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A Case Study of a Reverse Osmosis Based Pumped Energy Storage Plant in Canary Islands

Juan Carlos Lozano Medina, Carlos Alberto Mendieta Pino, Alejandro Ramos Martín and Federico León Zerpa *

Process Engineering Department, EIIC, University of Las Palmas de Gran Canaria, 35001 Las Palmas de Gran Canaria, Spain; juancarlos.lozano@ulpgc.es (J.C.L.M.); carlos.mendieta@ulpgc.es (C.A.M.P.); alejandro.ramos@ulpgc.es (A.R.M.)

* Correspondence: federico.leon@ulpgc.es; Tel.: +34-686169516

Abstract: Gran Canaria, due to its status as an island, has an isolated energy system (IES). This has made it dependent on itself for energy production, which is basically obtained from: (a) Wind and solar energy, which equals 19% of the total energy produced, (b) Energy obtained from the burning of fossil fuels in the energy production equipment of the existing thermal power stations, which equals 81% of the total energy produced. A solution must be found to the current production system, which is already partially obsolete and is due for renewal and/or decommissioning, in order to avoid "Energy Zero", which means a change in the production cycle. In addition, the incorporation of a pumped hydroelectric energy storage plant "Chira-Soria" into the Gran Canaria electricity system represents another, even more important, change in the dynamics followed up to now. Basically, this plant, which is hydraulically stabilized by means of a seawater desalination plant, incorporates energy storage by storing water at high altitude to be turbined under appropriate conditions. The new situation will be analyzed with this incorporation and the option of an integrated operation in the overall energy system of Gran Canaria will be considered.

Keywords: pumped hydroelectric energy storage; renewable energy; reverse osmosis; seawater desalination; insular electric systems; CO_2 mitigation

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1. Introduction

Pumped hydroelectric power plants (PHEs) are one of the most widely used renewable energy production systems in the world [1–10]. The need for decarbonization, the penetration of renewable energies, and the broader vision of the management of our resources could be obtained with these technologies by improving their storage capacity [11–15]. Moreover, this is not different to other island energy systems [5,7,8,16], for instance in the Canary Islands [2,4,9,17,18] and specifically in Gran Canaria, which faces a fourfold challenge in the coming years:

(a) To meet the energy production objectives to satisfy a growing demand, using the current production plants that will be replaced with the progressive incorporation of new production technologies and to satisfy the needs opened by these obsolete units to be dismantled, plus the increase in demand that is foreseen [1,4,19–23]. It currently covers a growing demand of 3350 GWh (demand in 2021), supported by an installed capacity of 1278.45 MW.

(b) Avoiding the collapse of the system, a possible "Energy zero" or "blackout", due to the incapacity and obsolescence of the energy system, which requires an action plan that addresses with technical solvency the incorporation of systems capable of satisfying the current growing demand. Renovating the partially obsolete energy production plant in Gran Canaria is the great challenge, which is already in the process of being renovated and/or dismantled. This plant is more than 30 years old, and its technological standards in terms of the current demanded requirement of minimum fuel consumption, maximum energy production, and minimum emissions are far from the desired expectations for such production [3,24–30]. All of this is aggravated by the types of fuel used, fuel oil, and diesel oil, ignoring other alternatives that are environmentally better and even energetically more efficient [24–26]. Gran Canaria's energy production depends 79.4% on imported fossil fuels for electricity generation [26,27]. In the year 2021, this has a direct impact on the increase of electricity costs and CO emissions [2,9,23].

(c) To achieve a progressive decarbonization of the generation system by incorporating more renewables or environmentally neutral systems [23,28]. Currently, in the year 2021, the penetration of renewable energies in Gran Canaria stands at 20.6%, [23,29] but is still the great challenge [1,4]. Environmental awareness has increased, this has led to the mobilization of island governments, promoting wind farms and encouraging the installation of solar panels, etc. Synthetic fuels with neutral CO_{2eq} emissions, could be one of the solutions, it is a question of promoting this use [2,18,30,31].

(d) Similarly, and due to the scarcity of water resources [32], it is necessary to optimize and integrate alternative water resource systems into the island's energy system by means of a reverse osmosis desalination plant (SWRO), to stabilize the water levels required by the PEHS. SWROs have proven their suitability, currently representing 65% of those implemented in the world [33,34]. In addition, these SWRO systems have implemented energy consumption reduction systems to minimize their carbon emission [33,35–37]. On the other hand, we find the adjustment and integration of the operating dynamics of the PEHs within an energy system [38–40]. All of this represents a change in the dynamics of the island's energy system to date, as it provides energy storage that can be used under appropriate conditions to pump water to the upper level, improve the penetration of energy from renewable and neutral sources and reduce greenhouse gases (GHG) emissions.

The aim of this article is to analyze the proposed incorporation of the new "Chira-Soria" PHEs into the global energy system of Gran Canaria, considering whether their integration into this energy system is effective and helps to alleviate the current shortcomings, and evaluating their operation, their virtues and shortcomings. Likewise, a study of the stabilization of water levels in the face of losses in the dams is proposed to guarantee the operation of the system, studying the capacity of the SWRO to satisfy the losses associated with the operation of the hydroelectric system, considering that variations in rainfall would not affect the operation of the PHEs.

2. Current Energy Production Situation in Gran Canaria

The analysis data of the anon 2021 is taken, as it is the last official data available. Based on such data, Gran Canaria's current energy production in 2021 is supported by four steam turbines, five diesel units, five gas turbines, two combined cycles with double gas turbines and steam turbines, all of which represents 80.1% of the installed power (1024.06 MW), with the percentage of installed power from renewables being 19.9% (254.39 MW), which brings the total installed power to 1278.45 MW. The total energy demand was 3,350,094 MWh of which 2,661,453 MWh (79.4%) were produced in thermal power plants by fossil fuel combustion and 668,641 MWh (20.6%) by wind and photovoltaic systems of which 55,823 MWh are produced by photovoltaic panels (1.7%) and 632,818 MWh by wind generation (18.9%), as can be seen in Table A1.

As can be seen from the data taken from the average daily usage, Table A2 is the operation of the equipment is below the recommended level. This is due to its age which leads to difficulty in its use, more breakages, more hours in repairs, more hours of maintenance, in short, increasing variable operating costs, and the solution that is finally given is to have a lot of equipment in reserve ready for use when breakages occur.

This leads to excess power due to an excess of equipment close to the limit of its useful life. From the data extracted from the average daily usage, in Table A2, we obtain the average daily use data (h/day) for all the technologies, which is 7.30 h/day for combustion equipment, representing an average use of 30.41%. The highest figure is for the combined cycle with a use of 10.41 h/day, which represents an average use of 43.46%.

The study of the day of highest energy demand is a good indicator of the situation that the energy system of Gran Canaria must face in the immediate future, 17 August 2021 at 14:53, with 529.0 MW of instantaneous power. This day and time of peak power is the maximum since 2007. At that peak time, the point demand was met with 138.7 MW of renewables and 390.3 MW of non-renewables. The behavior of energy supply in response to this peak demand, distinguishing between renewables and non-renewables, is shown in Figure 1.

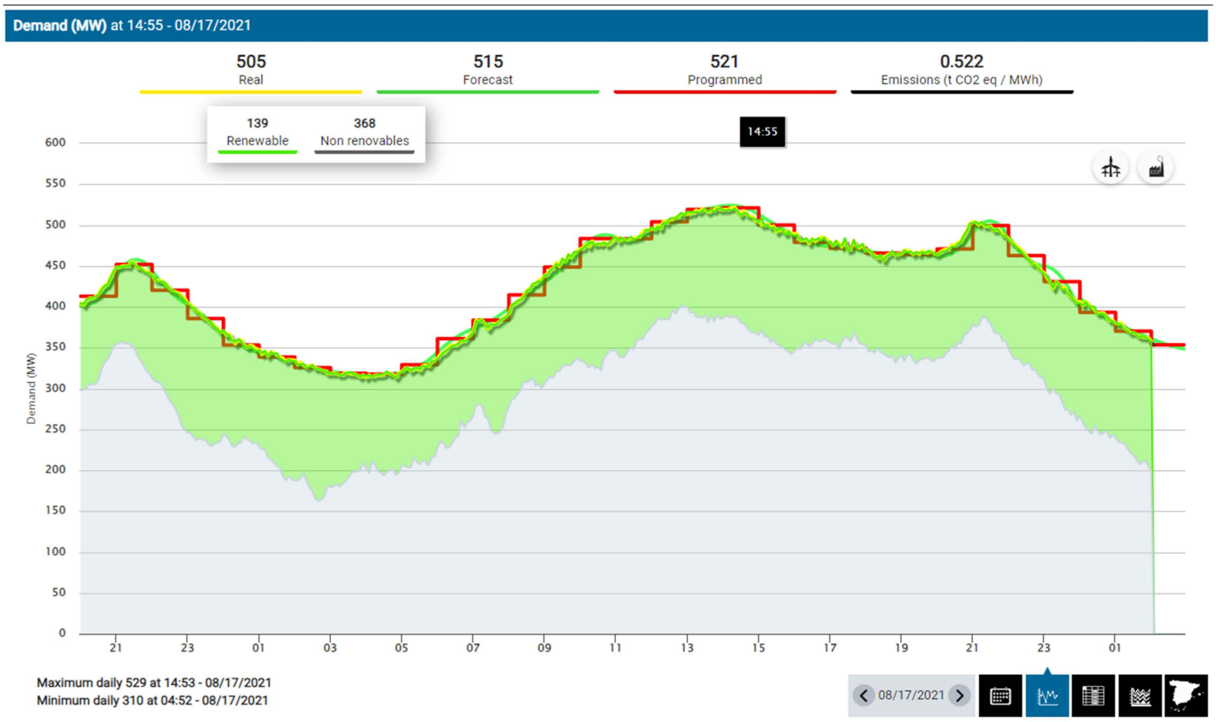

Figure 1. Response to peak demand 2021. Distinction between renewables and non-renewables [31].

In Figure 2, all the production equipment is differentiated. At the time of highest annual demand, the equipment that contributed the most was the combined cycle with 218.2 MW (43.09%), followed by the steam turbine with 115.0 MW (22.69%), wind with 112.4 MW (22.18%), solar with 26.3 MW (5.19%), diesel engines with 22.0 MW (4.34%), and the one that contributed the least was the gas turbine with 12.9 MW (2.55%).

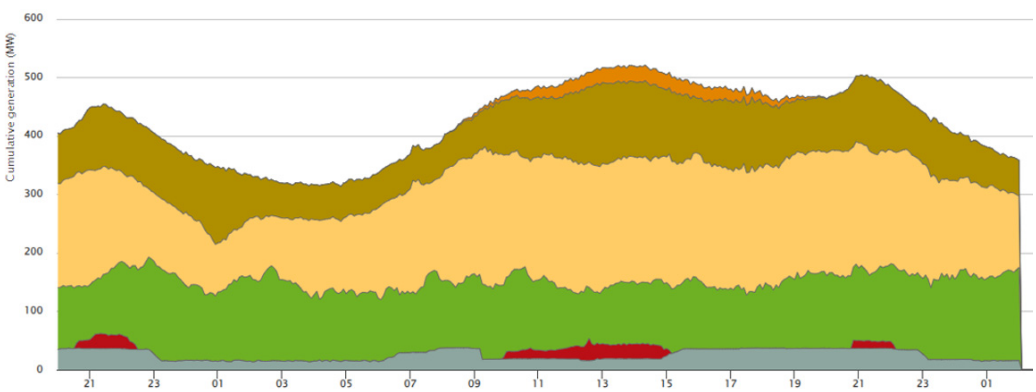

Figure 2. *Cont.*

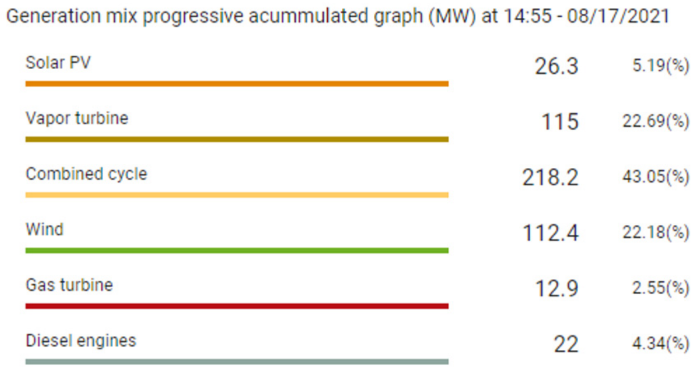

Figure 2. Peak demand response in 2021. Distinction between all renewable and non-renewable technologies [31].

Table 1 shows the type of fuel burned by technology and the type of GHG emitted.

Table 1. Fuels used (t) and GHGs produced (tCO_{2eq}) in Gran Canaria in 2021.

Type Technology	Fuels			GHGs		
	Fuel	**Diesel**	**Diesel Oil**	**CO_2**	**CH_4**	**NOx**
	(t)	**(t)**	**(t)**	**(tCO_{2eq})**	**(tCO_{2eq})**	**(tCO_{2eq})**
Steam turbine	160,119.0	129.0	0.0	524.382	427.0	1260.0
Diesel engine	37,852.0	1561.0	0.0	128.793	105.0	310.0
Gas turbine	0.0	21,781.0	0.0	68.710	58.0	172.0
Combined cycle	0.0	334,369.0	0.0	1.054,799	897.0	2648.0
Total	197,971.0	357,840.0	0.0	1,776,684.0	1487.0	4390.0

Note: Source: Canary Islands Energy Yearbook 2021 [18].

The total tons of fuel consumed in energy production in 2021 amounted to 555,811 t and the total tons of GHGs in 2021 as a result of their combustion amounted to 1,782,561 tCO_{2eq}, with the final energy supplied, net losses being 3,076,109 MWh, and the GHG emissions 1,782,561 tCO_{2eq}, the emission factor on the island of Gran Canaria for the year 2021 was 0.579 tCO_{2eq}/MWh.

3. "Chira-Soria" PHEs Analysis

"Chira-Soria" is a new pumped hydroelectric power plant, PHEs, designed and thought of several years ago and currently being built on the island of Gran Canaria. It is focused on taking advantage of the unevenness of two existing dams to produce energy through turbines. It is estimated that it will be operational in 2026 and will be the first facility of its kind on the island, and together with the rest of Gran Canaria's energy production equipment, it will serve a population of approximately one million inhabitants. This facility is located in the municipality of Tejeda.

3.1. Expectations of the Chira-Soria Pumped-Storage Hydroelectric Power Station (PHEs)

The wind power station installed on Gran Canaria in 2021 is 205.24 MW in an electricity system whose valley demand in 2021 was 257 MW, and where there is a contingent of new installation projects (wind and photovoltaic) with a potential of 725 MW, that at least have authorization for access to the grid.

The objective of the PHEs "Chira-Soria" would be to provide security of supply, ensuring the integration of the non-manageable renewable energy system. The high variability of the already installed wind generation introduces rapid frequency changes in the electricity system. These changes will continue to increase as installed wind power capacity increases. Frequency changes negatively affect consumers and could even lead to market disruptions. In this respect, the PHEs "Chira-Soria" would help mitigate the increasing degradation of frequency quality, making the system more stable, robust, and secure. It would also enable the penetration, under safe and quality of service conditions, of the expected large contingent of renewable energy. In this way, it would be possible to store surplus renewable energy that cannot be directly integrated into the system, making power balances viable and minimizing surpluses of renewable energy.

Because of the greater integration of renewables using an energy storage system, there would be a displacement of thermal generation in favor of renewable energy, with the consequent reduction of emissions, CO_2 and NO_x, which would bring economic and environmental advantages. It will allow adding flexibility to the energy system where the existing thermal generation park, designed for another energy context, lacks the necessary features for the adequate integration of renewable energies for the energy transition. The PHEs "Chira-Soria" would be characterized by a massive energy storage capacity, as well as by using a technology that would allow, depending on its operating mode, maintenance of the synchronous characteristic of the electricity system, necessary for its operation, providing inertia, short-circuit power, etc.

In addition, a desalination plant would be incorporated to produce sufficient water to compensate for the losses associated with the operation of the hydroelectric system, and variations in rainfall would not affect the operation of the PHEs. At present, the productive uses linked to the crops that supply the Chira and Soria reservoirs are subject to the availability of resources, an aspect that depends on the rainfall regime in the south of Gran Canaria. The desalination plant would keep the water in the reservoir within the appropriate volume limits.

3.2. Technical Characterisation of the PHEs 'Chira-Soria'

3.2.1. Description of Units

A simplified schematic of the hydraulic network of this installation is shown in Figures 3–5 show the general plan of the hydraulic circuit, with the Chira reservoir on the right and the Soria reservoir on the left (image oriented south instead of north).

The turbomachines that make up the PHEs Chira-Soria pumped-storage hydroelectric power station are listed in Table 2, as well as the operating characteristics for turbining and pumping.

The capacity of the Chira dam is 5,640,000.00 m^3 and that of the Soria dam is 32,300,000.00 m^3, with a maximum transfer capacity of 4,080,000.00 m^3.

The seawater reverse osmosis plant will keep the reservoir water within the proper volume limits. Its production figures are negligible compared to those of pumping and turbining, produce 7900.00 m^3 in 24 h compared to turbine, 3,939,840.00 m^3 in 16 h and pumping 1,537,920.00 m^3 in 8 h. This seawater desalination plant, installed in the system as a complement to the natural inputs of the system, consists of an open intake seawater intake, a collection tank, raw water pipes, an outfall with Venturi diffuser, and a product water pumping tank with capacity of 1000 m^3.

Table 2. Turbine characteristics according to their operation.

Type Operation	Ud	Stipulated Hours of Work	Power Unit	Total	Flow Rate	Volume of Water Displaced	Energy/Day
	Ud	**h**	**MW**	**MW**	**m^3/s**	**m^3**	**MWh**
(T1) Turbinating	6	16	33.33	200.00	68.40	3,939,840.00	3200.00
(B1) Pumping	6	8	36.67	220.00	53.40	1,537,920.00	1760.00

Note: Source: PHEs Project "Chira-Soria".

Figure 3. Ubication Chira-Soria PHEs.

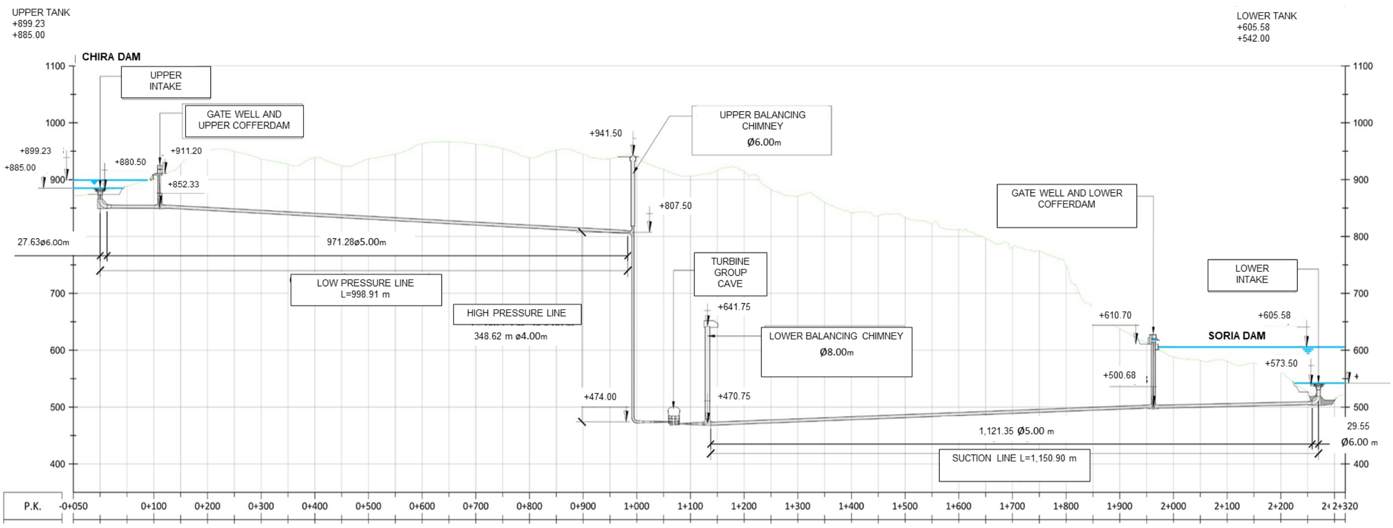

Figure 4. General diagram of the PHEs "Chira-Soria" pumped-storage hydroelectric power station (PHEs) hydraulic network.

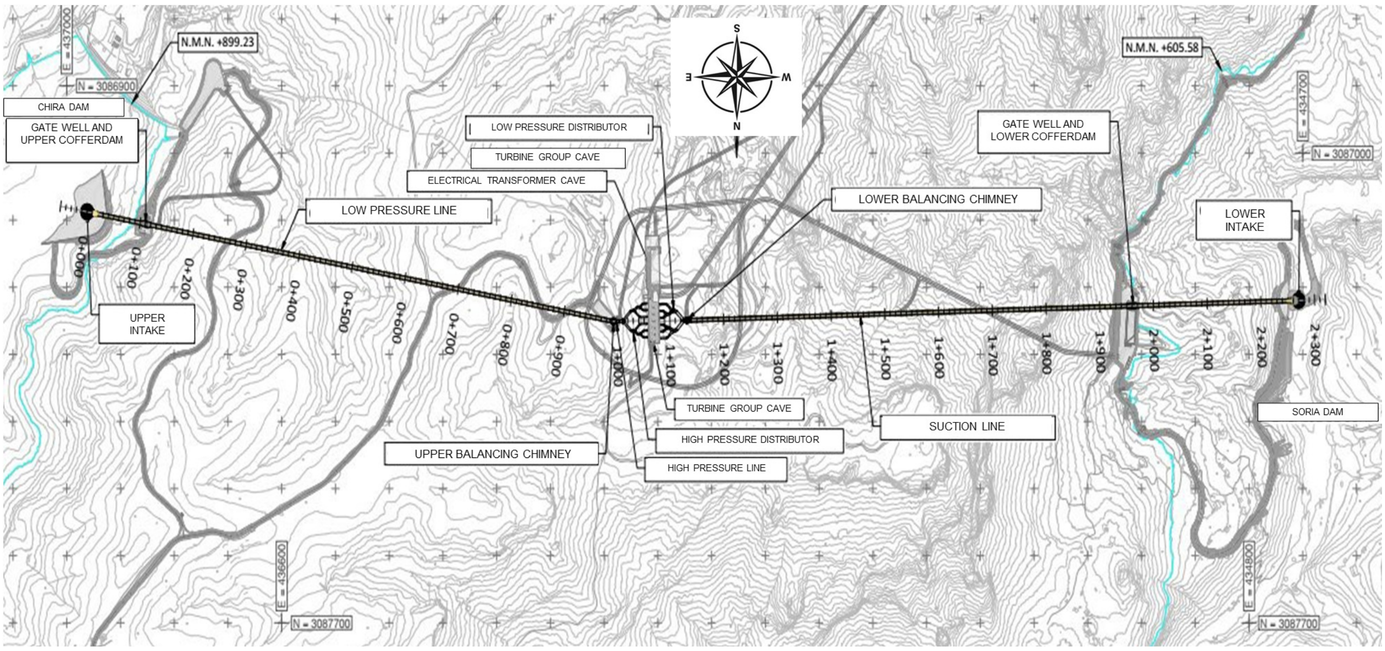

Figure 5. General plan of the Hydraulic Circuit, with the Chira reservoir on the right and the Soria reservoir on the left in this image (image oriented south instead of north).

3.2.2. Stabilization of the Water Resource

A detailed study has been carried out to determine the needs for industrial water supply to the Soria reservoir, and therefore to the hydroelectric power plant. The inflows must allow the hydroelectric system to operate at full capacity at any time during the operating period. Three different calculations have been made for the analysis of the industrial water production needs (Table 3):

Table 3. Simulation of reservoir exploitation during the period 1972–2019.

Scenario	Description	Annual Average Industrial Water Requirement in "Chira" (m^3/Year)
Lousy	Associated with a 10% probability of occurrence during the concession period.	1,574,872.91
Medium	Associated with a 50% probability of occurrence during the concession period.	1,104,571.81
More likely	Associated with a 90% probability of occurrence during the concession period.	615,389.27

Note: Source: PHEs Project "Chira-Soria".

(a) Firstly, the annual losses due to evaporation and filtration processes corresponding to own water were determined, resulting in a total of 1.63 hm^3/year.

(b) Analyzing the sensitivity to the climate change scenario, in accordance with the conclusions of the Paris Climate Summit, which set the objective of limiting the average annual temperature increase to 1.5 °C by 2010, it is found that annual losses would amount to a maximum of 1.68 hm^3/year.

(c) Next, in order to determine the average annual consumption of industrial water, a simulation of the operation of the reservoirs during the period 1972–2019 was carried out, resulting in the following scenarios:

(d) Finally, the time necessary to have a volume of water at 5 hm^3, which, according to the requirements of the Concession, must be less than 60 months (5 years), was analyzed. The results obtained were as follows:

- In the case of not having the natural contributions to the Soria reservoir and filling it only with the industrial water produced in the SWRO plant, a total of 43 months would be required, and the flow to be produced would amount to 6,396,160.62 m^3.
- With 20% of the natural water reaching the Soria reservoir, as indicated in the Concession, the filling process would produce the following scenarios: Unlikely scenario (5% probability of occurrence): 24 months. Medium scenario (50% probability of occurrence): 38 months. Worst case scenario (100% probability of occurrence): 43 months.

The basic capacity data of the resulting seawater reverse osmosis plant is in Table 4.

Table 4. Water resource and impulsion.

Concept	Value
Capacity	1.80 hm^3/year
Availability Factor	0.95
Reverse Osmosis Conversion	45.0%
Total Production	5200.00 m^3/day
Reverse Osmosis Feed Flow	11,644.50 m^3/day

Note: Source: Chira-Soria Hydroelectric Pumping Plant Project.

SWRO's surplus production will also be used to supply the town of Arguineguín, close to the installation (Figure 6).

3.3. Operational Description

As established in the PHEs "Chira-Soria" Project, the power plant's groups would operate in pumping mode when there is excess energy, due to excess non-manageable generation, mainly wind, or due to low consumption, which would force the large thermal groups to operate in modes of poorer performance or below their technical minimum. Turbinating would occur at peak demand times, replacing the energy that would have been produced by thermal technologies with higher variable system costs and greater environmental impact. Thus, the plant will operate with a daily cycle in which:

- Turbomachines in pumping mode. The groups will consume energy to pump water from the lower basin (Soria) to the upper basin (Chira) in the off-peak period of the night demand (typically from 0:00 h to 7:00 h). This will allow, on the one hand, the use of renewable energy generated at night that is not consumed, as well as the base groups that will be able to operate with better performance during the night and, consequently, reduce the specific CO_2 emissions of the whole. It will also avoid shutting down certain units for a few hours, and the subsequent start-up, which is costly. On the other hand, in cases where there is excess wind energy production in the system, pumping will make it possible to "artificially" increase demand, making it possible to integrate the electricity production corresponding to this excess.

- Turbomachines in turbined mode. The units will produce energy by turbining the water conveyed from the upper basin to the lower basin, during peak demand hours (typically from 9.00 to 23.00) and the morning (typically from 10.00 to 13.00) and evening (19.00 to 21.00) peaks. They will thus replace, during the year, higher variable cost technologies (gas turbines running on diesel).

On the other hand, hydroelectric power is very fast in its start-up and power variation, allowing it to respond quickly to failures of grid or system elements. In the event of a total power failure (zero electricity) on the island, the Chira-Soria plant could initiate the recovery of supply in a few minutes, 10–20 min, given its enormous flexibility, being the generating equipment that will initiate the process of replenishing the system. The generation power is 200 MW, the pumping power consumed is 220 MW and the cumulative energy is 3.2 GWh (turbining for 16 h). The transferable volume from the Chira reservoir to the Soria reservoir is 4.08 hm^3. The sedimentation study shows that the calculated volume of diversion water will not be affected by the increase in sedimentation and therefore the decrease in the capacity of the dam for at least 50 years, after which it will have to be dredged, which gives us an initial useful life of 50 years of PHEs.

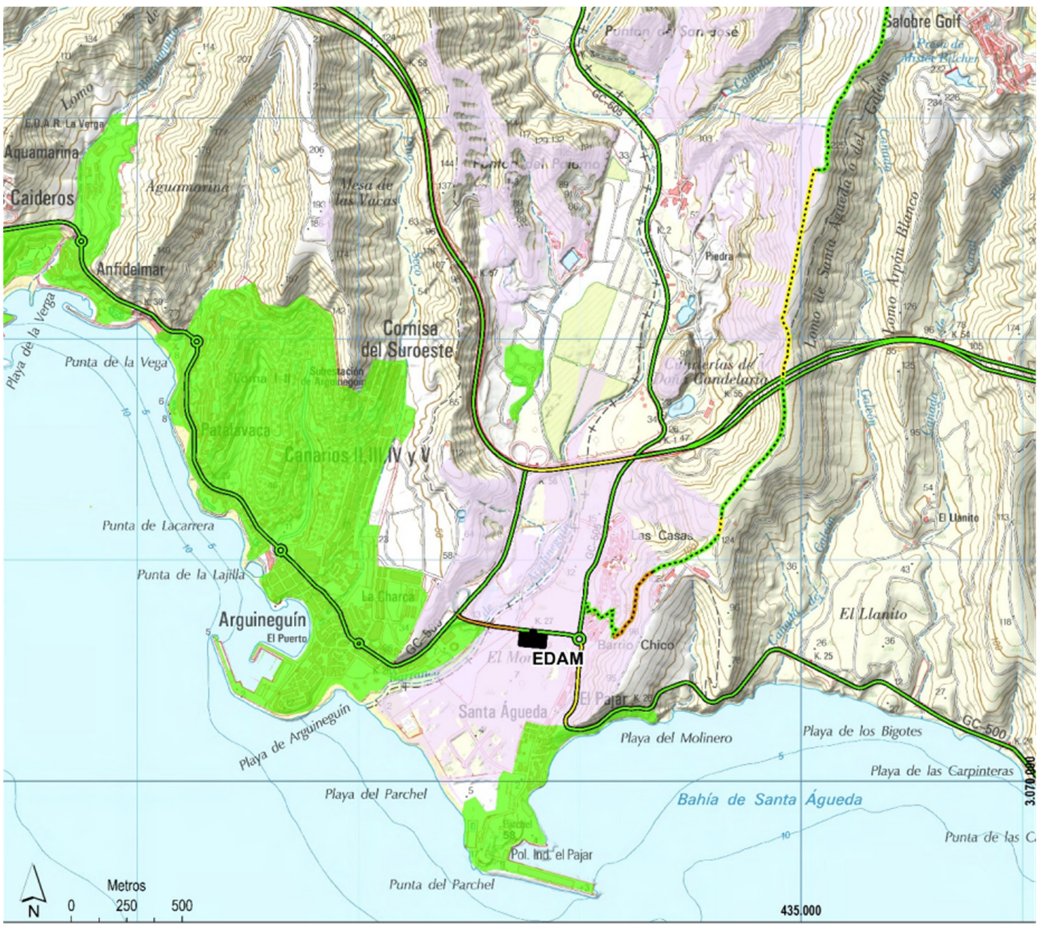

Figure 6. Location SWRO and city of Arguineguin.

3.4. Data Analysis. Search for Strengths and Weaknesses

3.4.1. Pumping-Turbine Balancing Operation

As indicated in the previous section, the plant's units would operate in pumping mode and in turbine mode at certain times of the day, and this situation is analyzed first. The table below shows the electricity demand required in both modes for the different operating hours, as well as the amount of water pumped and turbined.

If we want to maintain the transfer level, we cannot turbine without having first replenished the water levels. Consequently, it is always necessary to follow a balance between turbining and pumping in the unit of time that is valued and always without exhausting the transfer capacity. This balance is in Table 5.

Table 5. Equilibrium pump-turbine operation.

Operating Mode	Operation		Power	Energy/Day	Flow Rate	Volume of Water Displaced
	h/Day	%	MW	MWh	m/s^3	m^3
Equilibrium Turbinado	10.522	43.84%	200.0	2104.43	68.40	2,590,978.53
Balance pumping	13.478	56.16%	220.0	2965.12	53.40	2,590,978.52
Sum	24.000	100.0%				

This means that if 43.84% of the time (10 h and 31 min) we run the turbines, 56.16% of the time (13 h and 28 min) we need to pump. Obtaining 2104.43 MWh/day with turbine and need 2965.12 MWh/day for pumping.

3.4.2. Estimated Power and Renewable Energy Production

As mentioned above, the PHEs "Chira-Soria" project will maximize the integration of renewable energies, avoiding the discharges that would otherwise occur and enabling the development and installation of this type of energy.

There is a contingent of new installation projects (wind and photovoltaic) with a potential of 725 MW that have at least grid access authorization, the current reality is shown in Table A6, although currently only 400.97 MW are confirmed (which is the situation with final registration).

The forecast growth of energy produced in renewables is shown in Table 6, taking as a reference the data for 2021 on the average operating hours of renewable sources. For wind power, the average annual capacity factor for twelve-month operation is 36.76%, i.e., 8.82 equivalent hours/day (3220 equivalent hours per year). Considering the hours available to work, 24 h a day, 365 days a year, for photovoltaic, the Annual Average Capacity Factor is 24.27%, i.e., 2.91 equivalent hours/day, (1063 equivalent hours per year), considering the hours available to work, 12 h a day, 365 days a year.

Table 6. Forecast growth of energy produced in renewables.

Type Renewable	Chira-Soria Project Estimate	Situation Year 2021	Situation Year 2023	Situation with Final Registration
	MWh Year	MWh Year	MWh Year	MWh Year
Wind	1,829,629.76	641,990.72	955,572.72	1,001,585.60
Photovoltaic	148,905.04	52,246.45	77,769.08	85,858.51
Sum	1,978,534.80	694,237.17	1,033,341.80	1,087,444.11

3.4.3. Study of Installed Power in the Island Electricity System with the Incorporation of the PHEs "Chira-Soria"

Based on the above analysis, the following facilities are energy producers in Table 7.

Table 7. Estimated Installed Capacity (MW) including the PHEs "Chira-Soria".

Type Energy	Type Technology	Installed Power	
		MW	%
Energies Derivatives from oil	Thermal power plants. Steam turbine	280.00	18.94%
	Thermal power plants. Diesel engine	84.00	5.68%
	Thermal power plants. Gas turbine	173.45	11.73%
	Thermal power plants. Combined cycle	461.73	31.23%
	Cogeneration. Steam turbine	24.20	1.64%
	Cogeneration. Diesel engine	0.68	0.05%
	Cogeneration. Gas turbine	0.00	0.00%
	Sum	1024.06	69.72%
Energies renewables	Wind	205.24	13.88%
	Photovoltaics	49.15	3.32%
	Hydraulics	200.00	13.53%
	Sum	454.39	30.73%
Total		1478.45	100.00%

The installed capacity has increased by 13.53%, with total installed capacity in renewables accounting for 30.73% of total capacity.

3.4.4. Study of the Energy Demand and Production in the Gran Canaria System with the Incorporation of the PHEs "Chira-Soria"

In terms of demand, with the incorporation of the PHEs project, it should be borne in mind that the plant needs to pump water from Soria to Chira to achieve balance, which means an increase in demand due to pumping of 2965.12 MWh per day on average, or 1,082,268.8 MWh per year on average for maximum pumping use, i.e., 56.16% of the annual average time, which means that the demand with the incorporation of the PHEs project will increase from 3,350,094.00 MWh per year to 4,432,362.80 MWh per year as a maximum.

In terms of energy production, there is an increase, due to the turbine, of 2104.43 MWh per day on average, or 768,118.23 MWh per year on average for maximum turbine use, i.e., 43.84% of the annual average time. With the incorporation of the Chira-Soria hydroelectric pumping station project, electricity production would increase from 3,350,094.0 MWh per year to a maximum of 4,118,212.23 MWh per year, generating a deficit in demand of 314,151,72 MWh per year. Table 8 shows different hypotheses for the increase in demand and electricity production due to the different percentages of pumping and turbine use in the PHEs.

Table 8. Increase in electricity demand and production with the incorporation of the PHEs "Chira-Soria".

Increase in Energy Demand with the Incorporation of the PHEs "Chira-Soria".							
Percentage Pumping performance (%)	56.16%	50.00%	40.00%	30.00%	20.00%	10.00%	0.00%
Hours per day Pumping (h/day)	13.48	12.00	9.60	7.20	4.80	2.40	0.00
Increase Demand (MWh year)	1,082,269.95	963,600.00	770,880.00	578,160.00	385,440.00	192,720.00	0.00
Pre-existing demand (MWh year)	3,350,094.00	3,350,094.00	3,350,094.00	3,350,094.00	3,350,094.00	3,350,094.00	3,350,094.00
Sum (MWh year)	4,432,363.95	4,313,694.00	4,120,974.00	3,928,254.00	3,735,534.00	3,542,814.00	3,350,094.00
Increased energy production with the incorporation of the Chira-Soria Turbine.							
Percentage Turbined Operation (%)	43.84%	39.04%	31.23%	23.42%	15.61%	7.81%	0.00%
Hours per day Turbined (h/day)	10.52	9.37	7.49	5.62	3.75	1.87	0.00
Production increase (MWh year)	768,118.23	683,894.74	547,115.79	410,336.84	273,557.90	136,778.95	0.00
Pre-existing production (MWh year)	3,350,094.00	3,350,094.00	3,350,094.00	3,350,094.00	3,350,094.00	3,350,094.00	3,350,094.00
Sum (MWh year)	4,118,212.23	4,033,988.74	3,897,209.79	3,760,430.84	3,623,651.90	3,486,872.95	3,350,094.00
Demand-Production Difference (MWh year)	−314,151.72	−279,705.26	−223,764.21	−167,823.16	−111,882.10	−55,941.05	0.00

3.4.5. Calculation of the New Needs for Renewable Wind Power Production in the Gran Canaria System with the Incorporation of the " PHEs "Chira-Soria

To compensate for the new energy production and need to cover the new demand, two scenarios are considered, (a) to cover the difference between pumping and turbining, (b) to cover all pumping. For this purpose, we calculate the wind power requirements for different capacity factors. As indicated above, the average annual capacity factor for twelve-month operation is 36.76%, i.e., 8.82 equivalent hours/day (3220 equivalent h/year).

For the first scenario, Table A7, it turns out that we would need 97.56 MW to cover the net difference in consumption and running pumping and turbining for as long as possible, i.e., 56.16% and 43.84% of the time, and assuming a wind capacity factor of 36.76%, (8.82 h/day) which is the figure achieved in 2021. For the second scenario, Table A8, we would need 336.11 MW to cover pumping for the maximum possible time, i.e., 56.16% of the time, and assuming a wind capacity factor of 36.76% (8.82 h/day), which is the figure achieved in 2021.

On the other hand, these data on installed power and wind energy production versus pumping operating hours must be compared. The operating hours of pumping must be coordinated with the operating hours of wind power. To do this, let us consider the most extreme case, that is, when the entire transfer capacity from Chira to Soria has been turbined and must be pumped back to Chira. The volume that can be transferred from the Chira reservoir to the Soria reservoir is 4.08 hm^3 (Table 9).

Table 9. Maximum Turbinating and Pumping capacity limited by maximum racking capacity.

Operating Mode	Operation		Flow Rate	Volume of Water Displaced
	Hours	**%**	**m/s^3**	**m^3**
Equilibrium Turbinado	16 h 34 min	43.84%	68.40	4,080,000.00
Balance pumping	21 h 13 min	56.16%	53.40	4,080,000.00
Sum		100.00%		

As shown, the maximum pumping capacity is produced by pumping for 21 h and 13 min. In this case, it is possible to obtain the power shown in the table depending on the capacity wind factor.

Therefore, for the extreme case that concerns us, working the pumping for 21 h and 13 min, we would need 529.27 MW, which could demand 1,703,878.91 MWh per year, assuming a wind power capacity factor of 36.76% (8.82 h/day).

3.4.6. Calculation of the Volume of Volume of Water Transferred in the Soria Reservoir

The number of water renewals in the dam per year to obtain the maximum annual power with the turbine is estimated as follows, i.e., 768,118.23 MWh per year.

As determined above, it takes 16 h and 34 min to empty the dam and 21 h and 13 min to refill it, for a total renovation time of 37 h and 47 min, requiring 231.8 annual renovations to produce the maximum annual turbine power.

4. Integration of the Chira-Soria Hydroelectric Pumping Station into the Overall Energy System of Gran Canaria

4.1. Contribution to the Current Energy System of Gran Canaria

As shown, where the day of highest electricity demand in 2021 is analyzed, among others, the wind energy contribution remains almost constant during the 24 h, instantly disposing of an average of 119.21 MW out of a total of 205.24 MW installed, with its maximum average per hour being 147.5 MW and its minimum average per hour being 91.1 MW. However, these are one-off events as it is practically constant. The following graph shows the average hourly values of wind power during 24 h (Figure 7).

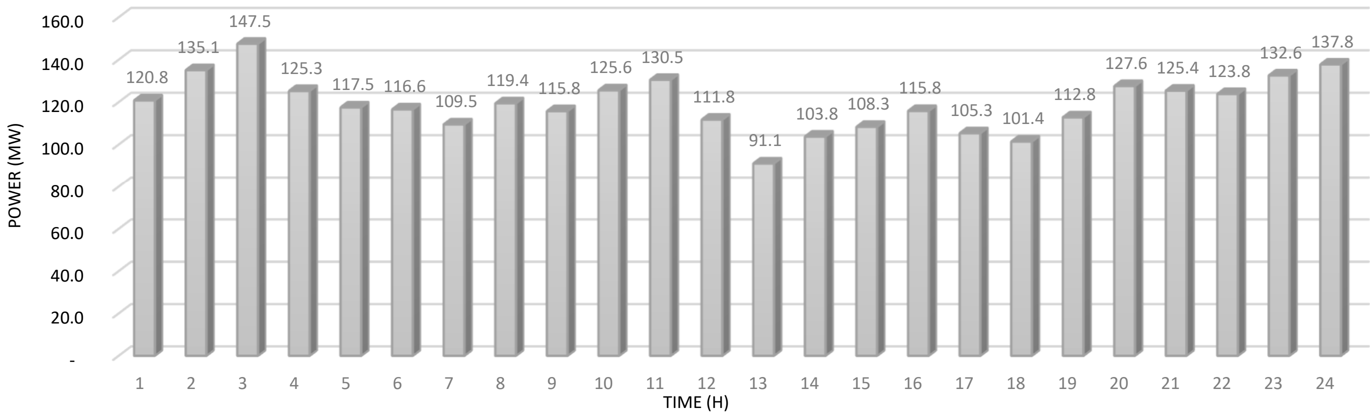

Figure 7. Instantaneous wind power production (MW) on 17 August 2021 [18].

This behavior is repeated annually. This corroborates what we know about installed wind power production: it is far below what is desirable. Therefore, there is still no possibility of waste due to excess wind power production.

The increase in wind power, in addition to that currently existing, to cover the maximum pumping operation (MW) of the PHEs "Chira-Soria" (Table 10), assuming a wind power capacity factor of 36.76% (8.82 h/day), results in 529.27 MW. There is currently 205.24 MW of wind power installed, so the integration and commissioning of the Chira-Soria hydroelectric plant could be carried out, but this would be at the cost of subtracting installed capacity and energy production from the system. In the average that more wind power is installed and we get closer to the proposal, the PHEs "Chira-Soria" will be closer to the objective for which it has been designed (Figure 8).

Table 10. Wind power increase to cover maximum pumping operation (MW).

Pumping Operating Hours (h)		**13.48 h**	**21.22 h**
		13 h 28 min	**21 h 13 min**
Capacity Factor Wind	**Operating Hours Equivalents/Day Wind**	**Power (MW)**	**Power (MW)**
25.00%	6.00	494.19	778.19
29.17%	7.00	423.49	667.02
33.33%	8.00	370.64	583.65
35.71%	8.57	345.99	544.84
36.76%	8.82	336.11	529.27
37.50%	9.00	329.46	518.80
41.67%	10.00	296.51	466.92
45.83%	11.00	269.56	424.47

Another analysis carried out for better integration looks for daily production differences. The weekly energy production-energy demand has been analyzed to study the possible variations in demand on days when there is less work activity and to take advantage of the lower energy production from combustion in that period for use in pumping, thus helping to comply with the minimum technical operating requirements of the groups, almost exclusively in the combined cycle. This situation would be a good transitional contribution until the expected demand in the plant is covered by wind turbines and would be usable on days of less work activity.

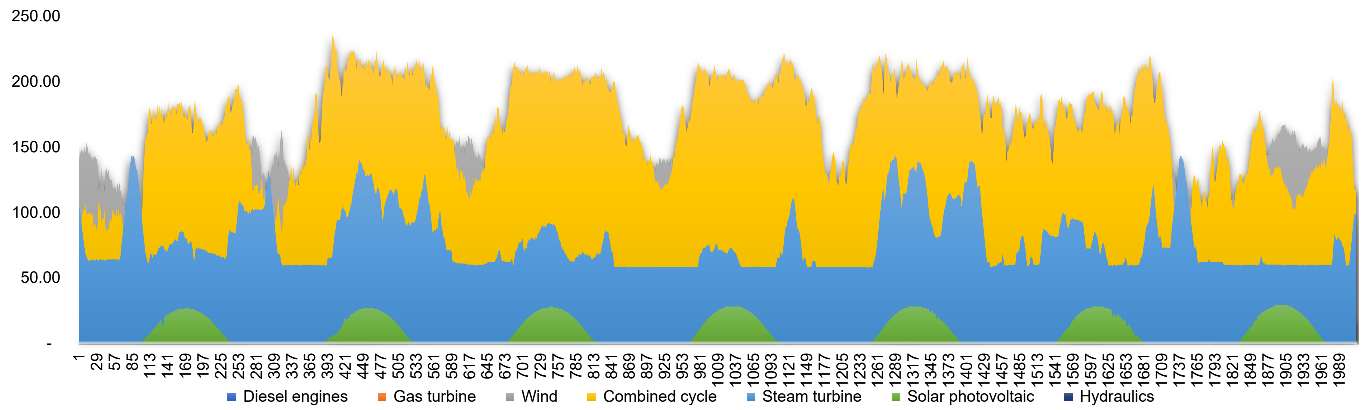

Figure 8. Instantaneous production (MW) from 16 to 22 August 2021 [18].

4.2. Contribution to the Immediate-Future Energy System of Gran Canaria

The case for which the PHEs "Chira-Soria" has been designed is studied, i.e., according to the results of this study, a minimum additional wind power of 529.27 MW, bringing the total wind renewable energy to 734.51 MW.

Table 11 shows the new power table for this scenario. The total installed capacity is 2007.72 MW, if 49.0% of the capacity comes from renewable sources. In terms of generation, it should be noted that the possible generation includes generation from the hydro turbine and new wind renewables, and that a new demand appears, which is from pumping from the power plant, as shown in Table 12.

Table 11. Estimated Installed Capacity (MW).

Type Energy	Type Technology	Installed Power	
		MW	%
Energies Derivatives from oil	Thermal power plants. Steam turbine	280.00	13.9%
	Thermal power plants. Diesel engine	84.00	4.2%
	Thermal power plants. Gas turbine	173.45	8.6%
	Thermal power plants. Combined cycle	461.73	23.0%
	Cogeneration. Steam turbine	24.20	1.2%
	Cogeneration. Diesel engine	0.68	0.0%
	Cogeneration. Gas turbine	0.00	0.0%
	Sum	1024.06	51.0%
Energies Renewables	Wind	734.51	36.6%
	Photovoltaics	49.15	2.4%
	Hydraulics	200.00	10.0%
	Sum	983.66	49.0%
TOTAL		2007.72	100.0%

This means that there is an increase of 1,389,727.64 MWh per year over the current situation of over-production in renewables. This production can be used, among other things, to mitigate the demand covered by non-renewable production, which is 2,661,453 MWh, and for pumping. It would mean a reduction of almost 47.78% in polluting generation and therefore in emissions and would mean that renewable electricity production would be 71.31%.

Table 12. Estimated increase in production and demand (MWh).

Type Technology	Powers	Situation 2021	Increase Production	Increase Demand	Proposal Demand—Equilibrium Production	
	MW	MWh	MWh	MWh	MWh	%
Current non-renewable generation	1024.06	2,661,453.00	2,661,453.00	2,661,453.00	1,271,725.36	28.69%
Current photovoltaic renewable generation	49.15	55,823.00	55,823.00	55,823.00	55,823.00	1.26%
Current wind renewable generation	205.24	632,818.00	632,818.00	632,818.00	632,818.00	14.28%
Generation by new wind renewables	529.27	-	1,703,878.91	-	1,703,878.91	38.44%
Hydro turbine generation	200.00	-	768,118.23	-	768,118.23	17.33%
Demand Pumping	−220.00	-	-	1,082,269.50	-	-
		3,350,094.00	5,822,091.14	4,432,363.50	4,432,363.50	100.00%

5. Results and Discussions

During the analysis process, it has been determined what the incorporation of the PHEs "Chira-Soria" in the energy production system in Gran Canaria entails and the stabilization of the water levels of the dams for their guaranteed operation has been exposed. In short, with the PEHS, great benefits would be achieved.

5.1. Associated with the Characteristics of the Installation

- The use of turbo hydraulic machines that operate in pumping have a worse performance (more power demanded for lower hydraulic consumption), generate a deficit of 20 MW and a lower pumping flow than the turbine.
- As a consequence, more time is required in the pumping phase and more energy than that obtained in the turbine to restore the normal operating levels of the reservoirs. Out of a maximum of 24 h of operation, 13.5 h of pumping are required versus 10.5 h of turbineing. Under these conditions, an annual energy deficit of 314,152 MWh would be obtained.
- The capacity of the Chira reservoir with 5.64 hm^3 allows a transfer capacity of 4.08 hm^3, this being the limiting value for the determination of the maximum energy delivery in the planned power plant. This maximum value would be obtained in the continuous turbine phase for 16 h and 34 min to deliver 3313.84 MWh that must be compensated with 21 h and 15 min of pumping, requiring 4669.16 MWh.

5.2. Associated with the Integration of Renewables

- According to the PHEs "Chira-Soria", an installed renewable energy capacity forecast of 725 MW is indicated.
- The need to re-establish the level of the Chira reservoir may eventually require an increase in renewable power of 529.22 MW, to reach 734.51 MW, data obtained because of our study, which, considering the required operating time (21 h and 15 min), will have to be used in the field of wind energy.
- With the above result (734.51 MW), the installed wind power capacity in the island's energy park would account for 49% of the total.
- If the maximum power production per turbine is sought, 768,118.23 MWh per year, 231.8 annual renewals of the maximum volume of transfer of the reservoir would be needed.

5.3. Associated with Beneficial Contributions to the System

The PEHS, confirming the final installation of 725.00–734.51 MW, would achieve great benefits:

- It would maximize the integration of renewable energies, avoiding spills that would otherwise occur and enabling the development and installation of this type of energy.

- It would provide security to the electrical system and guarantee of supply.
  - ✓ It would stabilize the frequency, the quality of which worsens as the installation of non-dispatchable renewables increases.
  - ✓ It would increase the flexibility of the electrical system, improving its response and making it safer in the face of disturbances.
- It would reduce the costs of the electricity system.
- It would reduce energy dependence on the outside world.

5.4. Challenges

The PHEs “Chira-Soria” would bring new challenges to the system. As proposed by the project, this PHEs would cooperate with wind energy to make better use of it.

- To make up for this deficit in wind energy production, it is certain that future wind energy production in Gran Canaria will reach 725 MW.
- As has been shown, the Chira-Soria Pumped Hydroelectric Power Plant would need a maximum of 529.27 MW of wind power in addition to the installed capacity to cover pumping.
- Until wind energy production does not reach the expected 725 MW, and during the transition, pumping can be encouraged on days of less working activity to comply with the technical minimums of the combined cycle and due to the absence of the necessary wind power quota. It cannot yet be properly exploited due to the shortfall in installed wind power.

Its immediate commissioning would result in an installed power deficit of 97.56 MW in the Gran Canaria electricity system. As more wind power is installed, up to an increase of 529.27 MW, and we get closer to the proposed 734.51 MW, the PHEs “Chira-Soria” will get closer to the objective for which it was designed.

6. Conclusions

The use of turbohydraulic machines that operate in pumping have a worse performance (more power demanded for a lower hydraulic consumption), generate a deficit of 20 MW, and a lower pumping flow than the turbine. This means that, for the maximum operating value, (continuous turbine phase for 16 h and 34 min) it could produce 3313.84 MWh that must be compensated with pumping, (21 h and 15 min), requiring 4669.16 MWh. A deficit of 1355.32 MWh.

For maximum production, 231.8 annual renewals of the maximum transfer volume of the reservoir would be required.

PEHs would maximize the integration of renewable energies, avoiding spills that would otherwise occur and enabling the development and installation of this type of energy and would provide security to the electricity system and guarantee of supply.

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Data Availability Statement: The data presented in this study are available on request.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Installed Capacity (MW) and Demand Coverage (MWh). Gran Canaria, year 2021 [18].

Type Energy	Type Technology	Installed Power		Demand Coverage	
		MW	%	MWh	%
Energies derivatives from oil	Thermal power plants. Steam turbine	280.00	21.9%	647,519	19.3%
	Thermal power plants. Diesel engine	84.00	6.6%	199,206	5.9%
	Thermal power plants. Gas turbine	173.45	13.6%	60,853	1.8%
	Thermal power plants. Combined cycle	461.73	36.1%	1,753,875	52.4%
	Cogeneration. Steam turbine	24.20	1.9%	0	0.0%
	Cogeneration. Diesel engine	0.68	0.1%	0	0.0%
	Cogeneration. Gas turbine	0.00	0.0%	0	0.0%
	Sum	1024.06	80.1%	2,661,453	79.4%
Energies Renewables	Wind	205.24	16.1%	632,818	18.9%
	Photovoltaics	49.15	3.8%	55,823	1.7%
	Sum	254.39	19.9%	668,641	20.6%
Total		1278.45	100.0%	3,350,094	100.0%

Note: Source: Canary Islands Energy Yearbook 2021.

Table A2. Average daily use (h). Gran Canaria, year 2021 [18].

Type Energy	Type Technology	Average Daily Usage	
		(h/Day)	(%)
Non-renewable Energies	Thermal power plants. Steam turbine	6.34	26.40%
	Thermal power plants. Diesel engine	6.50	27.07%
	Thermal power plants. Gas turbine	0.96	4.01%
	Thermal power plants. Combined cycle	10.41	43.36%
	Cogeneration. Steam turbine	-	-
	Cogeneration. Diesel engine	-	-
	Cogeneration. Gas turbine	-	-
	Media	7.30	30.41%
Renewable Energies	Wind	8.45	35.20%
	Photovoltaics	3.11	12.97%
	Media	7.42	30.90%
	Total average	7.32	30.51%

Table A3. SWRO plant and annexes.

Installation	Flow Rate of Design	Range Operation	Length	Diameter
	m^3/Day	m^3/Day	m	mm
Seawater SWRO plant	5200.00	5200.00–7900.00	-	-
Catchment tower	17,468.00	11,643.50–17,468.00	-	-
Open-take catchment inmisario	17,459.00	11,643.50–17,468.70	994.93	560.0
Raw water impulsión	11,643.50	11,643.50–17,468.70	839.56	450.0
Brine discharge outfall. With Venturi type diffuser	9668.70	6443.50–9668.70	1485.49	450.0
Product water pumping. Pumping1 to Pumping II	5200.00	-	17,592.94	400.0
Product water pumping. Pumping II to Lower Platform	5200.00	-	4129.07	400.0
Product water impulsion. Lower Platform to Soria Reservoir	5200.00	-	402.00	-

Note: Source: PHEs Project "Chira-Soria".

Table A4. Turbine operation.

Operating Mode	No. Units	Distribution Operating Time
	Ud	Timetable
(T2) Theoretical continuous turbining	6	9:00–23:00 h
(T3) Theoretical tip turbinate	6	10:00–13:00 h and 19:00–21:00 h
(B2) Theoretical pumping	6	0:00–7:00 h

Note: Source: PHEs Project "Chira-Soria".

Table A5. Turbine characteristics.

Operating Mode	Operation	Power	Energy/Day	Flow Rate	Volume of Water Displaced
	h	MW	MWh	m^3/s	m^3
(T1) Maximum daily turnover	16	200.0	3200.0	68.4	3,939,840
(T2) Theoretical continuous turbining	14	200.0	2800.0	68.4	3,447,360
(T3) Theoretical continuous turbining	5	200.0	1000.0	68.4	1,231,200
(B1) Maximum daily pumping	8	220.0	1760.0	53.4	1,537,920
(B2) Theoretical pumping	7	220.0	1540.0	53.4	1,345,680

Table A6. Forecast growth in installed capacity in renewables.

Type Renewable	Chira-Soria Project Estimate	Situation Year 2021	Situation Year 2023	Situation with Final Registration
	MW	MW	MW	MW
Wind	584.92	205.24	305.49	320.20
Photovoltaic	140.08	49.15	73.16	80.77
Sum	725.00	254.39	378.65	400.97

Table A7. Increase in wind power capacity to cover the difference in demand with the incorporation of the Chira-Soria Hydroelectric Pumping Station.

Percentage Pumping Performance (%)		56.16%	50.00%	40.00%	30.00%	20.00%	10.00%	0.00%
Hours Pumping Operation per Day (h/Day)		13.48	12.00	9.60	7.20	4.80	2.40	0.00
Capacity Factor Wind	Equivalent Operating Hours/Day Wind	Power (MW)	Power (MW)	Power (MW)	Power (MW)	Power (MW)	Power (MW)	Power (MW)
25.00%	6.00	143.45	127.72	102.18	76.63	51.09	25.54	0.00
29.17%	7.00	122.96	109.47	87.58	65.68	43.79	21.89	0.00
33.33%	8.00	107.59	95.79	76.63	57.47	38.32	19.16	0.00
35.71%	8.57	100.43	89.42	71.54	53.65	35.77	17.88	0.00
36.76%	8.82	97.56	86.86	69.49	52.12	34.75	17.37	0.00
37.50%	9.00	95.63	85.15	68.12	51.09	34.06	17.03	0.00
41.67%	10.00	86.07	76.63	61.31	45.98	30.65	15.33	0.00
45.83%	11.00	78.24	69.67	55.73	41.80	27.87	13.93	0.00

Table A8. Increase in wind power to cover exclusively the increase in total pumping demand with the incorporation of the Chira-Soria hydroelectric pumping station.

Percentage Pumping Performance (%)		56.16%	50.00%	40.00%	30.00%	20.00%	10.00%	0.00%
Hours Pumping Operation per Day (h/Day)		13.48	12.00	9.60	7.20	4.80	2.40	0.00
Capacity Factor Wind	Equivalent Operating Hours/Day Wind	Power (MW)	Power (MW)	Power (MW)	Power (MW)	Power (MW)	Power (MW)	Power (MW)
25.00%	6.00	494.19	440.00	352.00	264.00	176.00	88.00	0.00
29.17%	7.00	423.49	377.14	301.71	226.29	150.86	75.43	0.00

Table A8. *Cont.*

Percentage Pumping Performance (%)		56.16%	50.00%	40.00%	30.00%	20.00%	10.00%	0.00%
Hours Pumping Operation per Day (h/Day)		**13.48**	**12.00**	**9.60**	**7.20**	**4.80**	**2.40**	**0.00**
Capacity Factor Wind	**Equivalent Operating Hours/Day Wind**	**Power (MW)**	**Power (MW)**	**Power (MW)**	**Power (MW)**	**Power (MW)**	**Power (MW)**	**Power (MW)**
33.33%	8.00	370.64	330.00	264.00	198.00	132.00	66.00	0.00
35.71%	8.57	345.99	308.06	246.45	184.83	123.22	61.61	0.00
36.76%	8.82	336.11	299.25	239.40	179.55	119.70	59.85	0.00
37.50%	9.00	329.46	293.33	234.67	176.00	117.33	58.67	0.00
41.67%	10.00	296.51	264.00	211.20	158.40	105.60	52.80	0.00
45.83%	11.00	269.56	240.00	192.00	144.00	96.00	48.00	0.00

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