lowest cost, while assuring the requirement of the users. Optimization challenges in MG planning are separated since the problem becomes a nonconvex and NP-Hard model of multilevel decision making [23]. To achieve successful MG planning, single and multi-objective optimization approaches have been proposed in the technical literature.

Some researchers have used several optimization approaches that can be classified into accurate algorithms, approximate algorithms, and commercial applications. For example, in [4], [22], [24], [29], authors have been implemented classical algorithms such as dynamic programming considering the variation of generation sources. In [14], [25], [28], [30], the mixed integer programming algorithm (MIPA) has been used to solve a single-objective problem. In [13], [17], [26], HOMER software tool (one of the most commercially widespread software) has been used, for microgrid modeling and designing; however, the main drawback is that HOMER does not permit freely manipulate MG parameters. The techniques below techniques have been extensively used in recent years: Multi-objective Particle Swarm Optimization (MOPSO), Gray Wolf Optimization (GWO), Improved Fruit Fly Optimization Algorithm (IFOA), Ant Colony Optimization (ACO), Genetic Algorithms (GA), Artificial Bee Colony (ABC), Whale Optimization Algorithm (WOA), Non-dominant Sorting Genetic Algorithm (NSGA-II), Multi-objective Genetic Algorithm (MOGA), and Particle Swarm Optimization (PSO) [5]-[32].

On the one hand, developing a tool for the sizing MG requires the evaluation of any resource forecasting techniques. Especially for weather of solar and wind sources, for obtaining better outputs in the process of optimization. On the other hand, in technical literature and commercial software, it is not frequent to consider the fiscal benefits that some national governments grant to renewable generation technology sources such as photovoltaic or wind. This paper considers both aspects.

The consulted papers do not present an open-source tool that allows the use of a methodology for designing MG in off-grid areas. So, this paper presents as a main contribution an open-source tool developed in programming language python that resolve a deterministic optimization model to sizing islanded microgrids in Colombia that considers fiscal incentives.

II. The Systems Asset and Optimization Model

The configuration of the islanded MG considered in this paper is shown in Fig. 1. It is considered a PV array system, a battery bank, and a diesel generator, while AC and DC busses are connected by using an inverter. Mathematical models used in the proposed tool are described below:

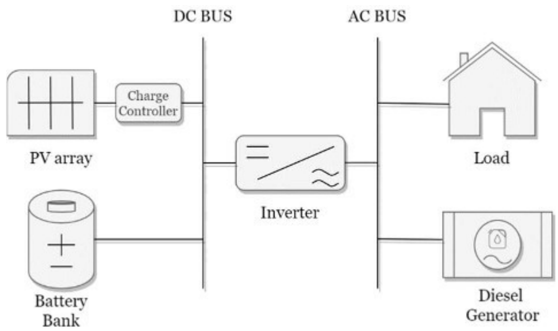

Fig. 1. Islanded microgrid model.

A. Photovoltaic Array

According to [33], the PV array is described by (1)

$$Ppv = npv * Ppvstc * \frac{G(\beta,\alpha)}{Gstc} * T * fpv \quad (1)$$

Where npv is the number of PV cells, $Ppvstc$ is the rated power, $G(\beta,\alpha)$ is the global irradiance on the plane, T is the cell temperature in Celsius and fpv is a derating factor.

B. Diesel genset

The fuel consumption can be calculated by (2)

$$Fcon = \sum_{i=1}^{x} a_i + pdg_i b_i + pdg_i {c_i}^2 \quad (2)$$

Where, a_i , b_i , c_i are technical coefficients of fuel consumption and pdg_i is the power generated by the diesel generator and x is the cluster of diesel generator.

C. Battery Bank

The power stored and managed by a battery bank

is defined by (3):

$$SoC_t = (1-\sigma) * SoC_{t-1} + Ebat_t^+ * \eta_c - Ebat_t^- / \eta_{inv} \quad (3)$$

Where, σ is the self-discharge rate per hour, $Ebat_t^+$ is the power delivered to the battery bank, η_c is the battery bank charge efficiency, $Ebat_t^-$ is the power of battery bank delivered to the load, η_{inv} is the inverter efficiency.

D. Optimization model

This paper uses a deterministic cost model for the developing of the proposed sizing tool.

The objective function is given by (4):

$$min \sum_{i \in G} ci \sum_{t \in T} gi,t \quad (4)$$

Where the main goal is to minimize the cost energy dispatch. G is the set of power generation resources and T the set of time horizon to evaluate the model. ci is the cost per kWh generated by the source i.

Constraints are described as follows:

$$\sum_{i \in G} \sum_{t \in T} g_{i,t} = Load \quad (5)$$

$$g_{i,t} \leq gmax_{i,t} \ \forall \ t \ \in T, i \ \in G \quad (6)$$

$$g_{i,t} \geq gmin_{i,t} \ \forall \ t \ \in T, i \ \in G \quad (7)$$

$$SoCmin \leq SoC_t \leq SoCmax \ \ \forall \ t \ \in T \quad (8)$$

$$Cycles \leq Cyclesmax \quad (9)$$

$$LPSP \leq LPSPmax \quad (10)$$

The constraint (5) is to meet the load demand of the user at time t. The constraints (6) and (7) are the maximum and minimum energy available at time t respectively, for the resource i. The constraint (8) is the maximum and minimum State of Charge of the battery respectively. The constraint (9) is the maximum cycles of charging/discharging allowed to the Battery Bank and the constraint (10) is the maximum Loss of Power Supply Probability allowed.

E. Study Case

This paper deals with the need to supply the energy demand of the community of "Santa Cruz del Islote" located in Bolivar, Colombia. This community has a high demand of energy at night and has a median of consumption of 24 kWh and a maximum of 47 kWh in October. The solar radiation is over 800 Wh/m^2 in March.

III. THE PROPOSED OPEN-SOURCE TOOL

The proposed open-source tool was developed in Python programming language and allows sizing hybrid islanded microgrids considering PV cells, diesel gensets and a battery bank. The optimization solver used is GUROBI that uses mixed integer programming (MIP) models with an academic license. Main window of the tool is shown in Fig. 2. From left to right: the first icon allows to enter the solar technical data, the second icon the battery technical data, the third icon the diesel generator technical data, the fourth icon allows to configure the optimizer, the fifth icon allows to enter the economic variables, and the sixth icon allows to enter the load data. This source is available in https://github.com/osim-microgrid-tool/osim_islanded_microgrids_sizing. The user can configure the technical parameters of the system equipment and the economic considerations of the project, and the user can even load the data from an external file such as excel. The information needs to be presented in hourly format and the file must contain, date, time, energy demand, temperature, and solar radiation. This is completely necessary for the correct use of the optimization model implemented in the proposed tool.

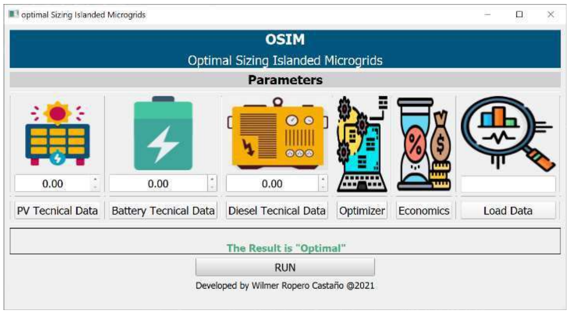

Fig. 2. Main window of open source tool.

A dashboard of the data from the study case is shown in Fig. 3. This dashboard can be visualized when the user clicks on the Load Data button. The dashboard lets graphically visualize: 1) Daily average load profile for one year, 2) Daily average temperature for one year by month, 3) Daily average solar radiation for one year by month, 4) Monthly solar radiation for one year, 5) Monthly load profile for one year and 6) Boxplot of load profile by month.

Fig. 3. Dashboard of the study case data.

Fig. 4 corresponds to the configuration window of PV solar cells. It can be configured: Maximum Power Wp, Module Efficiency (%), Nominal Operating Cell Temperature (NOCT(◦C)), Price per kWh generated (USD/kWh), Photovoltaic derating factor (%), O&M factor initial investment (%), Price per kW installed (USD/kW), Power Temperature Coefficient (%/◦C).

The user can edit and save the configuration he wants to use for sizing the islanded microgrid. Once the user has configured the parameters to be used in the simulation, he can use the "RUN" button available in the main window.

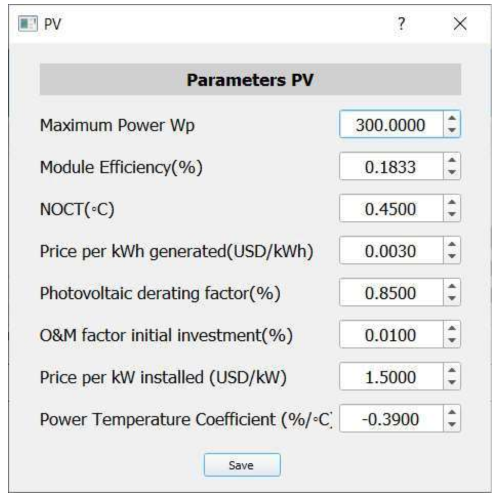

Fig. 4. Technical parameters of PV cells.

Fig. 5 corresponds to the configuration window of the diesel generator. It can be configured: Price per kWh installed (USD/kW), Minimum ratio allowed, Diesel efficiency (%), Price per kWh generated (USD/kWh), Factor of the initial capital cost invested (%), Specific consumption of fuel (gal/kWh), Specific consumption of oil (gal/kWh), Lifecycle (years), Average price of oil (USD/gal), Average price of fuel (USD/gal).

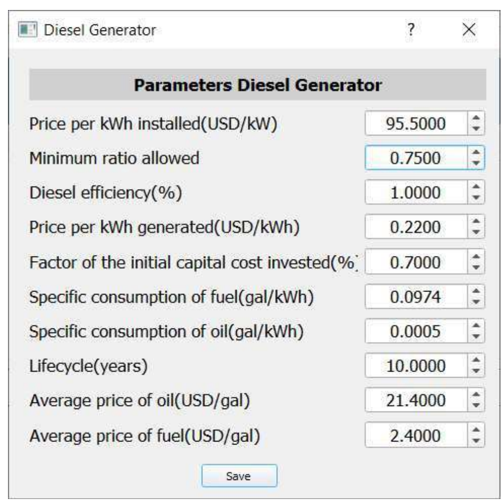

Fig. 5. Technical parameters of the diesel generator.

Fig. 6 corresponds to the configuration window of battery bank. It can be configured: Positive battery constant, Self-Discharge rate, Capacity Rate (h), Maximum depth of discharge (%), Maximum number of cycles, Price per kWh generated (USD/kWh), Battery cell capacity (kW), DC system voltage (V), Battery Voltage (V), Inverter efficiency (%), O&Mfactor initial investment (%), Factor initial capital cost invested (%), Lifecycle (years), Price per kWh installed (USD/kW), Discharge efficiency (%), Charge efficiency (%).

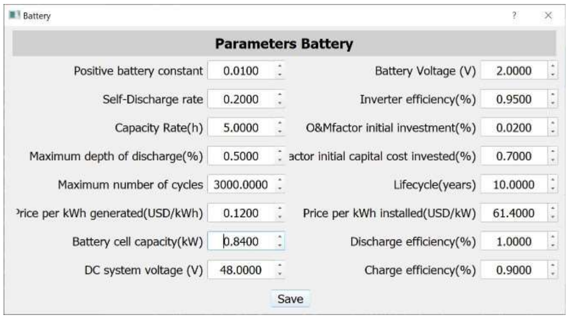

Fig. 6. Technical parameters of the battery bank.

Fig. 7 corresponds to the configuration window of the optimizer. It can be configured: Time Limit and MIP GAP (it is an option to obtain a solution of the MIP solver early. It will terminate (with an optimal result) when the gap between the lower and upper objective bound is less than MIP GAP).

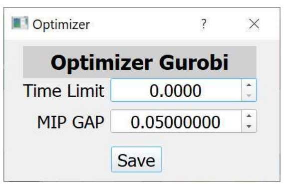

Fig. 7. Configuration of the solver optimizer.

Fig. 8 corresponds to the load window of a file with the data of the optimization problem. Once the user clicks on the Load Data button a window of the computer system will be displayed to select the file.

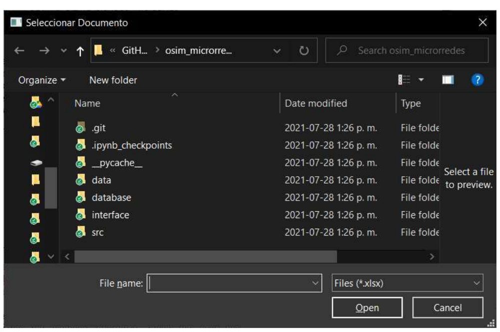

Fig. 8. The load window of a file with the data of the optimization problem.

The user can edit and save the configuration he wants to use for sizing the islanded microgrid. Once the user has configured the parameters to be used in the simulation, the user can use the "RUN" button available in the main window.

If the result is "optimal" a window will open as shown in Fig. 9. Also, the results can be exported to excel. The results contain cost information and equipment quantities. They also contain the detailed information of the hourly result.

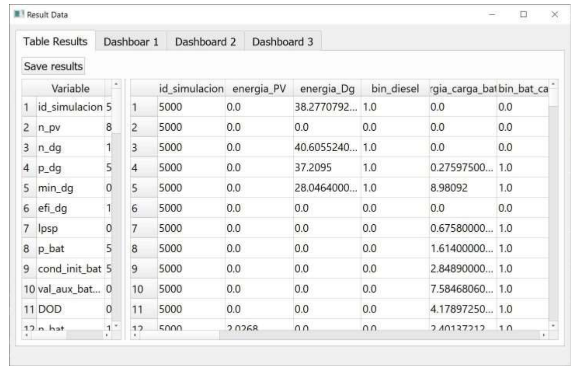

Fig. 9. Results of study case.

There are available three dashboards: The first dashboard, Fig. 10, lets visualize: 1) Energy Supplied to Load in a year, 2) Energy Supplied to Load in a day, 3) Energy Used on Microgrid, 4) Energy Supplied to Battery Bank in a year.

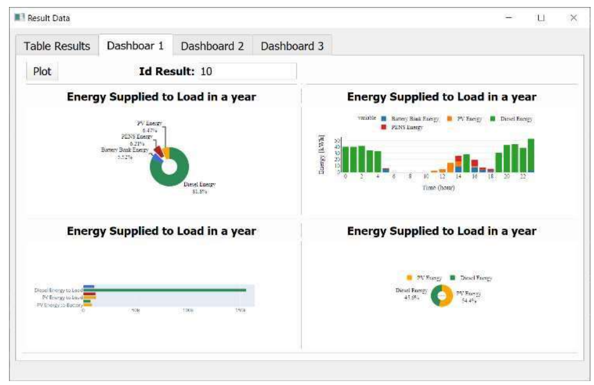

Fig. 10. First Dashboard of the study case results.

The second dashboard, Fig. 11, lets visualize: 1) Charging and Discharging Process of the Battery Bank in a day, 2) Average State Of Charge of Battery Bank, 3) Average Energy to charge the Battery Bank, 4) Average Energy Used from the Diesel Generator.

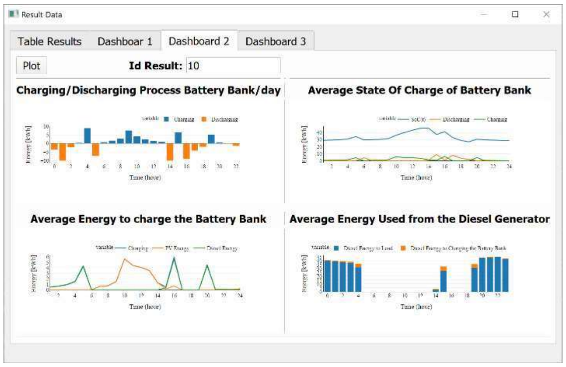

Fig. 11. Second Dashboard of the study case results.

The third dashboard, Fig. 12, lets visualize: 1) Average Energy Available from PV Energy, used to supply the load and charge the battery bank.

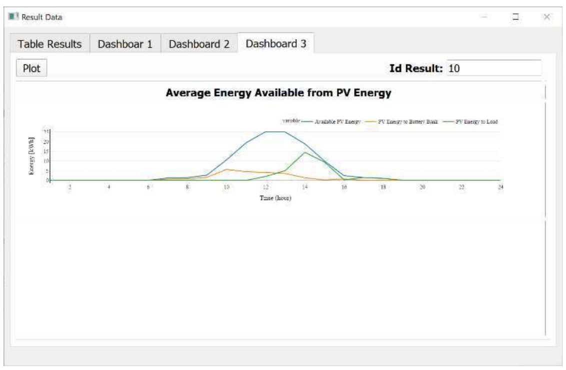

Fig. 12. Third Dashboard of the study case results.

For the case of study analyzed in the paper and according to the results shown in the dashboard. The energy provided from renewable resources is prioritized over the Energy provided by the diesel genset, which is according to the optimization model proposed. The Diesel genset and Battery Bank are only used when the PV Energy is not available or is insufficient, being the diesel generator the last option to supply the load and charge the battery bank. Also, the optimization model proposed ensures that the process of charging and discharging in battery bank not occur at the same time.

TABLE I. RESULT OF THE ESTUDY CASE

Main Results		
Variable	Unit	Value
Number of PV cell	Units	80
Battery Bank	kW	50.4
Diesel Genset Capacity	kW	50
Loss of Power Supply Probability	%	6.21

Table I show the result of system components and the maximum Loss of Power Supply Probability achieved by the optimization model using the developed open-source tool.

IV. CONCLUSIONS

In this paper, it was developed a open-source tool for sizing islanded MGs which includes solar and diesel generator, and batteries. This tool considers a deterministic optimization model. The optimization model considers the technical constraint of battery like maximum cycles allowed of charging and discharging. The reliability of the system was included as a constraint on the optimization model and the energy no supplied to the load was treated as a variable with a high cost in the objective function. The paper explained in detail the developed tool, showing that it is possible to configurate input data (solar, battery and diesel parameters) and ingress load data and weather variables. After running the open-source tool, it is possible to visualize the results in a friendly dashboard that can help to the users in the decision making by the easy configuration and visualization of results. Finally, it was analyzed a case of study for showing the usefulness of the proposed tool. The proposed tool can be used for designing islanded MGs in Colombia and can be improved by users due to is open source.

V. ACKNOWLEDGEMENTS

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