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Alternatives for the Optimization and Reduction in the Carbon Footprint in Island Electricity Systems (IESs)

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Abstract: The penetration of renewable energies in island electricity systems (IESs) poses a series of challenges, which include, among others, grid stability, the response to demand, and the security of the supply. Based on the current characteristics of electricity demand on the islands of the Canary Archipelago (Spain) and their electricity production systems, this study presents a series of alternative scenarios to reduce greenhouse gas (GHG) emissions and increase the penetration of renewable energies. The goal is to optimize combustion-based (nonrenewable) energy production and combine it with renewable-based production that meets the requirements of dynamic response, safety, scaling, and integration with nonrenewable systems in terms of efficiency and power. As verified in the research background, the combination of power producing equipment that is generally employed on the islands is not the best combination to reduce pollution. The aim of this work is to find other possible combinations with better results. A methodology is developed and followed to obtain the lowest GHG production and to determine the measures to be applied based on: (a) changing the fuel type by switching to natural gas in the equipment that allows it; (b) using optimal combinations of the least polluting energy production equipment; (c) integrating, to the extent that it is possible, the Chira-Soria pumped hydroelectric energy storage plant into the Gran Canaria electricity system. A series of alternative scenarios are generated with different operating conditions which show the possibility of increasing the renewable installed capacity in the Canary Islands by up to 36.78% (70% in Gran Canaria), with a 65.13% reduction in GHG emissions and a 71.45% reduction in fuel consumption. The results of this study contribute, through the different measures determined through our research, to the mitigation of GHG emissions.

Keywords: energy policy; Canary Islands; renewable energy; island electricity systems (IESs)

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1. Introduction

The transition to sustainable electricity generation and its challenges in island environments analyzed by [1,2], studying the reliability of total renewable electric systems under different scenarios, by [3], offering an approach between energy poverty and its correct energy planning, by [4], indicating the challenges facing the Canary Islands in terms of increasing the renewable energy penetration versus the security of the supply, or by [5,6], analyzing a literature review and the life cycle of renewable energy generation on islands, have highlighted the importance of decarbonization and a greater penetration of renewable energies, as well as the need for a broader vision regarding the management of energy resources and their corresponding technologies. The problems that arise when implementing decarbonization strategies are exacerbated in weakly interconnected island systems [6,7]. The island electricity systems (IESs) of the Canary Archipelago (Spain) face environmental, economic, and social sustainability challenges, as they rely heavily on imported fossil fuels for electricity generation [1,8], and aspects such as the optimization of the energy mix from an economic perspective has been analyzed by [8], but considering 100% renewable generation. While the cost of electricity and CO_2 emissions are high on the islands [9], single and multiaction initiatives can be considered that foster the deployment of renewable energy sources (RESs), energy storage systems (ESSs), demand-side management (DSM), and electric vehicles (EVs), and without considering changes to fuel types in the conventional systems by internal combustion engines (ICEs), already installed or with parity only with photovoltaic (PV) and wind energy (WE) [10,11]. This application of renewable fuels in diesel engines for power generation has been tested by [12], with reductions of up to 50%; [13] applied Syngas to internal combustion engines from biomass with equally satisfactory results. The difficulties involved in increasing the penetration of renewable energies on the islands are gradually being overcome thanks to hybrid power plants (PV + WE + ICE) with applicability in island systems, as demonstrated by [14], and, as an alternative, the comparative of different electricity storage technologies in insular grids [15]. Environmental awareness has grown, leading to the mobilization of both island governments (through, for example, the promotion of wind and solar PV farms) and the end-user (through, for example, solar panel installation or the use of electric vehicles) [16]. In the Canary Islands, this positive aspect contrasts with other realities that are less beneficial for the environment, including the aging power generation equipment, which, in many cases, exceeds 30 years, and the type of fuel that is used, mainly fuel oil and diesel [17–20] with no natural gas. The general goal in an IES is to find a balance between the types of combustion energy production technologies, fuels, and renewables that lead to an optimal energy production [9,21,22]. In other words, the aim is to meet the demand and ensure the security of the supply while at the same time: (a) obtaining the highest possible renewable-sourced energy production through the optimization and expansion of all renewable options, and (b) obtaining the lowest possible energy production through combustion technologies, with the most efficient and least polluting fuel possible, as well as the lowest possible greenhouse gas (GHG) emissions and tons of fuel consumed [4]. With the above in mind, in this study, several fully realistic alternative renewable penetration scenarios are established, the fossil fuel used in the different technologies are modified when possible, and the use of different technologies is considered [18–20]. For the purposes of the study, energy data up to 2020 were available. However, as the primary and final energy consumption values of 3,541,855 toe and 2,504,547 toe, respectively, were 27.49% and 31.85% lower than in 2019 due to the COVID-19 pandemic, it was decided to refer only to data at a general level until 2019 [23].

When considering a methodology for the analysis of energy generation systems both at the continental level [24–26] and the island level, [9,22,27,28], and particularly in the Canary Islands [1,3,4], several authors have opted for the Hybrid Optimization of Multiple Energy Resources (HOMER) model. This software, which was developed by the National Renewable Energy Laboratory (NREL) [1,8], estimates the best energy system, economic investment, and levelized cost of energy (LCE), among others, and contemplates different energy sources. For the different alternatives or scenarios in island environments, it is necessary to consider the existing systems responsible for nonrenewable sources, as well as the use of alternative fuels (both fossil and renewable) and their impact on the level of emissions. In addition, the fact that the generation systems already in use must be compatible with renewable generation systems to meet the existing energy demand has to be considered. Furthermore, the integration of new technologies, such as the Chira-Soria pumped hydroelectric storage (PHES) plant in Gran Canaria, needs to be considered. In consequence, a methodological alternative is required that includes all the above considerations. The objective and scope of this work is to review and improve IESs through the integration of renewable (including PHES) and nonrenewable sources for GHG emissions reduction. The challenge is to bring together, in a single study, the changes required in IESs to reduce the carbon footprint with the goal of facilitating the study and export of the changes required to other IESs with the same dynamics. For this purpose, the Canary Islands are used as a case study.

2. Energy Situation in the Canary Islands in 2019

2.1. Energy and Environmental Values

The share of the different energy sources and technologies in the coverage of electricity demand in terms of gross values in the Canary Islands in 2019, by island and technology, is shown in Table 1. Renewable penetration was just 15.9%.

Table 1. Energy produced (MWh). Source: Canary Islands Energy Yearbook 2019.

Technology	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro	Total
Steam turbine	1,233,316	1,146,979						2,380,295
Diesel engine	1,657,552	192,784	813,663	552,146	251,332	76,696	20,738	2,072,911
Gas turbine	31,758	105,645	12,791	841,585	603			235,382
Combined cycle	1,597,427	1,569,446						3,166,873
Renewable	553,880	696,096	79,623	80,108	29,081	154	41,692	1,480,634
Total	3,581,933	3,710,950	906,077	716,839	281,016	76,850	62,430	9,336,095

In 2019, the Canary Islands had an installed capacity of 3320.03 MW, of which 623.67 MW were from renewable sources and 2696.36 MW were nonrenewable. The installed capacity of each island is shown in Table 2.

Table 2. Installed capacity (MW). Source: Canary Islands Energy Yearbook 2019.

Technology	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro	Total
Steam turbine	280.00	240.00						520.00
Diesel engine	84.00	84.00	166.76	107.92	82.84	21.17	14.91	564.60
Gas turbine	173.45	265.70	62.50	79.10	22.50			603.25
Combined cycle	461.73	456.80						918.53
Refinery-Cogen.	24.88	65.10						89.98
Renewable	199.92	314.54	32.41	41.42	12.18	0.37		623.67
Total	1223.98	1426.14	264.67	228.44	117.52	21.54	22.83	3320.03

Fuel consumption for electricity generation in the Canary Islands in 2019 was 1,702,166.0 t (57.6% fuel oil, 41.2% gas oil, and 1.2% diesel oil), of which, by technology, steam turbines consumed 595,170 t of fuel oil and 515 t of gas oil, diesel engines consumed 384,935 t of fuel oil, 18,826 t of gas oil, and 21,259 t of diesel oil, gas turbine generators consumed 88,944 t of gas oil, and combined-cycle units (combined cycles with gas and steam turbines) consumed 592,517 t of gas oil as a substitute fuel, as the design fuel for these units was natural gas. The fuel consumption and GHG emissions for 2019 are shown in Table 3 and Figures 1 and 2.

Table 3. Fuel consumption (t) in the thermal power plants of the Canary Islands and greenhouse gas emissions (tCO_{2eq}) per fuel source used. Source: Canary Islands Energy Yearbook 2019.

Technology	Fuel Consumption (t)				Greenhouse Gas Emissions (tCO_{2eq})			
	Fuel Oil	Gas Oil	Diesel Oil	Total	Fuel Oil	Gas Oil	Diesel Oil	Total
Steam turbine	595,170	515	-	595,685	1,905,884	1652		1,907,536
Diesel engine	384,935	18,826	21,259	425,020	1,232,665	60,423	67,103	1,360,191
Gas turbine	-	88,944	-	88,944	-	285,467		285,467
Combined cycle	-	592,517	-	592,517	-	1,901,715		1,901,715
Total	980,105	700,802	21,759	1,702,166	3,138,549	2,249,257	67,103	5,454,909

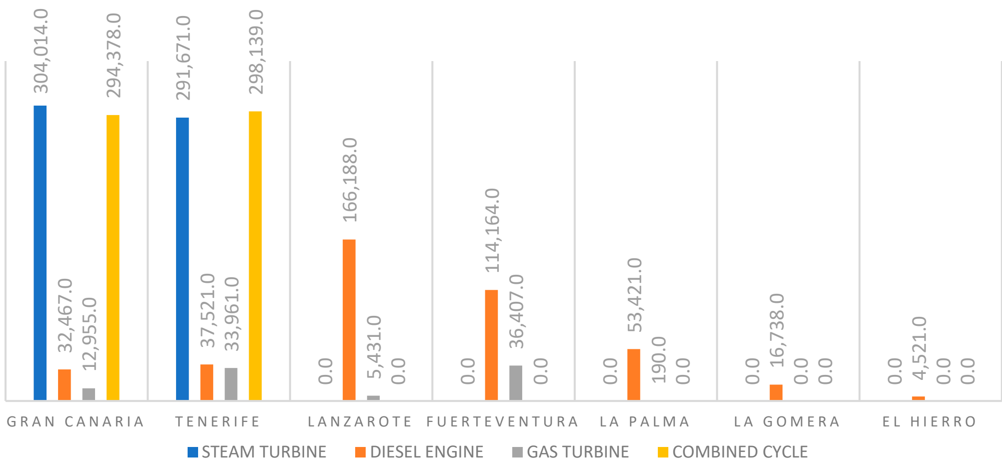

Figure 1. Fuel consumption (t) by island and technology in the Canary Islands. Source: Canary Islands Energy Yearbook 2019.

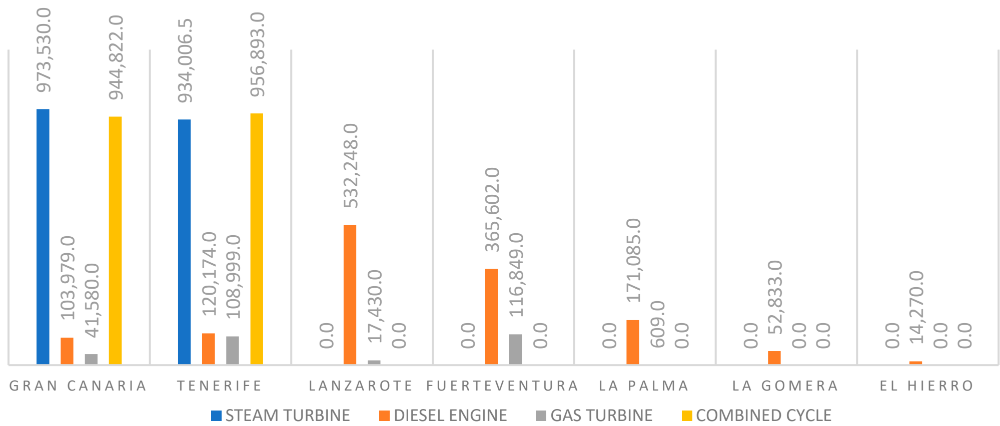

Figure 2. Greenhouse gas emissions by island and technology in the Canary Islands (tCO_{2eq}). Source: Canary Islands Energy Yearbook 2019.

GHG emissions for 2019 in all the Canary Islands amounted to 5,454,911 tCO_{2eq}. Of these, 99.7% were CO_2, 0.1% were CH_4, and 0.2% were NO_2 [29,30]. The emission factor (tCO_{2eq}/MWh) calculated based on the energy produced shows the results differentiated by islands and by power equipment. It is worth noting that the high emission factor for gas turbines and the drop in this factor on El Hierro island due to renewable energies. It can be seen from Figures 1 and 2 that the largest consumers of fuel (and therefore the largest GHG emitters) were the combined cycle and the steam turbine, with the latter being the most harmful because its emission factor was much higher (Figure 3).

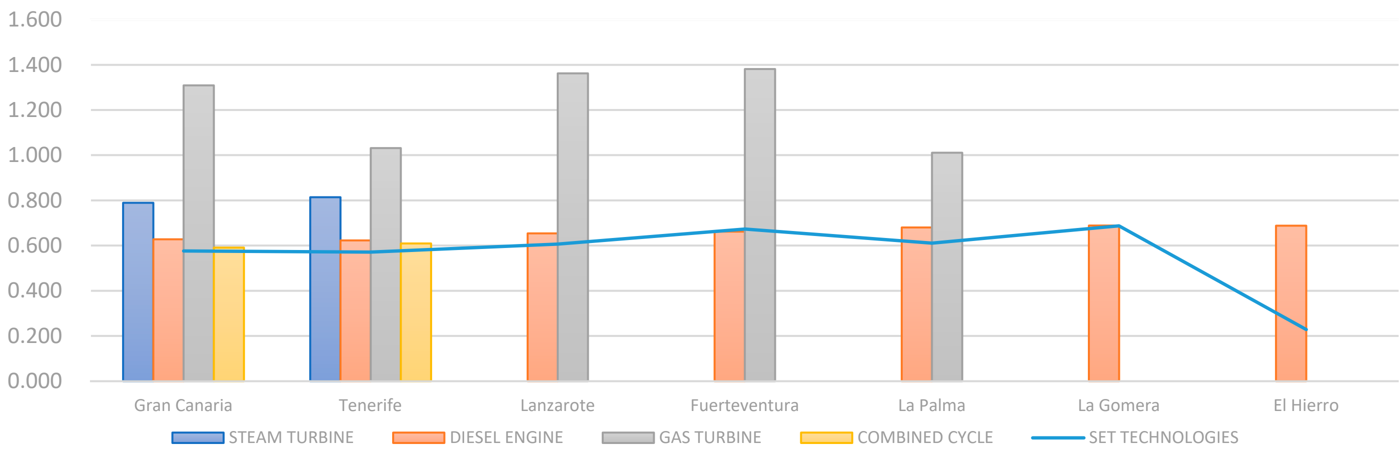

Figure 3. Emission factor by island and technology in the Canary Islands (tCO_{2eq}/kWh). Source: Canary Islands Energy Yearbook 2019.

The lowest emission factors were those of combined-cycle plants (0.601 tCO_{2eq}/MWh) and diesel engines (0.656 tCO_{2eq}/MWh). An overall emission factor for the Canary Islands, including renewable production, is estimated at 0.584 tCO_{2eq}/MWh.

The demand peaks in each island in 2019 are shown in Table 4:

Table 4. Demand peaks. Source: Canary Islands Energy Yearbook 2019.

Island	Date	Hour	MW
Gran Canaria	2 October	20:58	537.00
Tenerife	2 October	20:21	576.00
Lanzarote	31 December	19:06	139.00
Fuerteventura	17 August	20:53	113.00
La Palma	19 August	21:36	43.00
La Gomera	17 August	21:59	12.10
El Hierro	20 August	21:27	8.10

In Gran Canaria, the highest demand was on 2 October 2019 (20:58 h), with emissions of 0.631 tCO_{2eq}/MWh and a peak of 537.0 MW (Figure 4). The demand curve was very similar to the rest of the days, except for small fluctuations. The different groups are programmed to satisfy this demand curve. It is therefore necessary to carry out a good programming for the correct operation of the network. It is also worth highlighting the difficulty of predicting the curve correctly and ensuring the validity of the data obtained to provide the necessary power, particularly in systems based on renewable energies (wind and solar).

Figure 4 shows the combination of thermal and renewable generation in Gran Canaria on the day of the highest demand in 2019, and Figure 5 shows the technology employed.

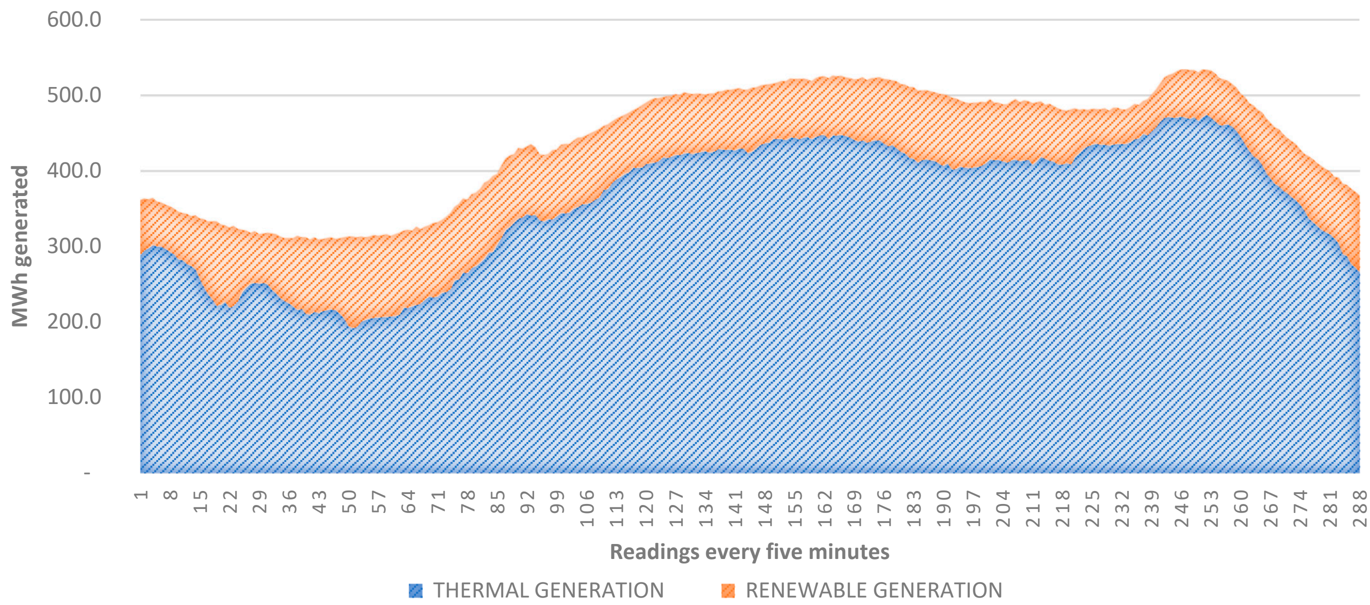

Figure 4. Demand curve in Gran Canaria on the day of highest demand in 2019 showing thermal and renewable generation. Source: Canary Islands Energy Yearbook 2019.

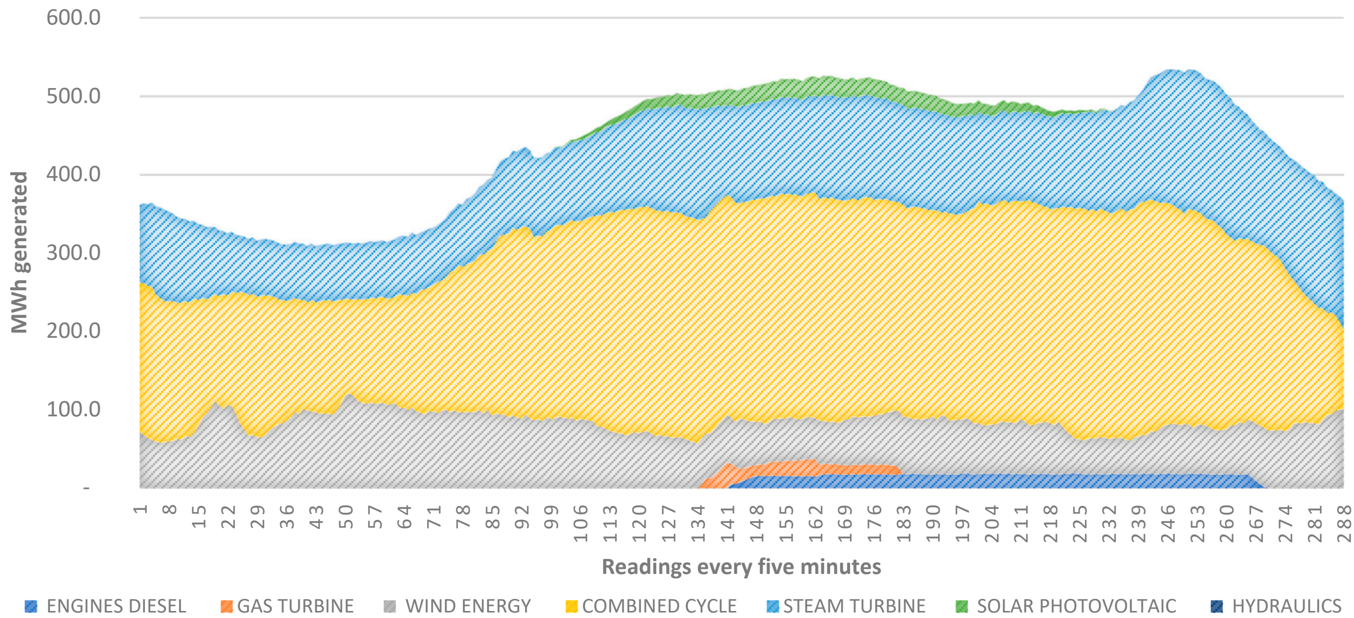

Figure 5. Demand curve in Gran Canaria on the day of the highest demand in 2019 showing the different generation technologies. Source: Canary Islands Energy Yearbook 2019.

The steam turbine and combined-cycle groups contributed 33.35% and 51.28%, respectively, of the electricity to the grid, with the contribution of the diesel and gas turbine groups and renewables (wind) at 11.83%. The combination of power producing equipment shown in Figure 5, which shows the energy generated by the different technologies on the day of maximum demand (kWh) in Gran Canaria in 2019, is not the best combination to reduce the emissions of GHGs, suggesting the need for other possible combinations which offer better results.

2.2. Penetration Values of Renewable Energies in the Canary Islands

The data collection starting point was 2004, when all the islands combined had an installed capacity of 138.22 MW and Gran Canaria on its own had a capacity of 75.85 MW. In the 2004–2019 time-horizon average, annual growth was 8%, with two years standing out in which there were very significant increases in the installed capacity compared to the previous years (2008 and 2018). In the case of Gran Canaria, the technology that drove the development of the sector was wind power generation. Nonetheless, the penetration of renewable energies was slow during the years studied. As previously mentioned, the penetration of renewables in 2019 was just 15.9%.

3. Methodology

The methodology followed (Figure 6) to obtain the possible operating hypotheses for the island energy generation process was based on the following steps:

1. The study of the situation and behavior of energy production on the island and its demand.
2. The study of the fossil fuel-based energy generation equipment on the islands, considering the type of technology employed, the level of consumption, the fuel type and its lower calorific value (LCV), the energy efficiency of each piece of equipment, the influence of its age, the hours of regular use, the maximum hours of use estimated by the manufacturer for its age, the emission factors, etc.
3. The study of renewable-based energy generation equipment on the islands, considering the type of technology and the normal hours of use. The estimation of historical mean use and generation, considering the intermittent nature of renewable energies and the verification of their complete integration in the energy system.
4. The study of the fuel type and the suitability for use.
    (a) LCV of the fuel used.
    (b) GHG production.
    (c) Impact on the efficiency of the equipment according to manufacturers.
    (d) Price.
    (e) Feasibility of incorporation into the system.
    (f) Feasibility of adaptability of the equipment.
5. The study of the PHES project in Gran Canaria, its integration options, and repercussions for the energy system.
6. The selection of suitable combinations for our objective, ranging from the least to most ambitious, and seeking in all cases the most realistic combinations of generation equipment.
7. The calculation of the strategic data: GHG emissions, fuel consumption, and the optimized combination of equipment.
8. The presentation of results.

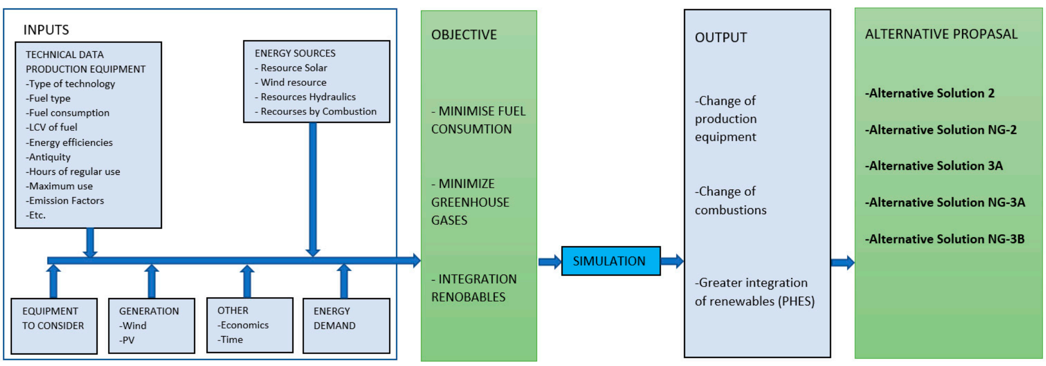

Figure 6. Methodology.

4. Nonrenewable Production System Alternatives Depending on the Expansion of Renewable Penetration and Optimization of Existing Equipment

This section proposes a series of combinations of measures to be adopted that will lead to a reduction in GHG emissions, hereinafter referred to as scenarios or alternatives. These measures are based on:

(a) Changes to the fuel type—switching to the use of natural gas in the equipment that allows it. The convenience of using natural gas is twofold: less fuel needs to be used to generate the same amount of electricity, because its LCV is higher than other fuels, and less CO_2 is generated per MWh.
(b) Using combinations with the least polluting generation equipment.
(c) Optimizing the integration of the Chira-Soria PHES plant.

Other measures, such as the renewal of production equipment, questioning the validity of the current performance and its optimization, etc., have not been considered in this study.

4.1. Starting Values in 2019

It is assumed that, in 2019, as indicated above, we have the following rates in the Canary Islands: 5,454,911.00 tCO_{2eq} of total GHG emissions, an emission factor of 0.584 tCO_{2eq}/MWh, and a fuel consumption from fossil fuel sources of 1,702,166.00 t.

4.2. Planning of Alternatives for Equipment Operation while Retaining the Current Type of Fuel

4.2.1. Alternative 1 (Table 5): Rearrangement of Power Plants Based on Historical Maximum Annual Production Values—Renewable Penetration of 15.9%.

In this alternative, the least polluting equipment in the different production centers of the islands is considered, taking it to a production ceiling marked by the maximum annual historical production. The historical annual maximum values of combined-cycle plants (3,418,748.0 MWh) and diesel engines (2,390,736.2 MWh), which are the least polluting, are considered, and the rest of the equipment is reordered proportionally. A renewable penetration of 15.9% (1,480,634.0 MWh) is maintained. This results in an overall emission factor of 0.563 tCO_{2eq}/MWh.

Table 5. Alternative 1.

Technology	Energy Produced (MWh)	GHG Emissions (tCO_{2eq})	Emission Factor (tCO_{2eq}/MWh)	Fuel Consumption Estimation (t)
Steam turbine	2,045,977.0	1,641,421.5	0.802	512,582.8
Diesel engine	2,390,736.2	1,562,556.1	0.654	488,206.3
Combined cycle	3,418,748.0	2,052,294.4	0.600	639,433.0
Renewable (15.9%)	1,480,634.0	-	-	-
Total	9,336,095.2	5,256,271.9	0.563	1,640,222.1

4.2.2. Alternative 2 (Table 6): Rearrangement of Power Plants Working Exclusively with the Least Polluting Equipment—Renewable Penetration of 15.9%

In this alternative, the least polluting equipment in the different production centers of the islands is considered, but the work is done exclusively by this equipment, while the rest of the equipment is ignored. This would mean producing 5,428,740.4 MWh in the combined-cycle plants and 2,426,720.8 MWh in the diesel engines, which are the least polluting, with the rest of the equipment remaining in disuse or as a reserve. A renewable penetration of 15.9% (1,480,634.0 MWh) is maintained. This gives an overall emission factor of 0.519 tCO_{2eq}/MWh.

Table 6. Alternative 2.

Technology	Energy Produced (MWh)	GHG Emissions (tCO_{2eq})	Emission Factor (tCO_{2eq}/MWh)	Fuel Consumption Estimation (t)
Diesel engine	2,426,720.8	1,585,013.5	0.653	495,218.0
Combined cycle	5,428,740.4	3,259,874.3	0.600	1,015,678.5
Renewable (15.9%)	1,480,634.0	-	-	-
Total	9,336,095.2	4,844,887.8	0.519	1,510,896.4

4.2.3. Alternative 3A (Table 7): Rearrangement of Power Plants Working Exclusively with the Least Polluting Equipment and Incorporation of the PHES Chira-Soria Project—Renewable Penetration of 29.1%

As in Alternative 2, in this alternative, the least polluting equipment in the different production centers of the islands is considered, with the work done exclusively by this equipment and with the rest of the equipment ignored. However, in addition, the PHES Chira-Soria plant is incorporated. As a result, the overall renewable penetration in Gran Canaria is expected to be between 51% and 70%. Based on the lower value of 51%, the overall renewable penetration in the Canary Islands rises to 29.1% (2,717,720.5 MWh). A total of 4,307,822.1 MWh is produced by combined-cycle plants and 2,310,552.60 MWh by diesel engines, which are the least polluting equipment, with the rest of the equipment remaining in disuse or as a reserve. The overall emission factor is 0.440 tCO_{2eq}/MWh.

Table 7. Alternative 3A.

Technology	Energy Produced (MWh)	GHG Emissions (tCO_{2eq})	Emission Factor (tCO_{2eq}/MWh)	Fuel Consumption Estimation (t)
Diesel engine	2,310,552.6	1,512,050.4	0.654	472,435.9
Combined cycle	4,307,822.1	2,596,890.5	0.603	809,112.7
Renewable (29.1%)	2,717,720.5	-	-	-
Total	9,336,095.2	4,108,940.9	0.440	1,281,548.5

4.2.4. Alternative 3B (Table 8): Rearrangement of Power Plants Working Exclusively with the Least Polluting Equipment and Incorporation of the PHES Chira-Soria Project—Renewable penetration of 36.8%

As in Alternative 3A, but assuming the higher renewable penetration value of 70% after the incorporation of the PHES Chira-Soria plant. In this case, the overall renewable penetration rises to 36.8% (3,434,107.1 MWh). Combined-cycle plants produce 3,658,707.6 MWh and diesel engines produce 2,243,280.5 MWh, which are the least polluting equipment, with the rest remaining in disuse or as a reserve. The overall emission factor is 0.394 tCO_{2eq}/MWh.

Table 8. Alternative 3B.

Technology	Energy Produced (MWh)	GHG Emissions (tCO_{2eq})	Emission Factor (tCO_{2eq}/MWh)	Fuel Consumption Estimation (t)
Diesel engine	2,243,280.5	1,469,798.2	0.655	459,242.9
Combined cycle	3,658,707.6	2,212,962.0	0.605	689,492.2
Renewable (36.8%)	3,434,107.1	-	-	-
Total	9,336,095.2	3,682,760.2	0.394	1,148,735.1

4.3. Consideration of Hypothetical Operation of Equipment by Changing the Current Type of Fuel

Variations in the alternatives are made by modifying the type of fuel. As far as possible, and as far as the equipment allows, the fuel type is changed to natural gas, with which CO_2 emissions are 40–50% lower than with coal and 25–30% lower than with fuel oil [13]. As for NO_x, the nature of the gas (combustion takes place in the gas phase) allows for a more perfect mixture with the combustion air, leading to a complete and more efficient combustion, with less excess air. Methane, which is the main component of natural gas, is a stronger GHG contributor than CO_2, although methane molecules have a shorter lifetime in the atmosphere than CO_2. According to independent studies, the direct losses of natural gas during extraction, transport, and distribution worldwide have been estimated at 1% of the total gas transported. The emission of CO_2 in the combustion of natural gas is 58 $kgCO_2$/GJ, which is considerably lower than with fuel oil or gas oil (79 $kgCO_2$/GJ and 70 $kgCO_2$/GJ, respectively). On the other hand, the calorific value of natural gas is higher than that of other fuels normally used in Canary Island plants.

This makes it doubly convenient to use natural gas, as less fuel needs to be burnt to produce the same electricity and less CO_2 is generated per MWh electricity produced (table 9). Table 10 shows the fuel distribution for the current situation (the baseline situation) in which all equipment, except diesel engines, are switched to natural gas. The distribution of emissions (tCO_{2eq}) expected for this new scenario is shown in Table 11.

Table 9. Calorific power.

Fuel Type	Higher Calorific Value (HCV) (kcal/kg)	Lower Calorific Value (LCV) (kcal/kg)
Fuel	10,430.00	9850.00
Diesel	9265.00	8713.00
Diesel oil	10,790.00	10,140.00
Natural gas	12,474.00	11,259.00

Table 10. Estimation of fuel consumption (t) in the thermal power plants of the Canary Islands when switching, where possible, to natural gas.

Technology	Fuel Consumption (t)				
	Natural Gas	Fuel	Oil	Diesel Oil	Total
Steam turbine	521,086.4	-	-	-	521,086.4
Diesel engine	-	384,935.0	18,826.0	21,259.0	425,020.0
Gas turbine	68,831.1	-	-	-	68,831.1
Combined cycle	458,531.0	-	-	-	458,531.0
Total	1,048,448.5	384,935.0	18,826.0	21,759.0	1,473,468.5

Table 11. Estimation of total GHG emissions (tCO_{2eq}) by technology and fuel type when switching, where possible, to natural gas.

Technology	GHG Emissions (tCO_{2eq})				
	Natural Gas	Fuel	Oil	Diesel Oil	Total
Steam turbine	1,400,625.8	-	-	-	1,400,625.8
Diesel engine	-	1,232,665.0	60,423.0	67,103.0	1,360,191.0
Gas turbine	236,529.8	-	-	-	236,529.8
Combined cycle	1,575,706.7	-	-	-	1,575,706.7
Total	3,212,862.3	1,232,665.0	60,423.0	67,103.0	4,573,053.3

As can be deduced by comparing Tables 3 and 12, as a result of the change to natural gas, pollutant gas emissions are reduced by 16.17% (from 5,454,911.4 tCO_{2eq} to 4,573,053.30 tCO_{2eq}) and fuel consumption is reduced by 13.44% (from 1,702,166.00 t to 1,473,468.48 t).

Table 12. Results of the change to natural gas (2019).

GHG Emissions (tCO_{2eq})	Emission Factor (tCO_{2eq}/MWh)	Fuel Consumption Estimation (t)
4,573,053.30	0.490	1,473,468.48

4.3.1. Alternative NG-1 (Table 13): Change in Fuel Type, where Possible, to Natural Gas—Rearrangement of Power Plants Based on Historical Maximum Annual Production Values—Renewable Penetration of 15.9%

In this alternative, the least polluting equipment is used at the various production sites on the islands up to a production ceiling set in accordance with the historical maximum annual production. The historical annual maximum values of combined-cycle plants (3,418,748.0 MWh) and diesel engines (2,390,736.2 MWh), which are the least polluting, are considered, and the rest of the equipment is reordered proportionally. A renewable penetration of 15.9% (1,480,634.0 MWh) is maintained. As a result, the overall emission factor falls from 0.563 tCO_{2eq}/MWh to 0.479 tCO_{2eq}/MWh.

Table 13. Alternative NG-1.

Technology	Energy Produced (MWh)	GHG Emissions (tCO_{2eq})	Emission Factor (tCO_{2eq}/MWh)	Fuel Consumption Estimation (t)
Steam turbine	2,045,977.0	1,205,228.3	0.589	448,391.4
Diesel engine	2,390,736.2	1,562,554.0	0.654	488,206.3
Combined cycle	3,418,748.0	1,700,472.5	0.497	494,837.9
Renewable (15.9%)	1,480,634.0	-	-	-
Total	9,336,095.2	4,468,254.7	0.479	1,431,435.6

4.3.2. Alternative NG-2 (Table 14): Change in Fuel Type, where Possible, to Natural Gas—Rearrangement of Power Plants Working Exclusively with the Least Polluting Equipment—Renewable Penetration of 15.9%

In this scenario, the least polluting equipment continues to be used at the different production sites on the islands and the rest of the equipment is ignored. This means producing 5,428,740.4 MWh with the combined-cycle plants and 2,426,720.8 MWh with the diesel engines, which are the least polluting, with the rest of the equipment remaining in disuse or as a reserve. A renewable penetration of 15.9% (1,480,634.0 MWh) is maintained. As a result, the overall emission factor falls from 0.519 tCO_{2eq}/MWh to 0.459 tCO_{2eq}/MWh.

Table 14. Alternative NG-2.

Technology	Energy Produced (MWh)	GHG Emissions (tCO_{2eq})	Emission Factor (tCO_{2eq}/MWh)	Fuel Consumption Estimation (t)
Diesel engine	2,426,720.8	1,585,011.2	0.653	495,218.0
Combined cycle	5,428,740.4	2,701,038.7	0.498	786,002.9
Renewable (15.9%)	1,480,634.0	-	-	-
Total	9,336,095.2	4,286,049.9	0.459	1,281,220.9

4.3.3. Alternative NG-3A (Table 15): Change in Fuel Type, Where Possible, to Natural Gas—Rearrangement of Power Plants Working Exclusively with the Least Polluting Equipment and Incorporation of the PHES Chira-Soria Project—Renewable Penetration of 29.1%

In this scenario, the least polluting equipment continues to be used at the different production sites on the islands and the rest of the equipment is ignored. However, in addition, the PHES Chira-Soria plant is incorporated. As a result, the overall renewable penetration in Gran Canaria is expected to be between 51% and 70%. Based on the lower value of 51%, the overall renewable penetration in the Canary Islands rises to 29.1% (2,717,720.5 MWh). A total of 4,307,822.1 MWh is produced by combined-cycle plants and 2,310,552.60 MWh by diesel engines, which are the least polluting equipment, with the rest of the equipment remaining in disuse or as a reserve. The overall emission factor falls from 0.440 tCO_{2eq}/MWh (Alternative 3A) to 0.392 tCO_{2eq}/MWh.

Table 15. Alternative NG-3A.

Technology	Energy Produced (MWh)	GHG Emissions (tCO_{2eq})	Emission Factor (tCO_{2eq}/MWh)	Fuel Consumption Estimation (t)
Diesel engine	2,310,552.6	1,512,048.9	0.654	472,435.9
Combined cycle	4,307,822.1	2,151,709.3	0.499	626,147.9
Renewable (29.1%)	1,480,634.0	-	-	-
Total	9,336,095.2	3,663,758.3	0.392	1,098,583.8

4.3.4. Alternative NG-3B (Table 16): Change in Fuel Type, Where Possible, to Natural Gas—Rearrangement of Power Plants Working Exclusively with the Least Polluting Equipment and Incorporation of the PHES Chira-Soria Project—Renewable Penetration of 36.8%

As in Alternative NG-3A, but assuming the higher renewable penetration value of 71% after the incorporation of the PHES Chira-Soria plant. In this case, the overall renewable penetration rises to 36.8%. Combined-cycle plants produce 3,658,707.6 MWh and diesel engines 2,243,280.5 MWh, which are the least polluting equipment, with the rest remaining in disuse or as a reserve. The overall emission factor falls from 0.394 tCO_{2eq}/MWh (Alternative 3B) to 0.354 tCO_{2eq}/MWh.

Table 16. Alternative NG-3B.

Technology	Energy Produced (MWh)	GHG Emissions (tCO_{2eq})	Emission Factor (tCO_{2eq}/MWh)	Fuel Consumption Estimation (t)
Diesel engine	2,243,280.5	1,469,797.0	0.655	459,242.9
Combined cycle	3,658,707.6	1,833,597.1	0.501	533,577.2
Renewable (36.78%)	3,434,107.1	-	-	-
Total	9,336,095.2	3,303,394.1	0.354	992,820.1

5. Discussion

As verified in the research background, the combination of power producing equipment that is generally employed on the islands of the Canary Archipelago is not the best combination to reduce pollution. Alternative combinations are required which offer better results, with this being the proposed objective of the present study. As a result of the methodology followed to obtain the lowest possible GHG emissions, this work considers the application of measures based on: (a) changing the fuel type by switching to natural gas in the equipment that allows it; (b) using a combination of the least polluting energy production equipment; (c) integrating, to the extent that it is possible, the incorporation of a pumped hydroelectric energy storage plant, named "Chira-Soria", into the Gran Canaria electricity system.

5.1. Summary of Alternatives: Production with Equipment Operating with Normal Fuel

Table 17 shows a summary of the improvements brought about by the four scenarios (alternatives) considered compared to the 2019 starting point:

Table 17. Summary and comparison of the proposed alternatives compared to the 2019 starting point with production based on operation with normal fuel.

2019 Starting Point and Alternatives	% Renewable Penetration	Greenhouse Gas Emissions (tCO_{2eq})	Emission Factor (tCO_{2eq}/MWh)	Fuel Consumption Estimation (t)	% Improvement
2019	15.86%	5,454.,11	0.58	1,702,166	-
1	15.86%	5,256,271	0.56	1,640,222	−3.8%
2	15.86%	4,844,887	0.52	1,510,896	−12.6%
3A	29.11%	4,108,940	0.44	1,281,548	−32.8%
3B	36.78%	3,682,760	0.39	1,148,735	−48.1%

Note especially the significant improvement with the entry of the Chira-Soria project.

5.2. Summary of Alternatives: Production with Equipment Working with Natural Gas

Table 18 shows a summary of the improvements brought about by the five scenarios (alternatives) considered compared to the 2019 starting point:

Table 18. Summary and comparison of the of the proposed alternatives compared to the 2019 starting point with production based on the use of natural gas, where possible.

2019 Starting Point and Alternatives	% Renewable Penetration	Greenhouse Gas Emissions (tCO_{2eq})	Emission Factor (tCO_{2eq}/MWh)	Fuel Consumption Estimation (t)	% Improvement
2019	15.86%	5,454,911	0.58	1,702,166.00	-
NG 2019	15.86%	4,573,053	0.49	1,473,468.48	-
NG-1	15.86%	4,468,254	0.48	1,431,435.58	−2.3%
NG-2	15.86%	4,286,049	0.46	1,281,220.92	−6.7%
NG-3A	29.11%	3,663,758	0.39	1,098,583.77	−24.8%
NG-3B	36.78%	3,303,394	0.35	992,820.10	−38.4%

Logically, the trend of improvements shown without the incorporation of natural gas increases after incorporation of this fuel. Again, note especially the significant improvement with the entry of the PHES Chira-Soria project.

5.3. Comparison of Alternatives

Figure 7 shows the evolution of GHG emissions and fuel consumption in the different scenarios compared to the 2019 starting point. It can clearly be seen that the change in the fuel to natural gas reduces the pollution and that the appropriate combination of combined-cycle with diesel equipment and renewable energies increases the reduction in GHG emissions. However, the incorporation of the PHES Chira-Soria plant has an even greater impact on this improvement. The different measures described in our research contribute to improving GHG reductions.

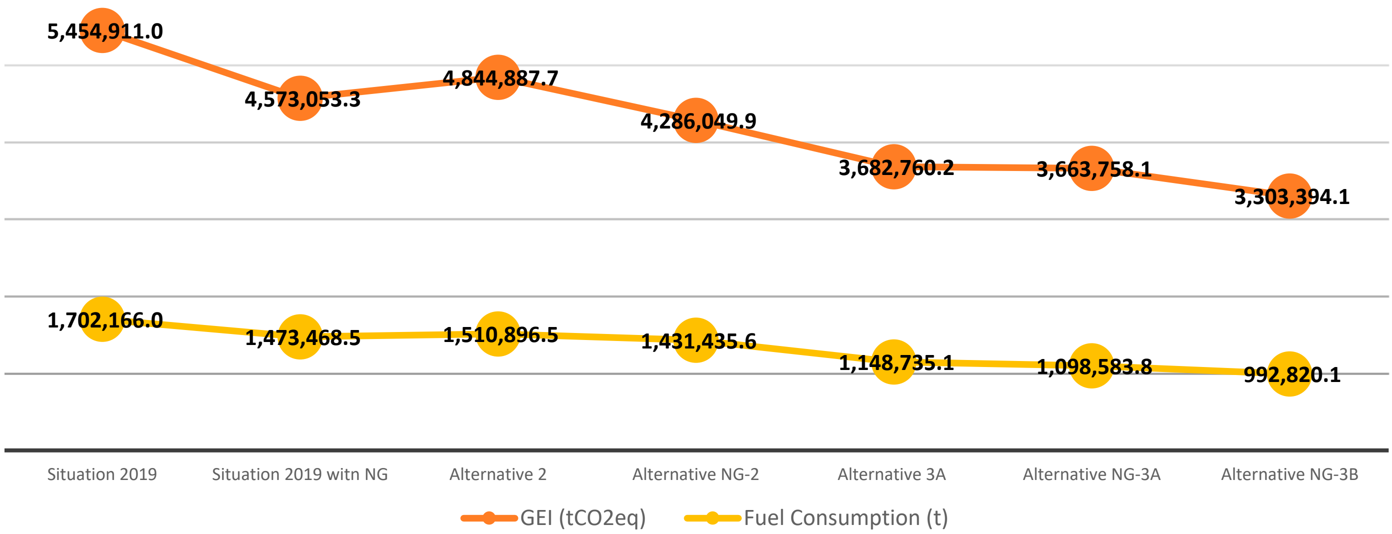

Figure 7. Comparison of GHG emissions and fuel consumption for different scenarios (alternatives).

The results will improve as these two factors increase. If they are ordered by environmental objectives based on the improvement of these factors, and if they are proposed in an increasing way, from the lowest economic cost and immediacy to the highest economic cost and with the need for more time, it is possible to obtain:

Alternative 2. This scenario is the one that offers immediate results at the lowest cost. It consists of working exclusively with the least polluting equipment (combined cycle and diesel engines) at the different production sites on the islands. Though the equipment may be subjected to higher mechanical stress, this should be within tolerable levels, provided the maintenance is commensurate with its use. Most affected would be the combined-cycle plants of Gran Canaria and Tenerife, whose use would be 67.83% and 67.10%, and the diesel engines of Fuerteventura and Lanzarote, whose use would be 67.35% and 55.57%. The rest of the equipment would have a use of below 45%. With this alternative, total GHG emissions (tCO2eq) are reduced by 12.59% and fuel consumption (t) is reduced by 12.66%, while the economic and time cost is practically zero.

Execution time—immediate; Economic cost—minimal; Total GHG emissions reduction (tCO_{2eq})—12.59%; Fuel consumption reduction (t)—12.66%; Renewable penetration—15.86%.

Alternative NG-2. This scenario involves working exclusively with the least polluting equipment (combined cycle and diesel engines) at the different production sites on the islands and changing the fuel used in the combined cycle from diesel to natural gas. Though this equipment may be subjected to higher mechanical stress, this should be within tolerable levels, provided the maintenance is commensurate with its use.

Execution time—medium; Economic cost—medium; Total GHG emissions reduction (tCO_{2eq})—22.08%; Fuel consumption reduction (t)—18.91%; Renewable penetration—15.86%.

Alternative 3A. This scenario involves working exclusively with the least polluting equipment (combined cycle and diesel engines) at the different production sites on the islands with their usual fuel, but also incorporating the PHES Chira-Soria project. It is estimated that this project will result in an overall renewable penetration in Gran Canaria of between 51% and 70%. In this alternative, the lower value of 51% is assumed (the minimum expectation for this project), increasing the overall renewable penetration in the Canary Islands to 29.11%.

Execution time—medium/high; Economic cost—medium/high; Total GHG emissions reduction (tCO_{2eq})—32.76%; Fuel consumption reduction (t)—32.82%; Renewable penetration—29.11%.

Alternative NG-3A. As in Alternative 3A, but changing the fuel to natural gas.

Execution time—medium/high; Economic cost—medium/high; Total GHG emissions reduction (tCO_{2eq})—48.89%; Fuel consumption reduction (t)—54.94%; Renewable penetration—29.11%.

Alternative NG-3B. This final scenario is the optimal one for our objective. It is the same as Alternative NG-3A (working exclusively with the least polluting equipment, changing the fuel to natural gas, and incorporating the PHES Chira-Soria project), but assumes an overall renewable penetration in Gran Canaria of 70% (the maximum expectation of the PHES Chira-Soria project), which increases the overall renewable penetration in the Canary Islands to 36.78%.

Execution time: medium/high; Economic cost—medium/high; Reduction in total GHG emissions (tCO2eq)—65.13%; Decrease in fuel consumption (t)—71.45%; Renewable penetration—36.78%.

6. Conclusions

According to the results obtained following the methodology employed in the study, several measures can be taken to achieve the environmental objectives of reduced power plant fuel consumption, reduced GHG emissions, and increased renewable penetration in the Canary Islands. These measures are based on: (a) changing the fuel type by switching to natural gas in the equipment that allows it; (b) using a combination of the least polluting energy production equipment; (c) integrating, to the extent that it is possible, the incorporation of a pumped hydroelectric energy storage plant, named "Chira-Soria", into the Gran Canaria electricity system. The measures that can be applied are affected by two main factors:

Economic: In general, the more costly the measure, the more satisfactory the result. However, the investment required will not always be directly proportional to the result.

Time: While some of the alternative scenarios considered in the study can be put into practice almost immediately, others would require several years. In general, the longer the time period required, the better the results in terms of the environmental objectives.

The following table (Table 19) summarizes the results of the different scenarios (alternatives) considered in the study, ordering the options by environmental improvement.

Table 19. Summary and comparison of the alternatives with respect to the different factors considered.

Factor	Alternative 2	Alternative NG-2	Alternative 3A	Alternative NG-3A	Alternative NG-3B
Execution time	Immediate	Medium	Medium/High	Medium/High	Medium/High
Economic cost	Minimal	Medium	Medium/High	Medium/High	Medium/High
Reduction in total GHG emissions (tCO_{2eq})	12.59%	22.08%	32.76%	48.89%	65.13%
Reduction in fuel consumption (t)	12.66%	18.91%	32.82%	54.94%	71.45%
Renewable penetration	15.86%	15.86%	29.11%	29.11%	36.78%

Possible future lines of work include the generation of a tool to optimize the methodology presented in this paper, facilitating an optimal distribution and the integration of the different power generation systems to reduce the carbon footprint.

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