




Article

Techno-Economic Feasibility Analysis through Optimization Strategies and Load Shifting in Isolated Hybrid Microgrids with Renewable Energy for the Non-Interconnected Zone (NIZ) of Colombia

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Abstract: In developing countries, electrification in remote areas, where access to energy is limited or null, has been one of the biggest challenges in recent years. Isolated microgrids with renewable generation are an efficient alternative for the energy supply in these areas. The objective of this work was to analyse the techno-economic viability of 6 isolated microgrids in different locations in the non-interconnected zone of Colombia, considering different climatic conditions, the availability of renewable resources, the current consumption profile, and a modified profile applying demand-side management. Modelling and simulation were performed considering storage systems based on lithium and lead-acid batteries. The resulting simulations provide the optimal system cost, emissions levels, electricity cost and battery lifetime. This study demonstrates that isolated hybrid microgrids with renewable energy are a feasible alternative to solve access to energy problems, reducing the need for diesel generators and optimizing the use of renewable energies and battery-based storage systems.

Keywords: lead–acid batteries; lithium batteries; load shifting; optimization; hybrid microgrids

1. Introduction

A modern and reliable electricity supply is crucial for human well-being and for the economic development of a country. Access to energy is vital and allows the provision of drinking water, lighting, heating, food, transportation, and telecommunications [1]. However, approximately 1 billion people still do not have access to electricity and live in areas without connection to the electricity grid [2].

In Colombia, as in the rest of the countries of Latin America, access to electricity in remote areas is very limited due to the lack of infrastructure necessary to bring electricity to these places [3] and due to the precarious economic conditions of potential users, so it is not profitable for electricity companies to invest in these areas. In the so-called non-interconnected zone (NIZ), which corresponds to 52% of the territory of Colombia, approximately 92% of the electrical energy is generated by thermal plants with diesel generators, and the rest is generated by small hydroelectric plants. In these areas, the population lives in places with difficult access, which increases the price of fuel (diesel) in thermal plants, which emit polluting gases and generate noise pollution [4], so this generation system is not the most recommended [5]. In addition to this insufficient and limited electricity supply, autonomous energy resources have not been improved or used [6], which has led to poor social and economic development of the population of these areas.

The Government of Colombia, through Law 697 of 2001, established that the rational use of energy was a matter of social character and of national interest. Law 1715 of 2014 [7] advocated the use

of nonconventional sources for energy generation. Programmes such as PROURE [8] (Rational and Efficient Energy Use Programme and unconventional energy sources) promoted the financing of energy generation projects in the NIZ. All these initiatives can foster distributed generation and microgrids since they allow electricity to be generated and supplied near the places where it is consumed. A microgrid can be defined as a system that includes generation sources, loads and small-scale energy storage devices [9]. They are called hybrid microgrids when they combine two or more energy sources, such as diesel generators, renewable energies, fuel cells, etc. [10]. Hybrid microgrids can be an alternative energy supply in remote areas and they have already been used in several countries for the electrification of rural areas or islands [11–20].

The use of more than one source of electric power generation, of storage systems, and the intermittent nature of solar and wind irradiation complicate the design of hybrid microgrids, since it is necessary to find the optimal design from an economic, technical and environmental point of view [21]. Several studies have attempted to determine the best design, maximizing the use of renewable energies and minimizing the use of fossil fuels [22–27]. In [28] the authors performed a technical and economic assessment, using HOMER, of a hybrid PV-wind-diesel system in a village located in a remote area. Kaabeche et al. [29] presented an iterative method for the optimization of an isolated PV-wind-diesel hybrid system. Ocon et al. [30] studied the behavior of 215 microgrids with a 20% reduction in energy costs. Bekel and Bjorn [31] presented a study on a hybrid system that supplied energy to 200 families in an isolated community. In another work [20], Gebrehiwot et al. performed a sensitivity analysis to determine the effect of variations in solar radiation, wind and diesel price in a hybrid system.

The optimization of isolated microgrids depends mainly on the cost and lifetime of the batteries, and there are several studies focusing on the technical and economic analysis of systems that use lead-acid batteries [32], since this is the most commonly used technology in these systems. Other studies focus on the techno-economic analysis of microgrids in rural areas, such as the one carried out by López-González et al. [33] where 13 microgrids were proposed for remote areas in Venezuela, including PV-wind generation systems with lead-acid batteries. Other authors, such as Dhundara et al. [34] have carried out a techno-economic analysis of a microgrid considering the state of charge of lead-acid and lithium batteries, taking into account consumption data, resources and current prices. A recent study conducted a techno-economic analysis of photovoltaic systems [35] for a locality of the NIZ of Colombia. In another study, Guacaneme et al. [36] presented several solutions using microgrids for rural areas of Colombia.

Considering all these previous works, it can be affirmed that it is necessary to carry out more studies to determine the characteristics that isolated microgrids must have in developing countries [37,38]. It will thus be possible to study their behavior from a technical, economic and environmental point of view in current climate conditions and in situations in which changes in consumption occur, determining the net present cost (NPC) of the system, the levelized cost of energy (LCOE) and the level of emissions [39–41].

This article presents a techno-economic analysis for 6 isolated microgrids with renewable energy generation located in the NIZ of Colombia. Section 2 describes the methodology used, considering factors such as geographical location, climate, the profile of current and managed demand, and the availability of renewable resources in the 6 localities. Section 3 shows the results of the microgrid optimizations. In Section 4, the discussion is presented, and finally, the conclusions of this work are presented.

2. Materials and Methods

The models of the 6 generation systems were simulated using iHOGA 2.5 software [42]. iHOGA (improved Hybrid Optimization by Genetic Algorithms) is a software developed in C++ by researchers of the University of Zaragoza (Spain) for the simulation and optimization of hybrid stand-alone and also grid-connected electric power generation systems based on renewable energies. It includes advanced optimization models (genetic algorithms), which implies the possibility of obtaining the

optimum system using very low computational times. iHOGA uses advanced models to accurately estimate the lifetime of the batteries, which are generally the most expensive components, with high requirements for costly replacements.

As a first criterion for the selection of microgrids, the availability of renewable resources was taken into account. The input data for the optimization correspond to irradiation and wind speed data for each location [43], as well as the actual daily load profiles, the modified profiles applying demand-side management, and financial data, such as the inflation rate and the interest rate of money. As a result of the optimizations, the sizes of each of the components were obtained, which corresponded to the solution with the lowest LCOE. In addition to the economic results, the total CO₂ emissions of the life cycle and the useful life of the batteries were obtained.

2.1. Geographic Location and Climate

The locations selected for this study are located within the NIZ. However, they have very different climatic conditions and renewable resources. The 6 selected locations have an altitude of less than 300 metres. The first three locations are found in tropical forests, Guacamayas is in the tropical savanna, Providencia has a dry tropical climate, and Puerto Estrella has an arid desert climate [44,45]. Figure 1 shows the map locations, and the Table 1 shows the geographic and climate information of the selected locations:



Figure 1. Geographical location of the isolated hybrid microgrids.

Table 1. Geographic and climate information [45].

Location	Geographic Coordinates	Altitude (m)	Precipitation (mm/Year)	Average Annual Temperature (°C)
Titumate	8.31 N, −77.08 W	16	2392	27
Tarapacá	−2.86 S, −69.73 W	62	2853	27
Santa Rosa	1.68 N, −78.59 W	56	2292	26
Guacamayas	2.21 N, −74.72 W	280	2145	25.5
Puerto Estrella	12.21 N, −71.18 W	69	100	30
Providencia	13.35 N, −81.36 W	72	2108	27.5

2.2. Population

The population density of these localities is very low, classified as populated centers according to the classification of the National Administrative Department of Statistics (DANE) [46]. These communities have the particularity that they belong to rural areas with accessibility problems and they lack access

to the electricity networks belonging to the National Interconnected System (NIS). Table 2 shows the number of households in each locality.

Table 2. Number of households for each location.

Department	Location	Number of Households
Chocó	Titumate	138
Amazon	Tarapacá	205
Nariño	Santa Rosa	173
Guaviare	Guacamayas	205
Guajira	Puerto Estrella	20
San Andres	Providence	1

2.3. Energy Demand and Current Generation Sources

Most of the energy demand of these communities corresponds to lighting, small appliances and refrigeration equipment. The demand for energy during daylight hours is low because the main activities in these communities are agriculture and fishing, which naturally take place outside of the home. For the preparation of meals, mainly firewood is used, and in some cases liquid propane gas (LPG) [47]. Table 3 shows the current situation of energy demand and generation systems of the 6 locations. In the case of Providencia, the average consumption for an isolated house was selected, and in the case of Puerto Estrella, the consumption for 20 houses was considered, and wind generation was not considered because the wind turbines currently installed were not in service [48]. Figure 2 shows 2 of the systems considered in this work; they are currently operating as hybrid systems in Titumate and Puerto Estrella.

Table 3. Current status of the power generation systems [49].

Location	Average Electricity Consumption (kWh/Day)	Power Factor	Generation Source	Installed Capacity (kW)	Average Daily Electricity Service (h)
Titumate	245	0.92	Diesel/PV	250	6.2
Tarapacá	890	0.93	Diesel	280	10.3
Santa Rosa	105	0.97	Diesel	175	1.5
Guacamayas	394	0.89	Diesel/SHP	150	20.2
Puerto Estrella ¹	52	0.90	Diesel/PV/Batteries	425	7.3
Providence ²	6	0.95	Diesel	4300	24

¹ Average electricity for 20 households. ² Average electricity for 1 household.



Figure 2. Current status of microgrids: (a) Titumate, and (b) Puerto Estrella.

The annual profiles of the daily demand for the 6 locations were prepared using data provided by the national monitoring center of the Institute of Planning and Promotion of Energetic Solutions (IPSE) in the Non Interconnected Zones [50]. Figures 3 and 4 show the average daily demand curves for one year, as well as the daily demand profile for the 6 locations. It is important to note that most of the

energy demand is produced at night, except in the case of Providencia, where consumption is similar during all hours of the day. In some of the simulations, a modified demand curve was used applying demand-side management [51,52].

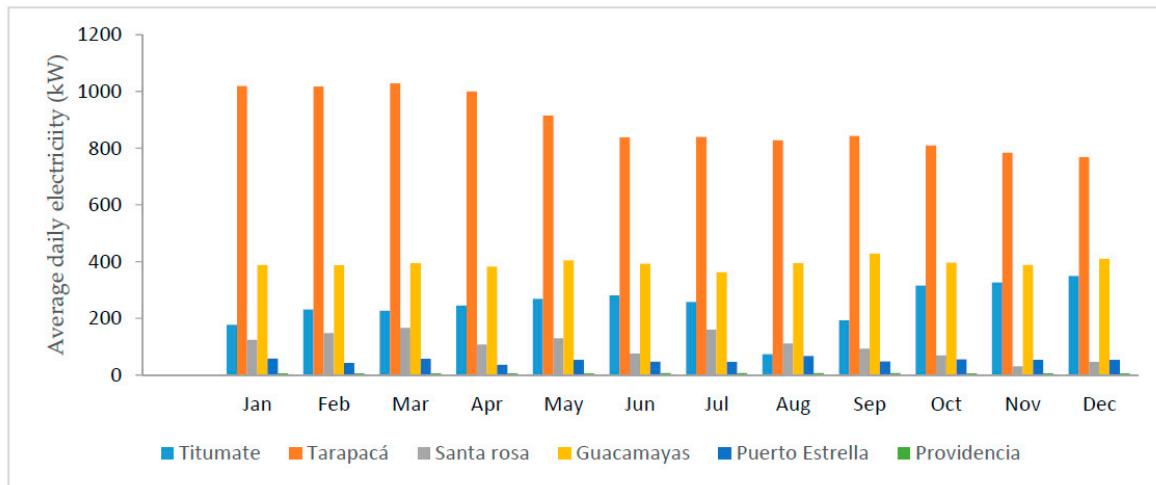


Figure 3. Average electricity consumption for each location.

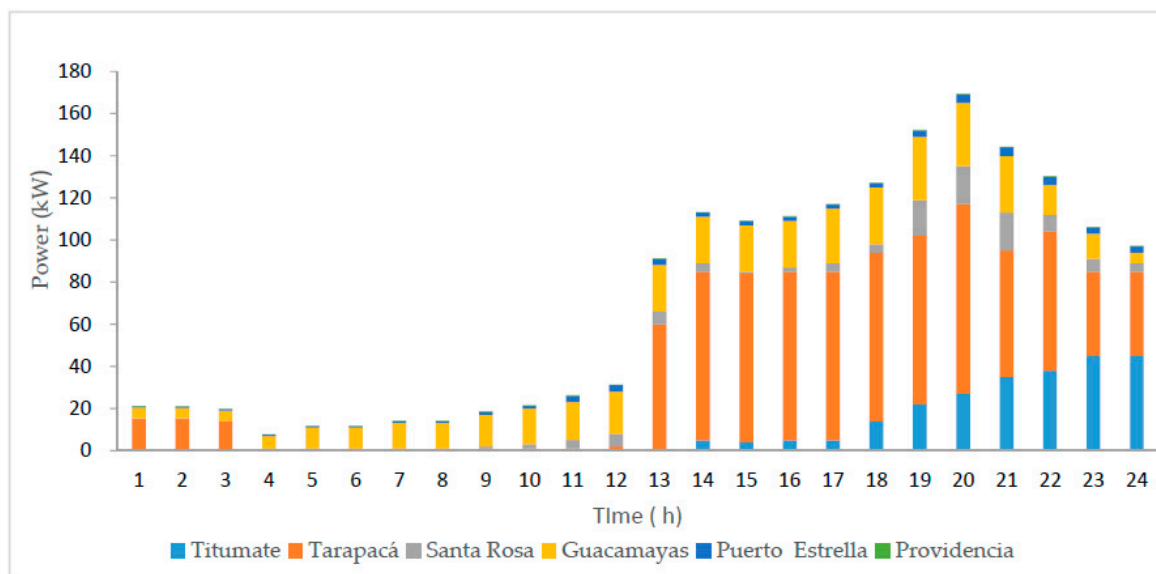


Figure 4. Typical daily load profile for each location.

2.4. Availability of Renewable Resources

The 6 locations selected for this study have average daily irradiation values of 4.5 kWh/m²/day, exceeding the global average value [53]. On the other hand, only in Puerto Estrella and Providencia is generation by wind resource viable, with both having an average wind speed greater than 8 m/s [54]. Figures 5 and 6 show the hourly irradiation and wind speeds over a whole year. Puerto Estrella is located in an area with the highest average wind speeds in South America, making wind power generation viable [55].



Figure 5. Global horizontal solar irradiation (in an average year) for the six locations [43].

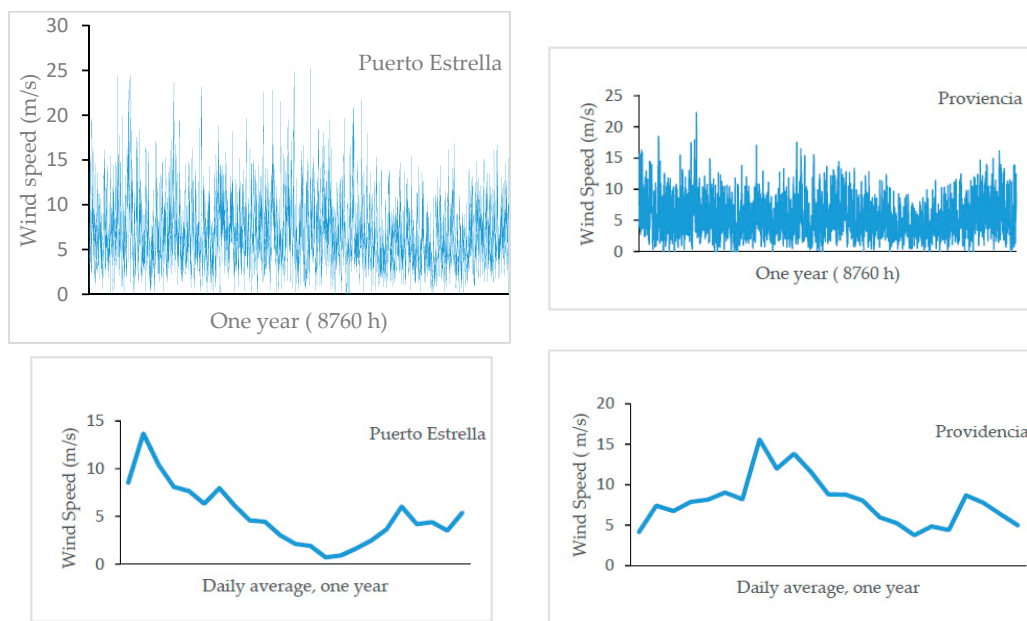


Figure 6. Wind speed (in an average year, hourly and daily values, for two locations) [43].

2.5. Parameters Used in the Optimization

Tables 4–9 show the parameters used in the optimization of the microgrids in the 6 locations. Commercial PV modules, wind turbines, batteries, diesel generators and inverter/chargers were selected. The minimum/maximum number of components in parallel shown in Table 9 were obtained with the pre-sizing calculations of iHOGA, these were needed to limit the search space in the optimization. In all cases, it has been considered that the lifespan of the system coincides with that of the photovoltaic generator (25 years). The models used to estimate battery lifetime were those of Schiffer et al. [56] for lead-acid, and the model by Wang et al. [57] for LiFePO₄/graphite lithium iron phosphate batteries. For the diesel generators and the wind and hydraulic turbines, the mathematical models are found in [58]. The calculations of life cycle emissions were based on previous work [59]. The inflation rate of Colombia was applied, which is currently 4% [60], and an interest rate of 7% was used. With these parameters, the iHOGA software was able to obtain the optimal solutions (generation of system configurations for each microgrid) using evolutionary algorithms [61].

Table 4. PV modules considered in the optimization.

Parameters	Data
Nominal Power	380 Wp
Short-circuit current (I _{sc})	10.11 A
Nominal operation cell temperature (NOCT)	47°
Temperature coefficient of power (α)	−0.37%/°C
Acquisition cost	220 €
Lifespan	25 years
Nominal voltage	24 V
Minimum/maximum number of modules in serial	2/13

Table 5. Wind turbines used in optimization.

Parameters	Model 1: WT600	Model 2: WT1500	Model 3: WT3000
Maximum power	660 W	1660 W	3471 W
Hub height	13 m	13 m	15 m
Acquisition cost	4255 €	4875 €	7555 €
Lifespan	15 years	15 years	15 years
O&M cost	85 €/year	98 €/year	150 €/year

Table 6. Batteries used in the optimization.

Parameters	Lead–Acid 1	Lead–Acid 2	Lead–Acid 3	Lithium 1	Lithium 2	Lithium 3
	OPZS	OPZS	OPZS	BYD B-Box 5.0	BYD B-Box 7.5	BYD B-Box 10
Capacity	162 Ah	546 Ah	3500 Ah	106.6 Ah	160 Ah	213 Ah
Acquisition cost	110 €	216 €	1457 €	3390 €	4700 €	6400 €
O&M cost (one cell)	1.1 €/year	2.16 €/year	14.57 €/year	20 €/year	20 €/year	40 €/year
Nominal voltage	2 V	2 V	2 V	48 V	48 V	48 V
Float life at 20 °C	15 years	15 years	15 years	10 years	10 years	10 years
Equivalent full cycles	1600	1600	1600	6000	6000	6000
SOC _{min}	20%	20%	20%	10%	10%	10%
Self-discharge	2%/month	2%/month	2%/month	2%/month	2%/month	2%/month
No. batteries in serial for 300 V DC voltage	150	150	150	7	7	7
No. batteries in serial for 48 V DC voltage	24	24	24	1	1	1

Table 7. Diesel generator considered in the optimization.

Parameters	Data				
Nominal Power	1.9 kVA	3 kVA	31 kVA	82 kVA	150 kVA
Minimal power	30%	30%	30%	30%	30%
Acquisition cost	800 €	1050 €	8850 €	14,000 €	18,000 €
Lifespan	10,000 h	10,000 h	20,000 h	30,000 h	30,000 h
O&M cost	0.14 €/h	0.17 €/h	0.35 €/h	0.42 €/h	0.52 €/h
Diesel fuel cost (including transportation)	0.8 €/l	0.8 €/l	0.8 €/l	0.8 €/l	0.8 €/l
Maximum number allowed in parallel	2	2	2	2	2

Table 8. Inverter/charger considered in the optimization.

Nominal Power	0.9 kVA	8 kVA	50 kVA	100 kVA	150 kVA
Efficiency	90%	90%	90%	90%	90%
Acquisition cost	800 €	3840 €	38,000 €	55,000 €	65,000 €
Lifespan	10 years	10 years	10 years	10 years	10 years

Table 9. Minimum/maximum number of components in parallel.

Location	DC Voltage	Batteries		PV	Diesel Generator	Wind Turbine
		Lead–Acid (OPZS)	Lithium (BYD)			
Titumate	300	1/3	1/36	0/31	1/1	-
Tarapacá	300	1/10	1/137	0/115	1/1	-
Santa Rosa	300	1/2	1/16	0/13	1/1	-
Guacamayas	300	1/5	1/63	0/52	1/1	-
Puerto Estrella	48	1/61	1/82	0/30	0/1	0/3
Providencia	48	1/1	1/6	0/5	1/1	1/1

In addition to the optimal configurations of the generation systems, iHOGA determined the most appropriate control strategy between the two that were considered. These two strategies are as follows:

- Load following (LF): In systems that include batteries and a diesel or gasoline generator, when the energy from renewable sources is not sufficient to satisfy the demand, the batteries are responsible for supplying this deficit. In the case that the batteries are not able to supply all the energy demanded, it is the generator that must provide it.
- Cycle charging (CC): Differs from the previous strategy in that in the event that the generator is required to operate, it will operate at its nominal power to satisfy the demand and, in addition, to charge the batteries only during that hour. There is a variant of this cycle charging strategy, called the setpoint strategy, in which the diesel generator continues to operate at its nominal power until the battery bank reaches a specific value of state of charge, which by default is 95%.

3. Simulation and Results

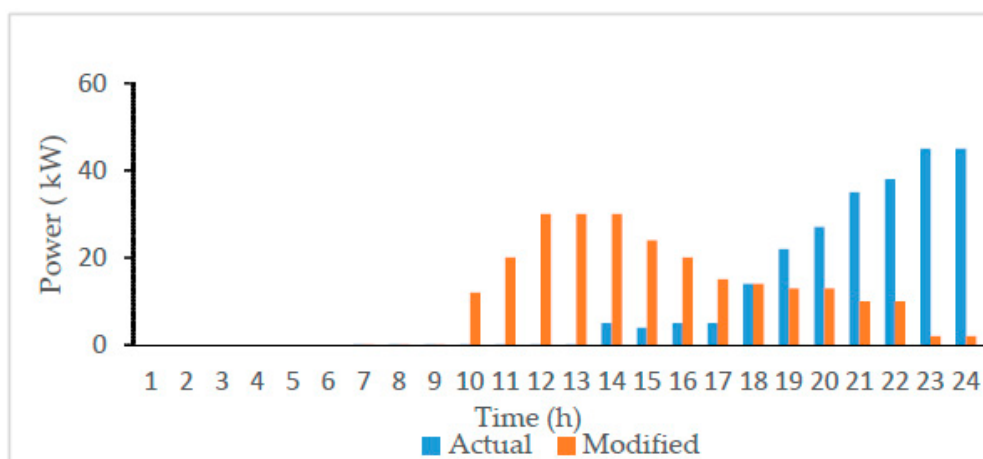
3.1. Simulation of the Current System

For the 6 locations, the current systems were simulated. In the six cases, taking into account that the generation of energy is carried out basically by diesel generators, high generation costs could be expected. However, a very low LCOE was obtained in the town of Guacamayas because in this case, in addition to diesel generation, there is a small hydroelectric plant. Table 10 shows a summary of the simulation results.

Table 10. Simulation of current status of power generation systems.

Location	Total Net Present Cost (NPC) (€)	Emissions kgCO ₂ /yr	Levelized Cost of Energy (LCOE) (€/kWh)
Titumate	2,963,765	414,571	1.32
Tarapacá	5,542,385	564,205	0.68
Santa Rosa	1,409,383	121,216	1.46
Guacamayas	106,506	9098	0.03
Puerto Estrella	361,235	3,3741	0.77
Providencia	156,015	9491	2.85

The most adequate isolated microgrid for the energy demand of the population of Titumate corresponded to a combination of PV-diesel-battery. Figure 7 shows the daily load curve for this location considering the current load and the modified load with demand-side management. The modified load was obtained by changing the timing of some of the consumptions, to coincide with hours of high irradiation. In many cases it is difficult to change the hours of electricity consumption, since it implies a change in the population's habits. However, in this work we want to see the implication of this change in the cost of the optimal system.

**Figure 7.** Daily load profile for Titumate.

The results are shown in Table 11, where a considerable reduction of the NPC is observed in systems with lead-acid batteries (52%) and in systems that use lithium batteries (56%). Similarly, the production cost of each kWh is reduced by 75–90% compared to the current system.

Table 11. Optimization for Titumate (average ambient temperature of 27 °C).

In All Cases: Diesel Generator Power = 31 kVA									
Load Profile ¹	Control Strategy	PV (Power kWp)	Battery Type	Battery Bank Capacity (kWh)	Inverter (kVA)	Lifetime (Years)	NPC (€)	Emissions (kgCO ₂ /yr)	LCOE (€/kWh)
Actual	LF	153	Lead-Acid	491	100	3.38	792,873	20,713	0.35
	CC	133.4	Lead-Acid	491.4	100	4.1	861,882	30,244	0.39
	LF	143.2	Lithium	288	100	6.08	830,833	7187	0.37
	CC	143.2	Lithium	288	100	6.08	830,833	7574	0.37
Modified	LF	138.32	Lead-Acid	163.8	50	4.3	357,241	8015	0.16
	CC	138.32	Lead-Acid	163.8	50	4.25	367,657	9783	0.16
	LF	138.2	Lithium	63.39	50	6.08	361,712	6761	0.16
	CC	138.32	Lithium	96	50	6.08	403,540	5058	0.18

¹ LF = load following, CC = cycle charging.

Figure 8 shows the results of the optimization for the first 4 days of the year in the town of Titumate considering the cases of the current load and of the modified load with the best NPCs. It is observed how the SOC of the battery bank increases when using the modified load profile, remaining practically above 60%. This can extend the useful life of the batteries and simultaneously reduce the operation time of the diesel generator.

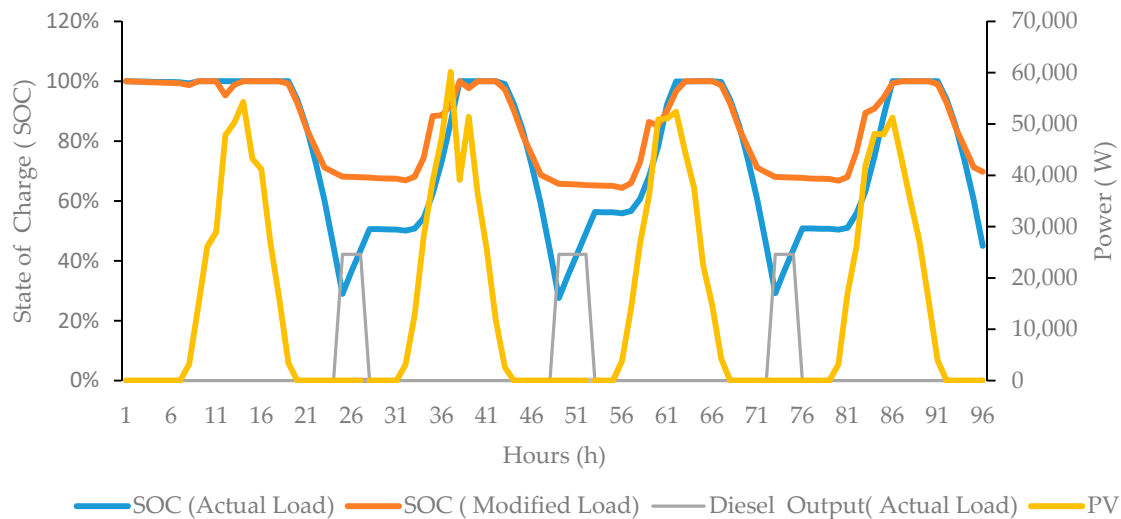


Figure 8. Comparative state of charge of the battery bank for 4 days (Titumate).

3.2. Tarapacá

Figure 9 and Table 12 show, respectively, the load profile and the results for the optimal system configuration. The lowest NPC value is obtained with the modified load profile (1,125,231 €), with an LCOE of 0.14 €/kWh and an emission level of 36,049 kgCO₂/year, with a useful life of batteries of 4.83 years.

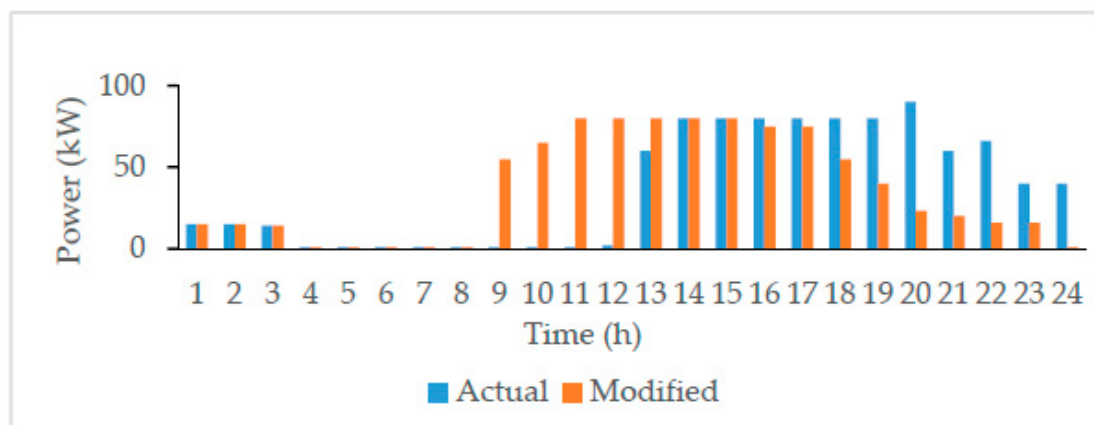


Figure 9. Daily load profile for Tarapacá.

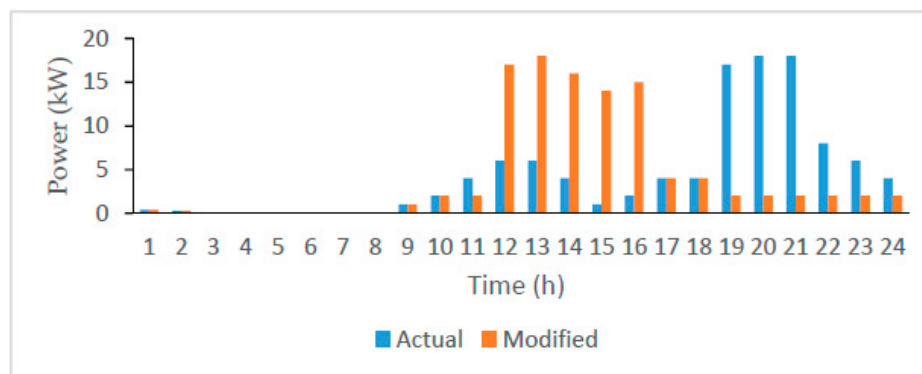
Table 12. Optimization for Tarapacá (average ambient temperature of 27 °C).

In All Cases: Diesel Generator Power = 31 kVA									
Load Profile ¹	Control Strategy ¹	PV (Power kWp)	Battery Type	Battery Bank Capacity (kWh)	Inverter (kVA)	Lifetime (Years)	NPC (€)	Emissions (kgCO ₂ /yr)	LCOE (€/kWh)
Actual	LF	582.92	Lead-Acid	819	150	3.76	1,365,502	35,401	0.17
	CC	582.92	Lead-Acid	840	150	3.87	1,365,502	35,401	0.16
	LF	518.7	Lithium	528	150	5.91	1,762,981	36,974	0.22
	CC	577.98	Lithium	576	150	5.91	1,821,317	26,183	0.22
Modified	LF	1007.7	Lead-Acid	327.6	100	4.83	1,125,662	36,084	0.14
	CC	1022.5	Lead-Acid	327.6	100	5	1,125,231	36,049	0.14
	LF	548.34	Lithium	240	100	5.91	1,136,681	24,931	0.14
	CC	568.1	Lithium	255.9	100	5.91	1,152,948	21,894	0.14

¹ LF = load following. CC = cycle charging.

3.3. Santa Rosa

Figure 10 and Table 13 show, respectively, the load profile and the optimization results for the Santa Rosa locality. The optimization of the hybrid PV-diesel system reduces the NPC by 41% using lead-acid batteries and the current load curve and 34% with lithium batteries if the consumption is concentrated during daylight hours. Similarly, the LCOE is reduced from 1.46 €/kWh (see Table 3) to 0.24 €/kWh when lithium batteries are used and consumption is displaced. These results present a great improvement with respect to the current situation.

**Figure 10.** Daily load profile for Santa Rosa.**Table 13.** Optimization for Santa Rosa (average ambient temperature of 26 °C).

In All Cases: Diesel Generator Power = 82 kVA									
Load Profile	Control Strategy ¹	PV (Power kWp)	Battery Type	Battery Bank Capacity (kWh)	Inverter (kVA)	Lifetime (Years)	NPC (€)	Emissions (kgCO ₂ /yr)	LCOE (€/kWh)
Actual	LF	59.28	Lead-Acid	163.8	50	4.18	361,764	10,900	0.38
	CC	59.28	Lead-Acid	327.6	50	4.87	394,403	5770	0.40
	LF	59.28	Lithium	96	50	6.48	345,806	2711	0.36
	CC	59.28	Lithium	96	50	6.48	345,086	2711	0.36
Modified	LF	59.28	Lead-Acid	48.6	50	4.28	232,190	3032	0.24
	CC	59.28	Lead-Acid	48.6	100	4.28	232,879	3107	0.24
	LF	59.28	Lithium	31.9	50	6.48	228,281	2168	0.24
	CC	59.28	Lithium	31.9	50	6.48	228,281	2168	0.24

¹ LF = load following. CC = cycle charging.

3.4. Guacamayas

For this location, the results are shown in Figure 11 and Table 14. The optimal system has an NPC of € 273,133 and an LCOE of € 0.08/kWh, corresponding to a PV-diesel-hydro system with lead-acid batteries and diesel-hydro with lithium batteries, under the same load profile. Having battery storage increases the reliability of the system, mainly against phenomena such as El Niño, in which the level of the rivers drops considerably [62].

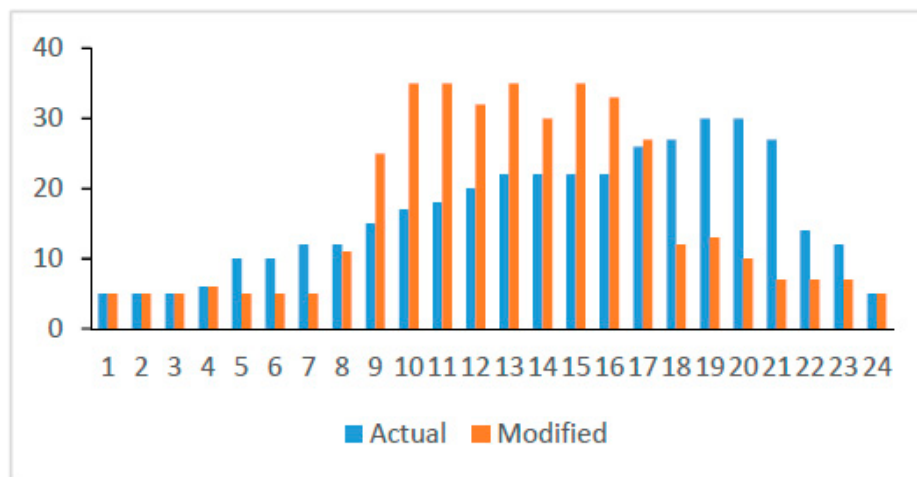


Figure 11. Daily load profile for Guacamayas.

Table 14. Optimization for Guacamayas (average ambient temperature of 25.5 °C).

In All Cases: Diesel Generator Power = 31 kVA										
Load Profile	Control Strategy ¹	Hydropower (kW)	PV (Power kWp)	Battery Type	Battery Bank Capacity (kWh)	Inverter (kVA)	Lifetime (Years)	NPC (€)	Emissions (kgCO ₂ /yr)	LCOE (€/kWh)
Actual	LF	20	34.58	Lead–Acid	252	50	9.89	301,270	3143	0.08
	CC	20	34.58	Lead–Acid	252	50	9.89	301,270	3143	0.08
	LF	50	-	Lithium	31.9	50	6.59	273,133	9364	0.08
	CC	50	-	Lithium	31.9	50	6.59	273,133	9364	0.08
Modified	LF	20	34.58	Lead–Acid	252	50	9.74	316,132	3797	0.09
	CC	20	34.58	Lead–Acid	252	50	9.74	316,132	3797	0.09
	LF	50	-	Lithium	31.9	50	6.59	273,133	9364	0.08
	CC	50	-	Lithium	144	50	6.59	273,133	9364	0.08

¹ LF = load following. CC = cycle charging.

It can be seen that the modified profile, with the lead-acid battery optimal system, cost is slightly higher than the actual profile optimal system cost. It happens because the battery lifetime is slightly lower in the modified case. The advanced lead-acid battery lifetime model used [56] considers many variables to determine the battery degradation, including, for each time step: current (charge and discharge rates), charge throughput, time between full charge, time at low SOC, partial cycling, temperature . . . A small difference in the load profile can imply low changes in these variables and therefore a small change in the battery lifetime estimation. In this case the modified load profile implies a slightly lower battery lifetime.

3.5. Puerto Estrella

Figure 12 shows the load curve, and Table 15 shows the optimization results. The high average wind speed and irradiation values confirm that the optimal hybrid system is PV-wind-diesel. The NPC decreases when considering the modified load profile, 45.3% when using lead-acid batteries and 32.8% when using lithium batteries. A shorter longevity of the useful life of the batteries is observed because the ambient temperature of the locality is 30°.

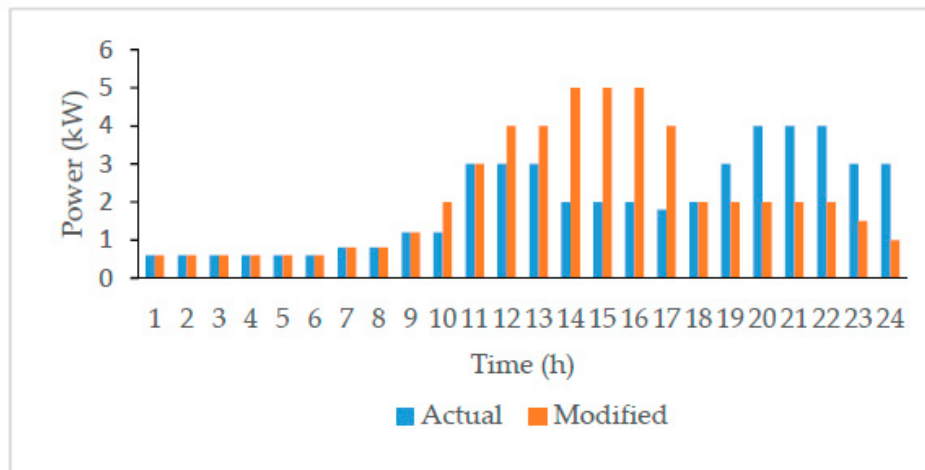


Figure 12. Daily load profile for Puerto Estrella.

Table 15. Optimization for Puerto Estrella (average ambient temperature of 30 °C).

In All Cases: Diesel Generator Power = 3 kVA										
Load Profile	Control Strategy ¹	PV (Power kWp)	Battery Type	Battery Bank Capacity (kWh)	Inverter (kVA)	Wind(kW)	Lifetime (Years)	NPC (€)	Emissions (kgCO ₂ /yr)	LCOE (€/kWh)
Actual	LF	15.96	Lead-Acid	100,8	8	3.47	5.92	110,319	2211	0.23
	CC	18.24	Lead-Acid	100,8	8	3.47	5.53	110,342	2156	0.23
	LF	36.48	Lithium	30,7	8	3.47	4.78	126,822	1708	0.27
	CC	43.32	Lithium	27,6	8	3.47	4.68	119,772	1867	0.25
Modified	LF	23.56	Lead-Acid	37,4	8	0	4.78	61,448	1253	0.13
	CC	23.56	Lead-Acid	26,2	8	0	4.69	52,437	1195	0.13
	LF	27.36	Lithium	17,9	8	3.47	4.55	85,176	1091	0.18
	CC	28.88	Lithium	12,7	8	3.47	4.7	84,349	1193	0.18

¹ LF = load following. CC = cycle charging.

Figure 13 shows the simulation for the first 4 days of the year for the town of Puerto Estrella. With the modified load, the output power of the wind turbine is better used in hours of low radiation, which leads to an increase in the SOC of the battery bank.

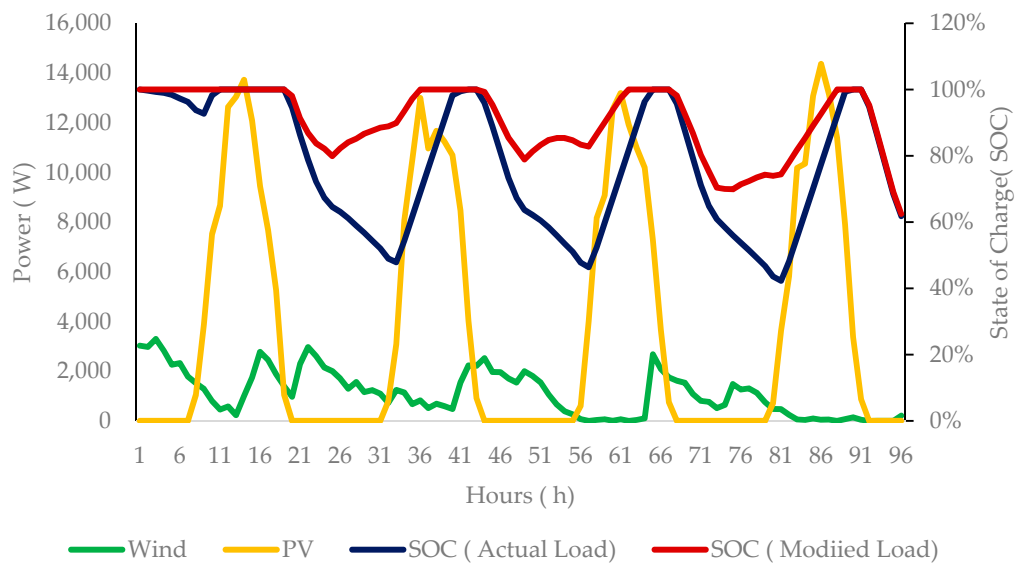


Figure 13. Comparative state of charge of the battery bank for 4 days (Puerto Estrella).

3.6. Providence

For this location, the optimal generation system is PV-wind-diesel, which has an LCOE up to 83% lower than the current system, based only on diesel generators. It also presents a considerable reduction in NPC and LCOE when the modified load profile is considered. Figure 14 and Table 16 show, respectively, the load profile and the optimization results for this location.

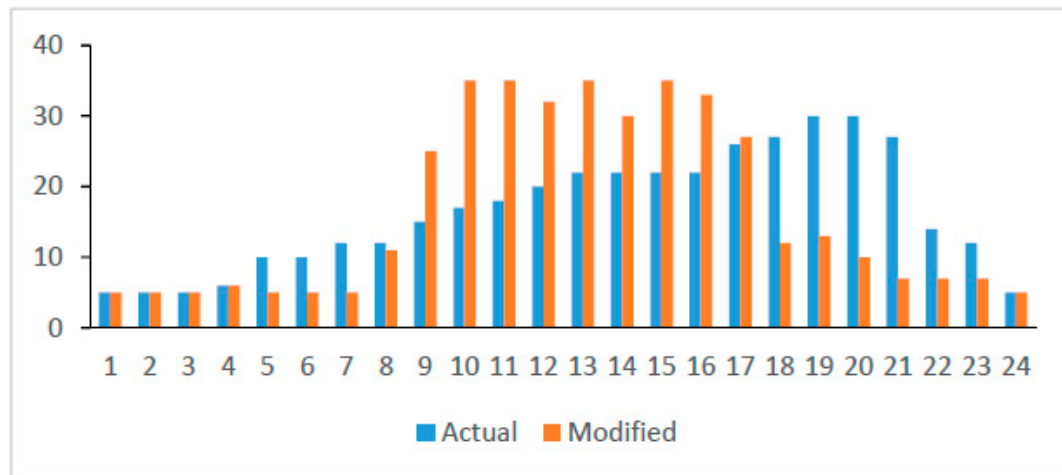


Figure 14. Daily load profile for Providencia.

Table 16. Optimization for Providencia (average ambient temperature of 27.5 °C).

In All Cases: Diesel Generator Power = 1.9 kVA										
Load Profile	Control Strategy ¹	PV (Power kWp)	Battery Type	Battery Bank Capacity (kWh)	Inverter (kVA)	Wind (kW)	Lifetime (Years)	NPC (€)	Emissions (kgCO ₂ /yr)	LCOE (€/kWh)
Actual	LF	3.04	Lead-Acid	7.7	0.9	0.66	4.55	31,447	285	0.57
	CC	3.04	Lead-Acid	7.7	0.9	0.66	4.51	31,626	304	0.58
	LF	2.28	Lithium	2.5	0.9	0.66	5.98	29,523	365	0.54
	CC	2.28	Lithium	5.1	0.9	0.66	5.98	30,878	195	0.56
Modified	LF	2.28	Lead-Acid	7.7	0.9	0.66	3.29	32,817	256	0.48
	CC	2.28	Lead-Acid	7.7	0.9	0.66	8.97	26,543	170	0.48
	LF	2.28	Lithium	2.5	0.9	0.66	5.98	26,696	169	0.48
	CC	2.28	Lithium	2.5	0.9	0.66	5.98	26,781	179	0.48

¹ LF = load following. CC = cycle charging.

4. Discussion

Figure 15 shows the different energy costs obtained with the current and modified load profiles for the 6 microgrids using lead-acid batteries and the load following strategy. A lower energy price is observed in 5 of the locations using a modified load profile. Figure 16 shows the NPCs of the 6 locations for optimization using lithium batteries and with the load following strategy, observing a decrease in costs in 5 of the 6 microgrids using modified load profiles. In three locations (Titumate, Santa Rosa and Puerto Estrella) the cost reduction is around 50% with the modified load profile.

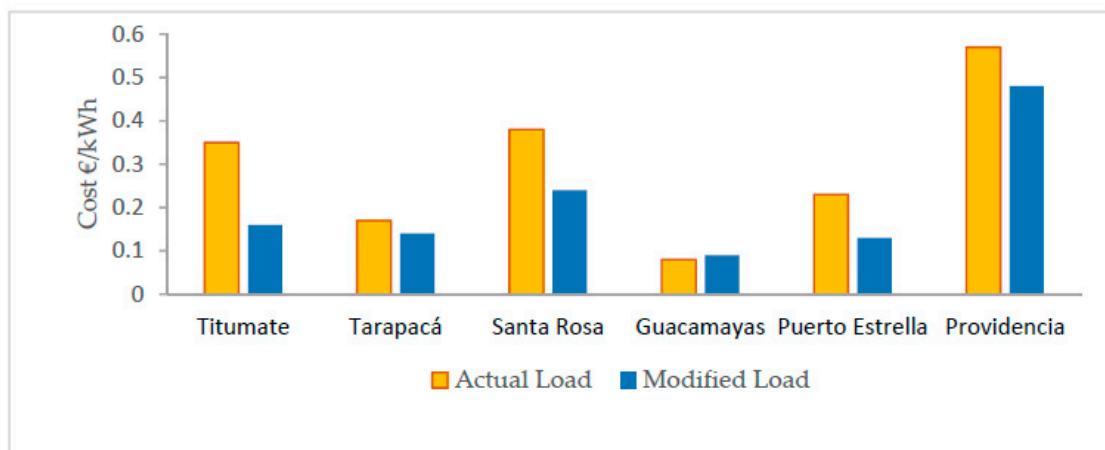


Figure 15. Cost of energy for different optimal systems.

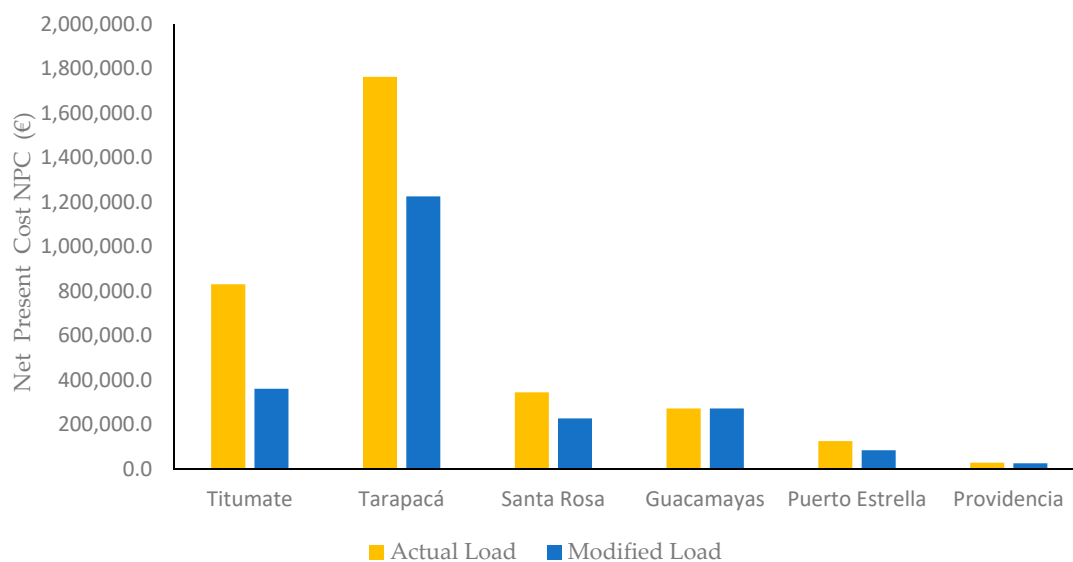


Figure 16. Total net present cost (NPC) for different optimal systems.

The level of emissions also decreases in 5 locations, as seen in Figure 17, where the results of the optimizations using lithium batteries with the cycle charging control strategy are presented.

The results obtained in the simulation model of the microgrid is performed during several years (usually 20–25 years), the performance is repeated considering all years the same, considering the load to be constant. This is a limitation, as load can change during the years.

Further research should be done for the accurate estimation of the diesel price, considering that diesel cost in the NIZ of Colombia is highly variable due to its drawbacks associated with the transportation in areas of difficult access. Further research could also include sensitivity analysis considering factors such as: load variation, the price of fuel, renewable energy subsidies, interest rates and acquisition cost of components of the system. In addition, the simulations were performed using mono-objective optimization (minimization of NPC), however future studies can address the use of multi-objective optimization including equivalent CO₂ emissions, human development index (HDI) and job creation. All of these features are available in the iHOGA software.

From a technical and economical point of view, this study opens the possibilities for exploring isolated hybrid microgrids in developing countries like Colombia, considering future technological improvements and cost reductions in batteries and PV modules.

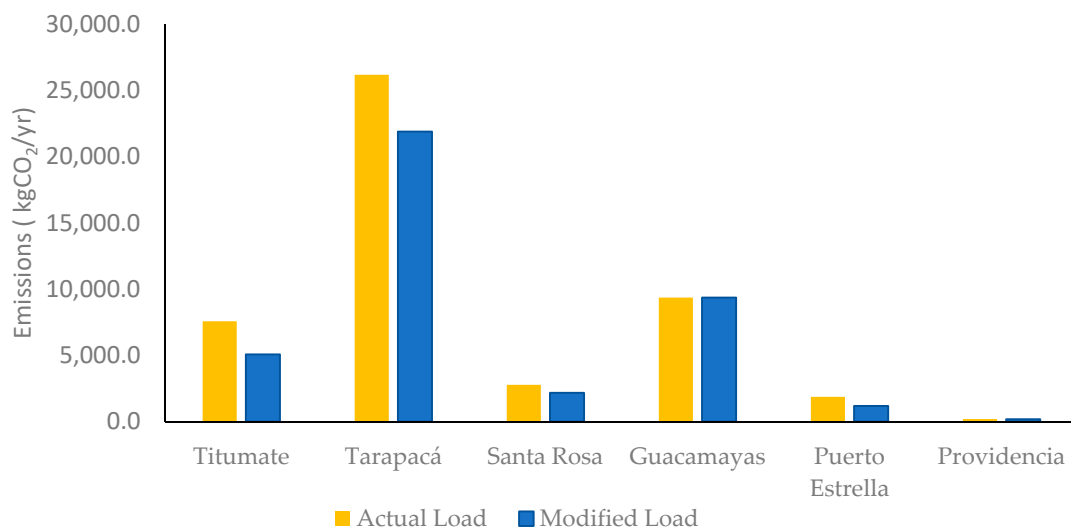


Figure 17. Total CO₂ emissions for different optimal systems.

5. Conclusions

This article presents a techno-economic study of isolated microgrids of the NIZ of Colombia. Optimal generation hybrid systems have been obtained for 6 locations, considering the possibility of using diesel generators, solar panels, hydraulic turbines, wind turbines and batteries. The results show that NPC values lower than the current ones (powered mainly with diesel) can be achieved in almost all scenarios thanks to the reduction in the number of operating hours of the diesel generators and the use of demand-side management. However, this demand-side management is limited, to a large extent, by the difficulty of changing the consumption habits of users. The results have also shown that lithium batteries can be a good alternative to lead-acid batteries, considering the useful life and costs of the system.

It is important to note that optimization strategies could include a demand side management program that can reduce operation cost. In addition, the development of microgrids with renewable energies in rural areas also will help to meet the challenge of energy supply of remote zones and will reduce the dependence on fossil fuels. The study findings provide a basis to explore optimization of microgrids with other technologies such as fuel cells and biomass. Nevertheless, the Colombian government will have to play a crucial role for the development of the isolated hybrid microgrids in remote areas.

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Nomenclature and Abbreviations

iHOGA	Improved Hybrid Optimization by Genetic Algorithms
HOMER	Hybrid Optimization Model for multiple Energy Resources
NPC	Net Present Cost
LCOE	Levelised Cost of Energy
NIS	National Interconnected System
NIZ	Non-Interconnected Zones
SHP	Small Hydroelectric Plant
SOC	State of Charge (%)
NOCT	Nominal operation cell temperature (°C)
IPSE	Institute of Planning and Promotion of Energetic Solutions

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