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Article

A Comprehensive Method for Designing Containerized Microgids in Non-Interconnected Zones

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Abstract: Many isolated rural communities lack basic electricity services and associated modern amenities. One proposed solution is the deployment of containerized microgrids, which are clusters of generation and storage assets packaged in a container for easy deployment. However, few works have described approaches for designing such solutions. This paper presents a five-step method for designing a containerized photovoltaic-based microgrid for isolated areas. The method includes defining system design requirements and constraints (technical, environmental, and legal), conducting preliminary studies on solar radiation and load profiles, selecting equipment, designing the control system, and performing a basic economic analysis. This method is verified in three scenarios of Colombian Non-Interconnected Zones (NIZs), resulting in a solution that can effectively provide electricity to the isolated communities, primarily from solar energy, store surplus generation in batteries, and minimize diesel backup generator use. The results show that the solutions can be scaled to feed larger loads and can be applied in other contexts, such as emergency supply after natural disasters.

1. Introduction

As a result of technological progress, many people enjoy certain amenities whose presence seems unquestionable, including basic electricity services. However, for many people living in some rural communities, it is not uncommon to lack access to the same commodities. These areas are known as Non-Interconnected Zones (NIZs), which are characterized for having a vast geographical extension in contrast to their low population density, complex social dynamics, sometimes related to ancient traditions, and even the presence of rebel groups. In Colombia, for example, Non-Interconnected Zones (NIZs) span approximately 52% of the national territory [1]. The previous factors complicate the construction of the

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necessary infrastructure to establish a connection to the National Interconnected System (SIN), leaving over 657.000 families [2] without a reliable energy supply.

Many different solutions have been proposed to solve this issue, besides the current use of on-site fossil fuel generators, which include expanding the current national grid to reach NIZs, deploying stationary microgrids, or implementing stand-alone Photovoltaic (PV) systems to individual households [3,4]. Another option, not extensively explored for applications in countries like Colombia, are containerized microgrids, which consist of systems designed to fit inside shipping containers and thus adapted for transportation from the place of assembly to its destination. This solution can be implemented as a modular and flexible plug-and-play scheme to answer the needs of different communities, complement erratic main grid power, and support military deployments or disaster relief efforts [5,6]. Prominent work has been done in recent years regarding this subject. For example, [7] describes a 20 kW containerized microgrid designed with the intention of meeting the electricity requirements of critical loads (clinics, control centers, cellular radio towers, and others) necessary to mitigate the effects of disasters that damage local electrical infrastructure, like the 2010 Haiti earthquake. Commercial solutions already available in the market, falling into the category of mobile microgrids, include Schneider Electric's Villasmart and Villaya Emergency, BoxPower's SolarContainer or Hitachi Energy's e-mesh PowerStore, all conventionally used to fulfill the previously described purposes; and some even add additional functions, like LEAPS' mobile clinic, which incorporates an ultraviolet water purification system [6].

This paper, which expands the work previously presented in the IEEE Colombian Caribbean Conference (C3) [8], proposes a method for designing containerized microgrids and showcases its use on three different scenarios located in Colombian NIZs, from the preliminary studies that need to be carried out, to the selection of components and economic analysis of the resulting design. Thus, the remaining of this paper is divided as follows: Section 2 describes the aforementioned method and the stages of the design, Section 3 depicts its application in the design of such a system as a generic solution for the study cases, and Section 4 discusses the main conclusions of this work.

2. Proposed Method

The proposed method for designing containerized microgrids can be split into five phases, which are presented in the following sections and summarized in Figure 1.

2.1. Design requirements and constraints

The criteria for the design and fabrication of the system must take into account the local bylaws and standards, as well as the characteristics of the environment it will be placed on. Moreover, the system must satisfy the following requirements [7]:

- Continuity of electricity supply: The system must be able to reliably provide power at any time of the day. Different circuits could be used to split critical load, which must be permanently fed, from non-critical load, which can be shed if the demand exceeds the available energy output.
- Required space: Most, if not all equipment, must fit inside the selected shipping container to allow its transportation to the intended NIZ. Although additional elements can be transported separately, it should not hinder the microgrids' mobility.
- Environmental conditions: All equipment sensible to the weather and environmental conditions must be isolated inside the container to prevent damages and ensure its appropriate functioning.
- Safety: Personnel and equipment must be kept safe from harm during the transportation, maintenance and operation of the system.

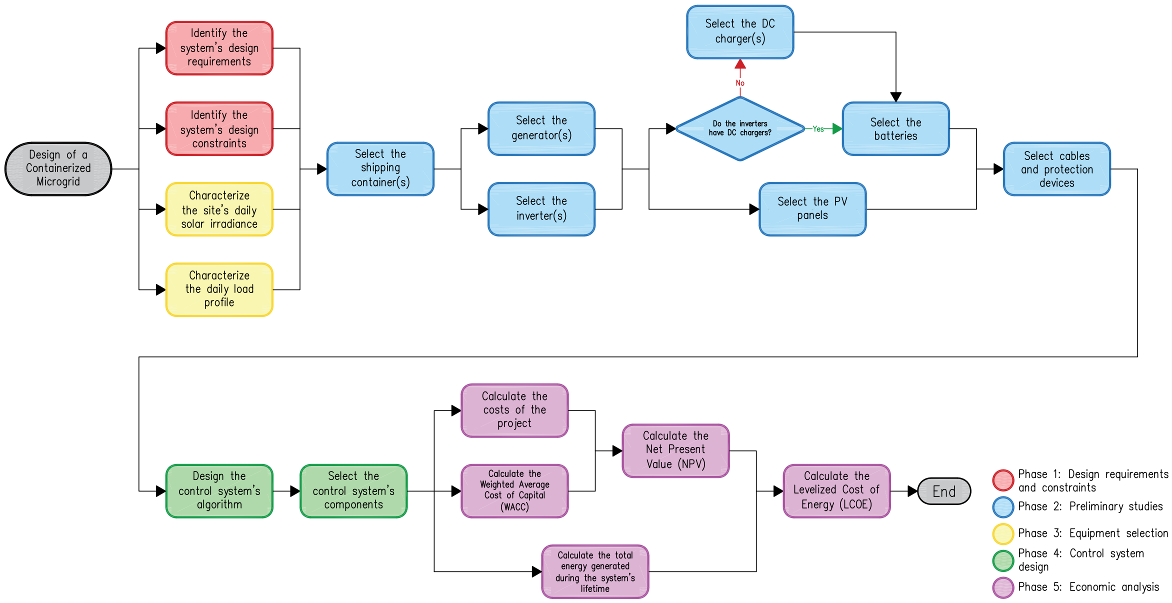

Figure 1. Proposed method for designing a containerized microgrid.

- Temperature: The inside temperature of the container must be kept within the working temperature limits of the devices to prevent overheating and the risk of fire.
- Sustainable energy: The system should use some form of sustainable power generation, instead of relying solely upon fossil fuels, to keep costs and carbon emissions low.
- Compliance with standards: The design must abide any regional and international standards regarding the operation of electrical systems and storage of its components.

2.2. Preliminary studies

To correctly size the elements forming the microgrid and analyze its operation, the following information is necessary: load profile of the users to be served, solar radiation at the operating location, minimum and maximum temperatures of the location, altitude above sea level, and humidity level.

The load profile, solar radiation, and temperature range are essential for sizing the generation equipment. The solar irradiance can be analyzed with different degrees of accuracy, from on-site measurements, mathematical equations, specialized software or public information available in databases; while the load profile can be obtained from the energy output of the existing generators feeding the NIZ, inquiring the population about their energy consumption habits, or from reports made by government institutions regarding NIZs. These factors are used to estimate the total energy the PV panels could provide, the power the load will demand at any given moment, and the moments of energy surplus/deficit for the batteries and generator to enter the system. On the other hand, temperature, altitude above sea level, and humidity data are used to define equipment specifications to ensure they can withstand the environmental conditions where the microgrid will operate.

2.3. Equipment selection

Some important aspects to consider regarding selection of the main components forming the microgrid are the following:

- Shipping container: The interior dimensions of the container delimit the space available to assemble and run the entire microgrid. Modifications may need to be applied to fulfill the requirements and attend to the constraints established on section 2.1.
- Generator: Due to the fire risk of batteries, the generator must be placed on a different room, divided by a fireproof wall [7], with openings to ventilate it. The size of this room determines the space available for the rest of the system.
- Inverters: The maximum number of parallel-connected inverters that are usable depends on the indications of the datasheets and the size of the wall for mounting, considering the minimum clearances the units must keep around to dissipate heat.
- PV panels: The maximum number of panels usable depends on their size and arrangement inside the container. The number of panels and arrays is also limited by the inverter's maximum PV array open circuit voltage and maximum input current.
- Batteries: Batteries constitute one of the most expensive investments in PV systems and proper risk mitigation strategies need to be implemented. For example, if the excess energy from the PV panels surpasses the capacity of the batteries, the inverters may need to be turned off to protect the batteries from overcharging.

Other necessary elements to ensure the appropriate functioning of the microgrid should be considered, including: temperature control systems, cable trays, distribution boards, and storage cabinets, among others. Every component of the circuits must be protected from possible overcurrents and short-circuits by either fuses or circuit-breakers. The latter presents an advantage over fuses, since breakers do not have to be replaced after every operation. To prevent damage from lightning strikes on the wiring, surge protectors should be installed in the main distribution panel board and inside each combiner box between the PV arrays and the inverters.

2.4. Control system design

The control system for the microgrid can be designed using the batteries' State of Charge (SoC) as an input to perform transitions between different states of the algorithm. The following variables are necessary for the state machine shown in Figure 2:

- SoC_{min}: The minimum SoC permissible to prevent the batteries from overdischarging.
- SoC_{max}: The maximum SoC permissible to prevent the batteries from overcharging.
- $t_{min-diesel}$: Minimum generator run time.
- $t_{op-diesel}$: Current generator run time.
- P_{load}: Power demanded by the load.
- P_{gen}: Power provided by the microgrid.

1. Normal operation: Both PV panels and batteries can supply energy to cover the load. If there is any surplus of solar energy, the batteries will instead use it to charge. This state is activated when the battery SoC is above SoC_{min} and below SoC_{max}.
2. Diesel back-up: If the battery SoC is below SoC_{min}, the generator is turned on to supply the energy that the rest of the system is not able to inject, while the batteries charge with any surplus. After the batteries charge again and $t_{op-diesel}$ is greater than $t_{min-diesel}$, the system returns to the first state.
3. Load shedding: If the battery SoC is below SoC_{min} and the PV panels are unavailable, or P_{load} is greater than P_{gen}, the generator is turned on and part of the load is disconnected. The system is left

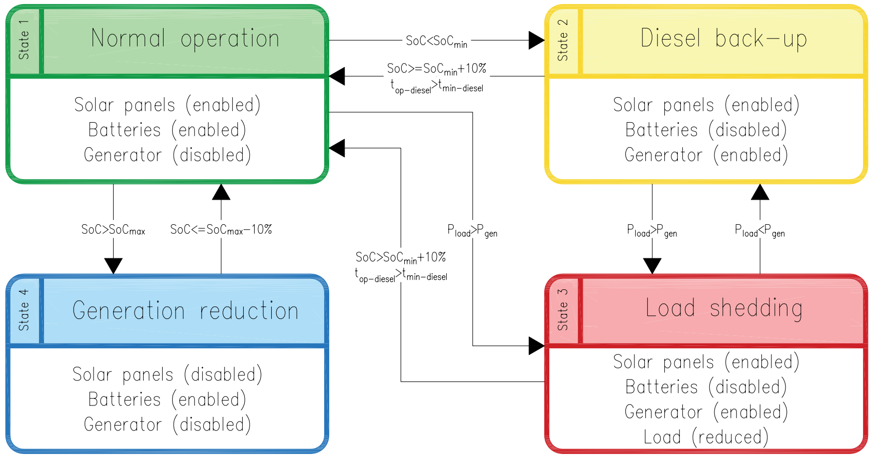

Figure 2. State machine diagram.

feeding only the critical load until the batteries are charged, the generator has been running for long enough, or other forms of generation become available.

4. Generation reduction: If the battery SoC is above SoC_{max}, there is an excess of generation coming from the panels that can not be stored. Thus, these are disconnected and the system is powered only by the batteries. Normal operation is resumed after the batteries discharge.

2.5. Economic analysis

The Levelized Cost of Energy (LCOE) is the ratio between the Net Present Value (NPV), equivalent to the future costs of production for the project, and the energy produced by the system over that period of time, and can be interpreted as the minimum price of energy necessary for a return on investment. It has been widely used as a criterion for comparing electricity supply options from different energy resources [9].

$$WACC = fdp \cdot cfd \cdot (1 - tr) + ep \cdot esr \quad , \tag{1}$$

$$NPV = \sum_{i=0}^{n} TC_i \cdot (1 + WACC)^{-i} \quad , \tag{2}$$

$$LCOE = \frac{NPV}{\sum_{i=0}^{n} E_i} \quad , \tag{3}$$

- $WACC$: Weighted average cost of capital.
- NPV: Net present value [\$].
- TC: Total costs [\$].
- fdp: Financial debt participation [%].
- cfd: Cost of financial debt [%].
- tr: Current tax rate [%].
- ep: Equity participation [%].
- esr: Expected shareholder return [%].
- TC: Annual total cost of the system [\$].
- i: Years of operation of the system.

- n: Lifetime of the system [years].
- E: Annual generated energy [kWh].

3. Study Cases and Results

The previous method was implemented to design a containerized microgrid for the purpose of providing electricity to any NIZ in Colombia. The performance of the resulting system is evaluated in three settings, including the best-case and worst-case scenario of solar generation possible on these places.

3.1. Design requirements and constraints

- Continuity of electricity supply: The system uses a back-up diesel generator to provide energy when there is no sun for the PV panels and the batteries are discharged. Three electrical connections are meant to feed different loads, with two being non-critical loads.
- Required space: Every element composing the microgrid is stored inside the container, except for the combiner boxes, AC condenser and the electrical conduits for the connections.
- Environmental conditions: The inverters, batteries and generator are protected inside the container. The devices operating outside have a suitable IP code to protect them from dirt and rain.
- Safety: The equipment is fastened to the floor and/or the walls of the container to avoid collisions during transport. The PV panels are transported in wooden boxes that can be dismantled after deploying the panels to allow for more ease of use.
- Temperature: To keep the interior temperature inside a suitable range for the equipment, the container includes rock wool insulation, selected due to its fire resistant properties [10], and a 9000 BTU Air Conditioning (AC) unit.
- Sustainable energy: The system relies mostly on solar power and prioritizes the PV panels and batteries over the diesel generator, which is used as back-up.
- Compliance with standards: The design complies with the following standards: RETIE [11], NTC 2050 [12], NFPA 37 [13] and NFPA 855 [14].

3.2. Preliminary studies

Given that the microgrid is meant to be a general solution able to operate on any NIZ, and could encounter different climatic conditions on each location, the performance analysis of the system is limited to three scenarios of daily solar irradiance that are possible in Colombia, instead of choosing a single town. These correspond to Puerto Estrella, La Guajira, in March; Mutis, Chocó, in December, and Inírida, Guainía, in September [15]. The three settings were selected to represent the best, the worst, and an average scenario of solar radiation possible in the country, respectively. The behavior of solar irradiance under this conditions is shown in Figure 3, created from the equations described in [16] relating the daily solar irradiance to variables like the sun's position in the sky and the average monthly irradiance.

The typical load profile for one user is obtained from [17] and scaled using the diversity factor provided by the same document and information on the current subsidies from [18] to better represent the energy consumption habits of 50 users residing on NIZs. This load profile, including the consumption of the AC unit throughout the day, is depicted in Figure 4.

3.3. Equipment selection

A 20 ft standard shipping container was selected to accommodate the system. Some of the modifications to its layout include the construction of insulated walls with frames, strong enough to support the weight of the inverters and AC unit; a fireproof wall to isolate the generator; openings for an extractor fan, a window and the generator's exhaust in the same room; and openings for the electrical conduits, the connections to

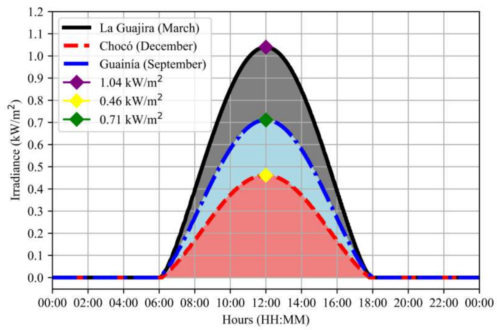

Figure 3. Daily solar irradiance.

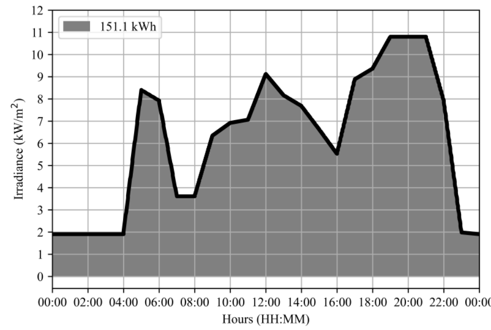

Figure 4. Typical load profile for 50 users on a NIZ.

combiner boxes and the AC unit's duct. The 3D model of the resulting containerized microgrid, including some of the previously mentioned additional elements, is shown on Figure 5. The corresponding single line diagram is shown in Figure 6.

- 1 × 6.6 kW RDE8500Ei3 diesel generator: The generator was sized to provide around half the power demanded by the load, since a generator with a bigger capacity would occupy too much space inside the container. It can be placed in a small room thanks to its dimensions (0.49 × 0.65 × 0.72 m) [19]. A diesel generator was preferred over a gasoline generator due to the lower price of diesel.
- 6 × 6.5 kW Axpert Max II Off-Grid inverters: The inverters were selected due to their rated power (6.5 kW), output voltage regulation (120 V±5%) and capacity to operate in parallel connection with up to 6 units. Each inverter has 2 MPPT solar charge controllers, a 48 V battery charger, and an entrance for the generator [20].
- 60 × 490 W Q.Peak Duo Ml-G11.2 PV panels: The solar panels were selected due to their rated power (490 W) and height (2.05 m) [21], allowing to pack them inside wooden boxes vertically to avoid cracks [22]. Aluminum angles could be installed on the frames of the panels as customized mountings to save space that would otherwise be necessary to transport the panels' metallic structures.
- 28 × US3000 batteries: Lithium-ion batteries were selected due to their specific energy and long life time compared to other energy storage technologies [23]. Their dimensions (442 mm × 420 mm × 132 mm) [24] allow for the possibility of using up to 28 batteries grouped together on 7 stacks.

3.4. Control system design

Figures 7 to 12 showcase the behavior of the proposed containerized microgrid design according to the control algorithm discussed on Section 2.4. For the purpose of this analysis, the following assumptions are established:

- The batteries start the day with an initial SoC of at least 30%.
- SoC_{min} is set to 20%.
- SoC_{max} is set to 90%.
- $t_{min-diesel}$ is set to 20 minutes.

In the case of minimum solar generation, set at Mutis, Chocó, during the month of December (Figures 7 and 8), the system is able to power the load using the batteries for over 4.5 hours, until their energy depletes.

Figure 5. 3D model of a containerized microgrid.

The back-up generator then turns on and half of the load is disconnected for the next 2 hours. Once the sun starts to rise and the PV panels activate, the energy output available becomes greater than the energy required and non-critical loads are reconnected. The generator runs for an additional hour, until the batteries charge over 30%. The current state continues until the sun sets and the batteries deplete again around 7:00 p.m., when part of the load is shed and the generator activates for the next 4 hours. Finally, after the batteries charge over the threshold, the generator is turned off. The final SoC is equal to 28%, and therefore a similar behavior can be expected on the coming days under similar solar radiation conditions.

Similarly, in the case of maximum solar generation, set at Puerto Estrella, La Guajira, during the month of March (Figures 9 and 10), the system starts by providing energy from the batteries in state 1 before switching to states 3, 2 and 1, once again. However, due to the larger amount of solar radiation in this scenario, the system disconnects the PV panels on 2 occasions, from 12:30 p.m. to 1:50 p.m. and from 2:40 p.m. to 4:00 p.m. Due to the additional energy input, the microgrid does not require to turn on the generator after the first instance, unlike the previous case, relying instead on the batteries.

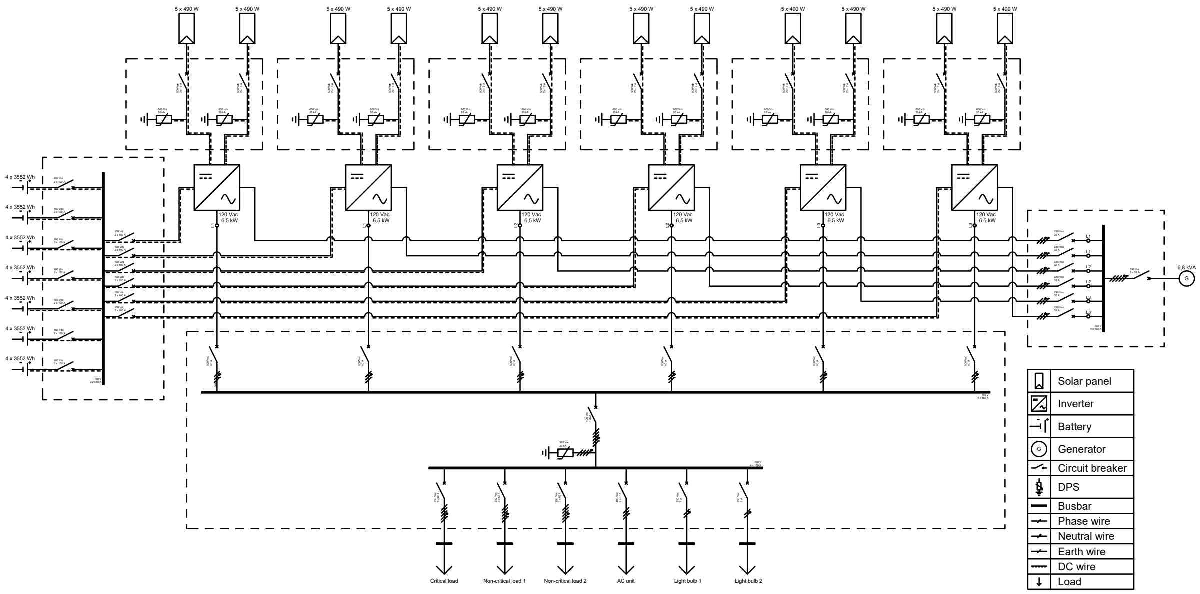

Figure 6. Single-line diagram.

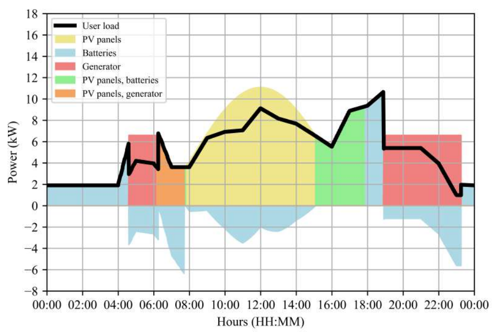

Figure 7. Dispatch for minimum solar generation.

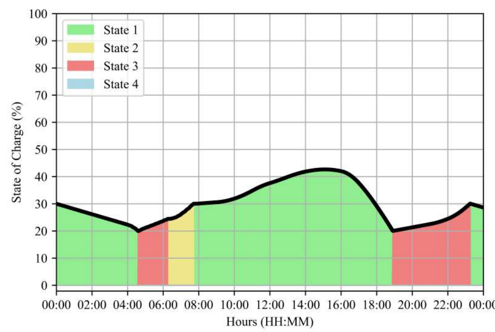

Figure 8. Battery SoC for minimum solar generation.

Although the third case, set at Inírida, Guainía, during the month of September (Figures 11 and 12), displays a very similar behavior to the scenarios at Chocó and La Guajira around the first 12 hours, requiring the activation of the generator from 4:30 p.m. to 7:10 a.m., the system is able to feed the load during the latter half of the day entirely with solar energy, without the need to disconnect the PV panels or turn on the diesel generator. Thus, the system remains in state 1 in this period, without transitioning to states 3 or 4, unlike the previous settings.

3.5. Economic analysis

Some assumptions can be made to calculate the LCOE, like the cost of operations and maintenance being equivalent to 7.5% of the costs of materials [4]. Since the proposed design is a generalized solution and customized changes to its arrangement are not considered in this paper, most costs regarding the construction and operation of the microgrid can be considered equal for the three analyzed cases, with two important exceptions being the total cost of diesel, which depends on how much the back-up generator is used, and the cost of transporting the containerized microgrid to its designated area, which may vary

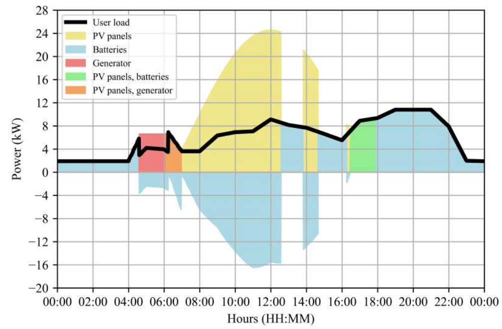

Figure 9. Dispatch for maximum solar generation.

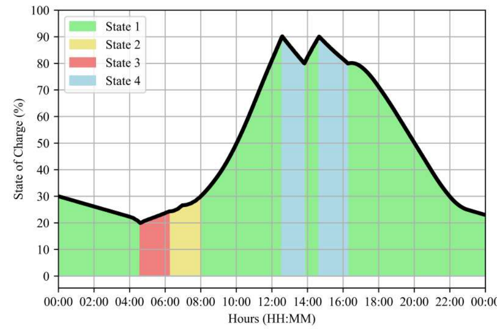

Figure 10. Battery SoC for maximum solar generation.

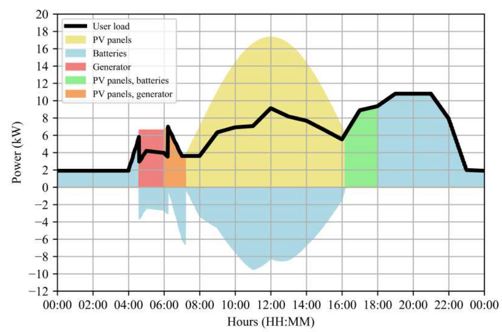

Figure 11. Dispatch for average solar generation.

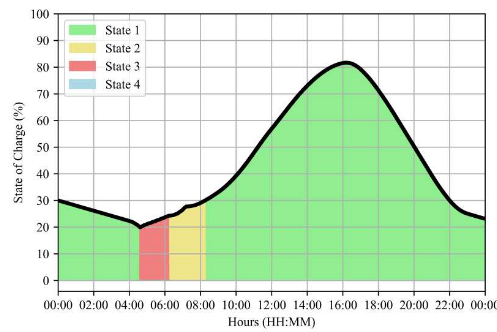

Figure 12. Battery SoC for average solar generation.

drastically depending on the distance between the sites of assembly and deployment. Because of this uncertainty, the latter is not included in this work.

$$NPV = \sum_{i=0}^{20} [MC_i + LC_i + (OC_0 + FC_0) \cdot (1+r)^i] \cdot (1+WACC)^{-i} \ , \tag{4}$$

$$LCOE = \frac{NPV}{\sum_{i=0}^{20} E_i} \ , \tag{5}$$

- Material costs (MC): The total cost of all material components used in the construction of the containerized microgrid.
- Labor costs (LC): The costs corresponding to the salaries and benefits of the employees involved in the labor of constructing the containerized microgrid.
- Operating costs (OC): The costs related to the maintenance and operation of the system after its deployment and activation on site.
- Fuel costs (FC): The total cost of the diesel used to power the generator.
- Inflation rate (r): The rate of increase in the value of the previous costs during the microgrid's lifespan, estimated to be 20 years.

Material and labor costs only affect the initial investment and any replacements that the microgrid may need, which is considered as an event occurring 10 years into the system's total running time; while operating and fuel costs are calculated using estimations of Colombia's inflation rate for future years. The most significant elements used for the calculation of material costs, and their prices as quoted in the first semester of 2023, are the following:

Table 1. List of materials.

Item	Unit	Unit price [COP]	Total price [COP]
20 ft standard shipping container	1	$ 13,500,000	$ 13,500,000
Rock wool sheet 61 × 122 cm, 2.5 inch, 100 kg/m^3	71	$ 57,952	$ 4,114,592
RDE8500Ei3 diesel generator	1	$ 6,753,131	$ 6,753,131
6.5 kW Axpert Max II Off-Grid inverter	6	$ 6,600,000	$ 39,600,000
490 W Q.Peak Duo Ml-G11.2 PV panel	60	$ 866,000	$ 51,960,000
US3000 battery	28	$ 6,099,000	$ 170,772,000
US3000 battery brackets	28	$ 254,600	$ 7,128,000
LV-HUB communication hub	3	$ 1,790,000	$ 5,370,000
9000 Btu/h AC unit	1	$ 1,600,000	$ 1,600,000
IP65 enclosure 3.16×3.16×11.4 cm	6	$ 118,115	$ 708,690
DC circuit breaker	25	$ 114,744	$ 2,868,600
AC circuit breaker	6	$ 25,330	$ 506,600
DC surge protector	12	$ 147,000	$ 1,764,000
AC surge protector	1	$ 120,000	$ 120,000
12 AWG solar cable	370 m	$ 5,400	$ 1,998,000
3×8 AWG rubber cable	60 m	$ 27,556	$ 1,653,360
3×4+6 AWG rubber cable	90 m	$ 74,100	$ 6,669,000

The costs, initial investment and cash flows for two decades in the three cases (minimum, maximum and average solar generation, respectively) are presented in Table 2. The resultant values of Weighted Average Cost of Capital (WACC), NPV and LCOE are shown in Table 3.

Table 2. Cash flows for 0, 10 and 20 years

Scenario	Item	Year 0	Year 10	Year 20
General	Material costs [COP]	$ 324,903,133	$ 245,586,352.31	
	Labor costs [COP]	$ 100,000,000		
	Operating costs [COP]	$ 24,367,734.98	$ 36,732,756.02	$ 52,825,191.25
Chocó	Fuel costs [COP]	$ 11,786,456.66	$ 17,767,307.35	$ 25,551,075.14
	Net flow [COP]	$ 461,057,324.64	$ 300,086,415.68	$ 78,376,266.39
La Guajira	Fuel costs [COP]	$ 3,717,875.59	$ 5,604,452.66	$ 8,059,735.11
	Net flow [COP]	$ 452,988,743.57	$ 287,923,560.98	$ 60,884,926.36
Guainía	Fuel costs [COP]	$ 4,060,685.45	$ 6,121,175.24	$ 8,802,831.26
	Net flow [COP]	$ 453,331,526.42	$ 288,440,283.57	$ 61,628,022.51

The cost of materials, labor and operation of the microgrid, shown in Table 2, remain the same in the three scenarios. However, there are discrepancies among the fuel costs resulting from the increased use of the generator at Chocó, in comparison to its use at La Guajira or Guainía, as seen in the energy provided by the device in Table 3, that ultimately lead to discrepancies in the NPVs. Another important difference between simulations is the energy provided by the PV panels, which is considerably lower at Chocó. On the other hand, the similarity between the results for both La Guajira and Guainía, despite the former being subjected to higher levels of daily radiation, can be attributed to the operation of the microgrid

Table 3. LCOE calculation.

Item\Case	Chocó	La Guajira	Guainía
Financial debt participation	70%	70%	70%
Cost of financial debt	14%	14%	14%
Current tax rate	33%	33%	33%
Equity participation debt	30%	30%	30%
Expected shareholder return	15%	15%	15%
WACC	11.07%	11.07%	11.07%
Projected inflation rate (2023)	8.7%	8.7%	8.7%
Projected inflation rate (2024-2043)	3.7%	3.7%	3.7%
Diesel price [COP/gallon]	9,064.99	9,064.99	9,064.99
NPV [COP]	$ 945,322,338.89	$ 848,367,739.14	$ 852,486,725.40
Energy provided by the PV panels and batteries [kWh]	550,858.73	893,159.38	883,488.35
Energy provided by the diesel generator [kWh]	318,249.34	96,598.71	99,296.06
LCOE [COP/kWh]	$ 1,087.69	$ 857.15	$ 867.42

itself regarding the SoC of the batteries, which limits the amount of solar energy the system can actually harness without overcharging the battery bank. For these reasons, the resultant LCOE in the second and third scenarios have similar values, while remaining lower than the LCOE in the first scenario.

4. Conclusions

This paper presented a design of a containerized microgrid combining both conventional and non-conventional sources of energy as a solution for the issue of NIZs. The method includes the definition of design requirements and constraints, sizing of the load to cover, the analysis of available solar radiation, selecting the necessary components, the definition of control strategies, and the cost analysis of the produced energy. The final design resulted in a system capable of running mostly on solar energy, either delivered directly to the load or stored for later use, reducing considerably the use of fuel-based generation that most of these towns tend to rely on.

In cases where a single containerized microgrid cannot meet the load profile due to potential limitations in generation capacity, imposed by container size, and where load shedding is not an acceptable measure, multiple additional encapsulated microgrids could be connected in parallel to supply the required power. This scenario requires a centralized control system to ensure synchronized operation of the microgrids. However, this operational mode is beyond the scope of the current research. Other potential aspects for future research and improvement could cover the costs not considered in the previous economic analysis, such as the logistics and transport of the container to the intended NIZs. Including these factors would provide a more accurate budget and LCOE, bringing the analysis closer to practical application requirements. In addition, although the process described in this paper focuses primarily on using solar energy as the main energy source and batteries as the elements controlling the operation of the microgrid, future work could explore the inclusion of other forms of renewable energy and control strategies, as well as the use of optimization techniques to improve the cost-benefit ratio of the solution and produce more adjusted designs in both power and cost.

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