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A Study of Energy Production in Gran Canaria with a Pumped Hydroelectric Energy Storage Plant (PHES)

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Abstract: The Canary Archipelago, in general, and the island of Gran Canaria, in particular, operate with an independent energy system (SIE), which depends largely on local power generation. Today, its energy supply comes mainly from two sources: (a) Renewable energy, accounting for 19.90%, and (b) Fossil fuel combustion in thermal power plants, contributing the remaining 80.10%. The existing energy infrastructure faces challenges due to aging technology, requiring either modernization or replacement to prevent a potential energy crisis and ensure a sustainable production cycle. A transformative step to improve the system is the completion and commissioning in 2030 of the Chira-Soria pumped hydroelectric energy storage (PHES) plant. This installation will allow water to be transported to high altitudes by pumping, to be deposited until the right time and to be turbined to generate electricity in optimal conditions. To fully understand the impact of this integration, detailed analyses of annual energy production patterns, equipment performance, and real-time demand data (collected at five-minute intervals) will be conducted. These assessments will provide insights into how the Chira-Soria PHES can be seamlessly integrated into Gran Canaria's energy network. Furthermore, they will help identify both the strengths and limitations of this storage solution, paving the way for a more resilient and efficient energy future for the island.

Keywords: pumped hydroelectric energy storage; renewable energy; insular electric systems; CO_2 mitigation

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1. Introduction

Pumped hydroelectric energy storage (PHES) systems are among the high-capacity energy storage technologies and energy produced by renewables. Achieving decarbonization goals, expanding the adoption of renewable energy sources, and taking a holistic approach to resource management are highly dependent on improving technological efficiency, with a particular emphasis on improving energy storage capacities [1–4]. This situation is especially relevant on islands that are energetically isolated [5–8], as is the case in the Canary Islands [2,4,9,10] and in Gran Canaria. The island faces a great energy challenge, which requires strategic measures to address its unique energy demands and constraints.

(a) To meet energy production targets and rising demand, it is essential to optimize the performance of existing power facilities while progressively introducing modern energy technologies [11–14]. This strategy must also consider the phased dismantling of obsolete plants and accommodate the forecasted increase in energy demand, which stood at 3,350,000.0 MWh in 2021.

(b) To prevent system failures or a potential "zero" scenario caused by outdated and insufficient energy infrastructure, a strategic plan is needed to integrate advanced systems capable of meeting growing demand. Renovating Gran Canaria's aging power plant, which has been in operation for over three decades, represents a significant challenge as it is currently undergoing updates or decommissioning. Its outdated technology no longer meets modern standards for fuel efficiency, energy output, and emission control—all essential for fulfilling current production requirements [15–23]. Additionally, reliance on fuels such as fuel oil, diesel, and diesel oil exacerbates the issue, as these are less environmentally friendly and energy-efficient alternatives [24–26]. In 2021, 79.4% of Gran Canaria's electricity was generated using imported fossil fuels [27–31], contributing to higher electricity prices and increased CO_2 emissions [2,9,23].

(c) The overarching goal is to progressively decarbonize the power generation system by integrating renewable and environmentally neutral technologies [23,28]. As of 2021, renewable energy accounted for only 20.6% of Gran Canaria's energy mix [23,29], highlighting a significant challenge [1,4]. Growing environmental awareness has prompted island governments to support wind farms, encourage solar panel installations, and explore environmentally neutral systems. Technologies such as synthetic fuels with CO_2-equivalent neutral emissions present viable alternatives, and efforts should be directed toward their adoption [2,18,32].

(d) Acritical component of Gran Canaria's energy strategy is the optimization and integration of the Chira-Soria PHES into the island's energy grid. The Chira-Soria pumped hydroelectric power plant represents a pivotal shift, providing a robust energy storage solution to balance supply and demand. By storing excess renewable energy through water elevation for later use in turbines, the system enhances the integration of renewable and neutral energy sources while contributing to the reduction of greenhouse gas (GHG) emissions.

The implementation of the Chira-Soria PHES marks a significant advancement in Gran Canaria's energy system, offering a reliable energy storage mechanism to stabilize the grid, improve renewable energy integration, and reduce dependency on imported fossil fuels. This strategic shift is essential for advancing the island's decarbonization and sustainability goals.

The Chira-Soria PHES is a project currently under construction and whose completion date is scheduled for 2030. It is a public work financed by the Government of the Canary Islands, the Government of Spain, and the European Union.

The aim of this research is to evaluate and innovate the best proposal for the inclusion of the Chira-Soria PHES, assessing its effectiveness in improving the energy contribution to Gran Canaria, addressing the existing deficiencies, and exploring the different innovations of applicability. In addition, the functionality of the system, as well as its strengths and limitations, will be explored. Additionally, the article proposes to study the water needs in response to the losses of the reservoirs, ensuring the continuity of the operation of the system. This includes examining the ability of SWRO (seawater reverse osmosis) to compensate for losses caused by hydroelectric operation, assuming that variations in precipitation do not influence the proper operation of the PHES.

Since they have been analyzed in the execution project of the Government of the Canary Islands, socioeconomic challenges, cost problems, conflicts over land use or uncertainty in the implementation of policies, reduction of the costs of the electricity system, financial analysis, cost-benefit evaluation (construction costs, operating costs, maintenance costs, expected benefits, etc.) are not the object of this article.

2. Materials and Methods

2.1. Methodology

Figure 1 illustrates the approach used to examine the system and suggest the most effective adaptation and commissioning strategy, taking into account the evolving energy landscape and the upcoming addition of the plant in 2030. This strategy builds on previous research while incorporating key innovations tailored to the unique demands of the off-grid variable power system. One of the main elements of this approach is the creation of a sophisticated optimization algorithm aimed at improving the integration of this hydroelectric plant. The main objectives of the algorithm are to boost energy efficiency, reduce operating expenses and carbon emissions, ensuring the best performance of available renewable and nonrenewable energy resources. This tool plays a vital role in enabling real-time decision-making and adapting the system to different energy demands and supplies.

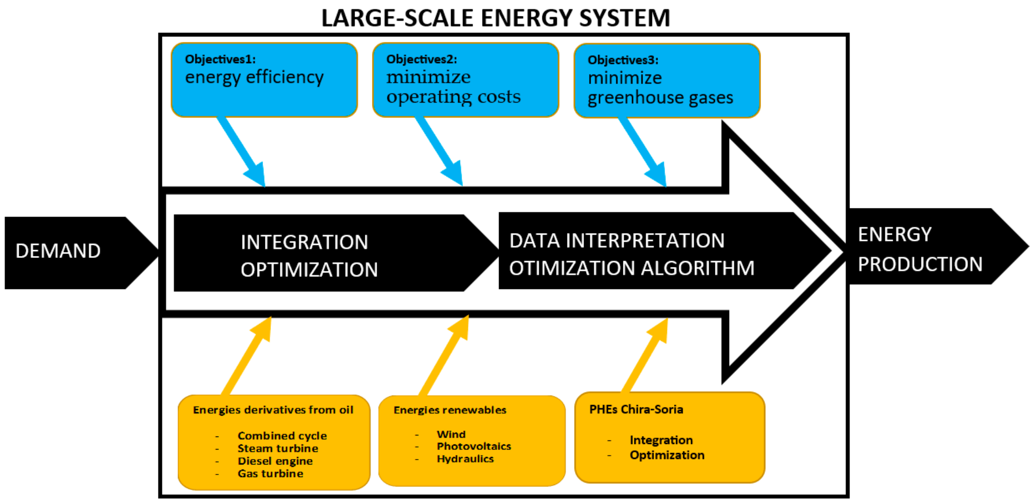

Figure 1. Methodology.

2.2. Energy Production in Force in Gran Canaria

The most up-to-date official statistics available for Gran Canaria are those for 2022, but they were not considered adequate for analysis because they were more restrictive and less representative. The data for 2021 were considered timelier after extensive analysis. According to these data, energy production was based on a combination of four steam turbines, five diesel engines, five gas turbines, and two combined cycle plants with gas and steam turbines. This configuration accounted for 80.10% of the total installed capacity (1.02 GW), while renewables accounted for 19.90% of the total installed capacity (0.25 GW). The total energy production for the year was 3350.09 GWh, of which 2661.45 GWh (79.44%) came from fossil fuel-fired thermal power plants and 668.64 GWh (20.56%) generated by wind turbines and solar systems. Specifically, 55.82 GWh (1.67%) were produced by solar photovoltaic systems and 632.81 GWh (18.89%) by wind energy, as detailed in Table 1.

The data on average daily usage reveals that the equipment is functioning below optimal levels. This is mainly due to its aging condition, which causes more operational challenges, frequent breakdowns, longer repair times, and greater maintenance demands. Consequently, variable operational costs are rising. To mitigate this, a policy has been put in place to maintain a significant stock of reserve equipment. However, this results in surplus capacity since many units are approaching the end of their useful life.

All units work an average of 7.30 h per day, and combustion units operate at a utilization rate of 30.41%. The combined cycle units have the highest usage, running for 10.41 h per day and achieving a utilization rate of 43.46%.

Analyzing the day with the highest energy demand provides important insights into the challenges facing Gran Canaria's energy system in the near future. On 17 August 2021, at 14:53, the instantaneous power demand reached 529.0 MW, marking the highest level since 2007. During this peak, 138.7 MW of the demand was met by renewable sources, while 390.3 MW came from nonrenewable sources. Figure 2 illustrates the response to the maximum demand for the year, differentiating the demand covered by renewables and nonrenewables.

Table 1. Installed power (MW) and energy Production (MWh) of Gran Canaria in 2021 [18].

Origin Energy		Installed Power		Energy Production	
		MW	%	MWh	%
Energies derived from oil	Steam turbine	280.00	21.90%	647,519.00	19.33%
	Diesel engine	84.00	6.57%	199,206.00	5.95%
	Gas turbine	173.45	13.57%	60,853.00	1.82%
	Combined cycle	461.73	36.12%	1,753,875.00	52.35%
	Cogeneration	24.88	1.95%	0.00	0.00%
	Total	1024.06	80.10%	2,661,453.00	79.44%
Energies produced by renewables	Wind turbines	205.24	16.05%	632,818.00	18.89%
	Photovoltaics	49.15	3.84%	55,823.00	1.67%
	Total	254.39	19.90%	668,641.00	20.56%
TOTAL		1278.45	100.0%	3,350,094.00	100.00%

Source: Canary Islands Energy Yearbook 2021.

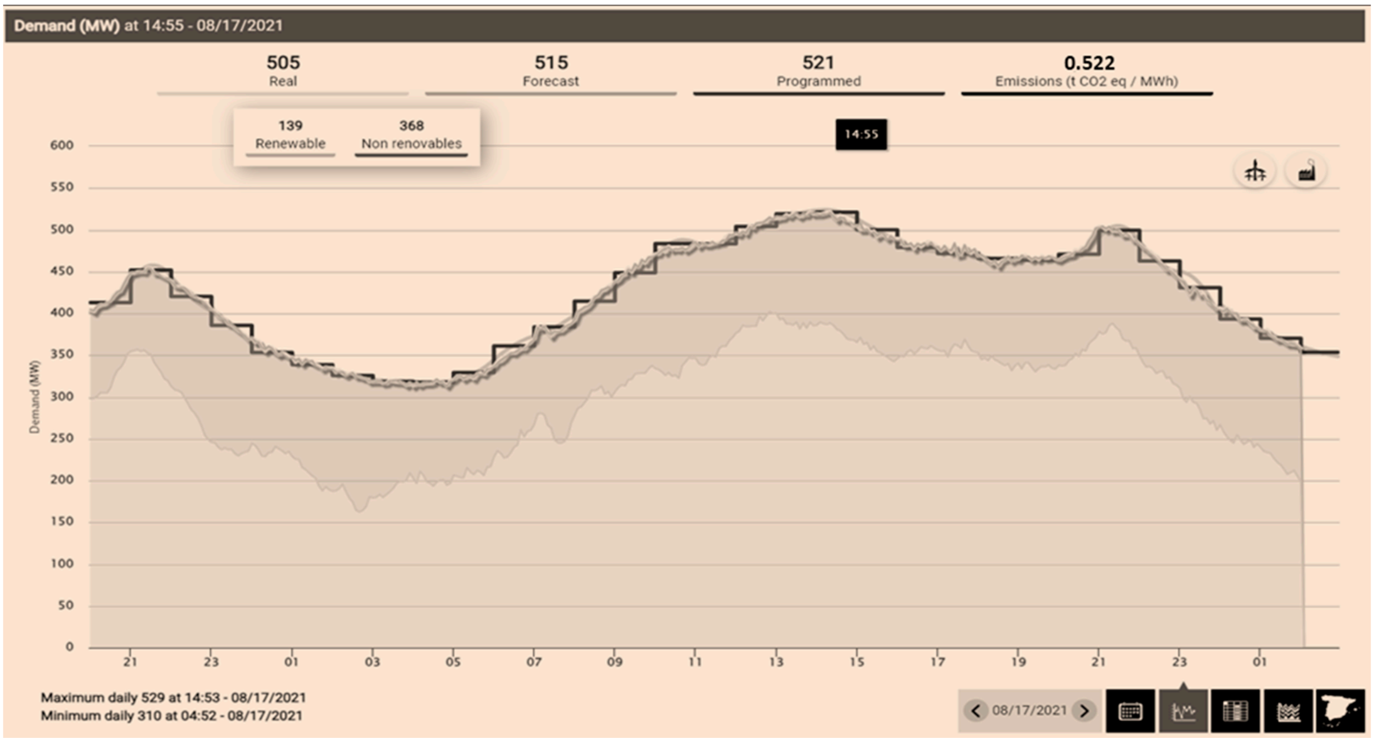

Figure 2. Behavior and response to the peak demand of 2021 [31].

Figure 3 breaks down the contributions of each production unit during this peak. On the day of highest demand of the year 2021, the combined cycle unit contributed the largest participation, 43.09%, which represents 218.20 MW; the steam turbine contributed 22.69%, which represented 115.00 MW; wind turbines accounted for 22.18% with 112.40 MW, photovoltaic energy 5.19% with 26.30 MW, 4.34% diesel engines with 22.00 MW, and the gas turbine was the one that contributed the least, 2.55% contribution with 12.90 MW.

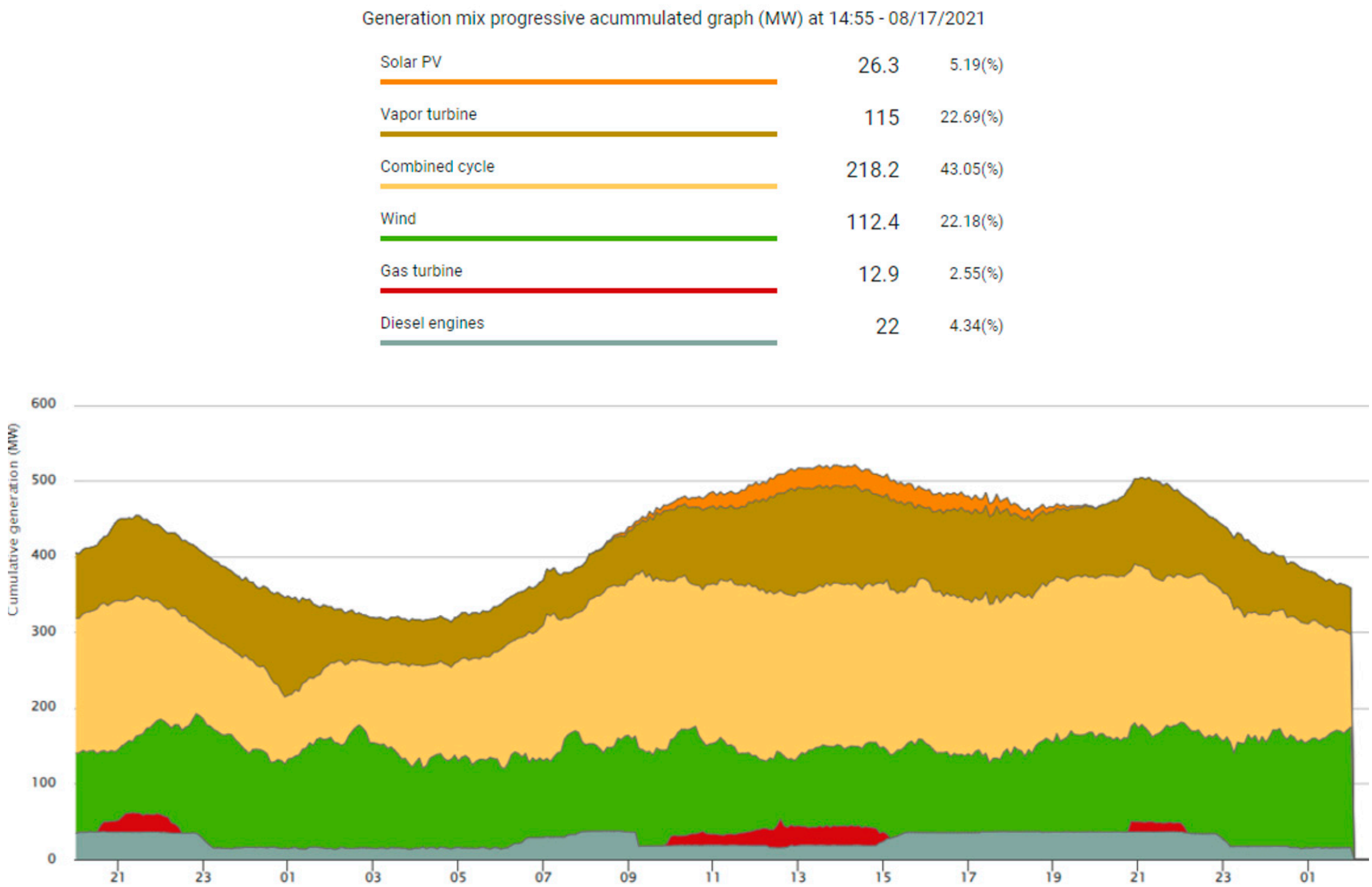

Figure 3. Energy production by technologies at peak demand in 2021 [31].

Table 2 provides a breakdown of the fuel types used by different technologies and the corresponding greenhouse gas (GHG) emissions. In 2021, 555,811 tons of fuel were burned for energy generation, leading to emissions of 1,782,561 tons of CO_2 equivalent (tCO_2eq). The net final energy delivered, after accounting for losses, was 3,076,109 MWh. As a result, the emission factor for Gran Canaria in 2021 stood at 0.579 tCO_2eq/MWh.

Table 2. Types of fuels (t) and GHG by technology (tCO_{2eq}).

Technology	Fuels (t)		GHGs (tCO_{2eq})		
	Fuel Oil	Diesel	CO_2	CH_4	Nox
Steam turbine	160,119.00	129.00	524,382.00	427.00	1260.00
Diesel engine	37,852.00	1561.00	128,793.00	105.00	310.00
Gas turbine	0.00	21,781.00	68,710.00	58.00	172.00
Combined cycle	0.00	334,369.00	1,054,799.00	897.00	2648.00
Total	197,971.00	357,840.00	1,776,684.00	1487.00	4390.00

Source: Canary Islands Energy Yearbook 2021 [18].

2.3. Chira-Soria PHE Analysis

Chira-Soria is an upcoming pumped hydroelectric power plant (PHE) that has been in the planning stages for several years and is currently under construction on Gran Canaria. It utilizes the elevation difference between two existing reservoirs to generate energy via turbines. Set to become operational in 2026, it will be the island's first plant of this type. Along with the other energy generation units on Gran Canaria, it will provide power to a population of around one million people. The plant is situated in Tejeda, a municipality in the island's central region, as shown in Figure 4.

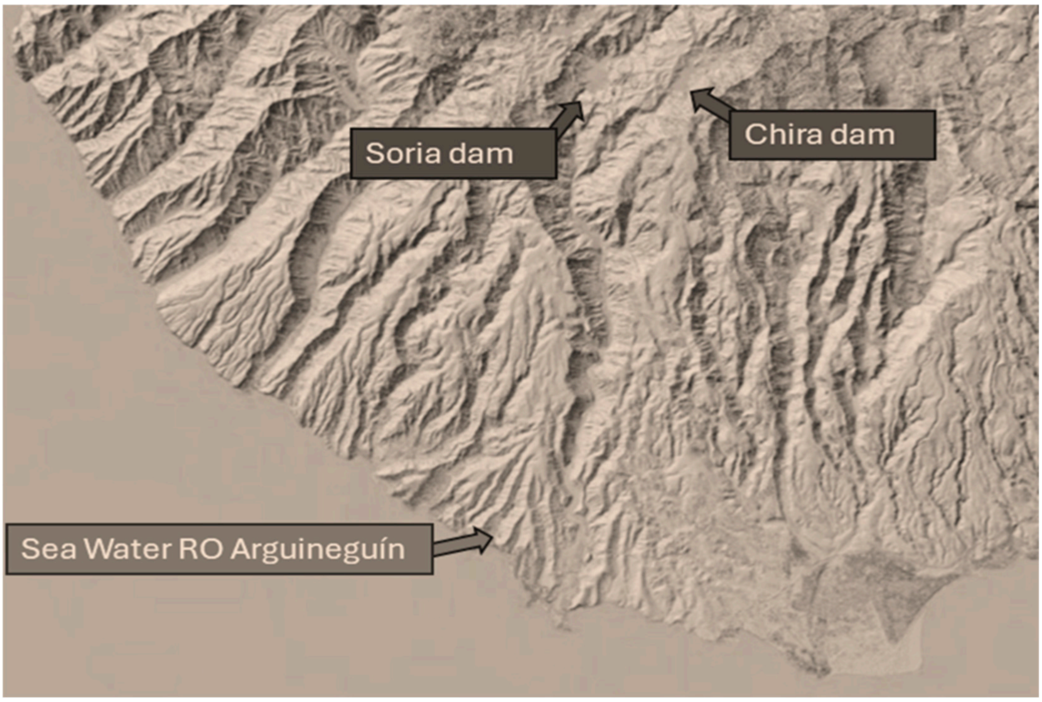

Figure 4. Location: Chira-Soria SWRO and PHEs.

2.3.1. Technical Forecasts Expected from the Plant

In 2021, Gran Canaria's wind capacity stood at 205.24 MW. In addition, future installations, including wind turbines and photovoltaic panels, are expected to total up to 725.00 MW, with grid access approval already secured.

The Chira-Soria pumped hydroelectric energy (PHE) power plant aims to improve the reliability of supply and increase the integration of intermittent wind and solar energy sources. The increasing variation in wind turbine power generation results in variations that cannot be absorbed by the electricity system, which are expected to intensify as wind power capacity expands. These fluctuations can negatively affect consumers and can cause disruptions in the energy market. The objective of the Chira-Soria PHE power plant is to alleviate these frequency problems, making the system more stable, solid, and safe. It will also achieve the smooth integration of large amounts of wind energy that are expected in the future.

With enhanced renewable energy integration through energy storage, thermal generation will be reduced in favor of renewables, leading to lower CO_2 and NO_x emissions, offering both economic and environmental benefits. This will introduce greater flexibility into the energy system, where existing nonrenewable technology, originally prepared for a different energy scenario, does not possess adequate capabilities to manage renewable energy during the transition effectively. The Chira-Soria PHE will be notable for its large energy storage capacity and its technology, which, depending on its operational mode, will help maintain the grid's synchronous characteristics by providing inertia, short-circuit power, and other critical functions.

Additionally, a desalination plant will be integrated into the system to ensure sufficient water supply to compensate for losses from the hydroelectric operations. This will guarantee that variations in rainfall do not impact the functioning of the PHE. Currently, agricultural activities linked to Chira and Soria depend on the rainfall patterns of the south of Gran Canaria. Because of this, the desalination plant will help keep the reservoir's water levels within optimal limits.

2.3.2. Characteristics of Chira-Soria PHE

- Hydraulic system

Figure 5 shows the hydraulic system of Chira-Soria PHE. Figure 6 shows the layout of the circuit followed by the water (hydraulic circuit).

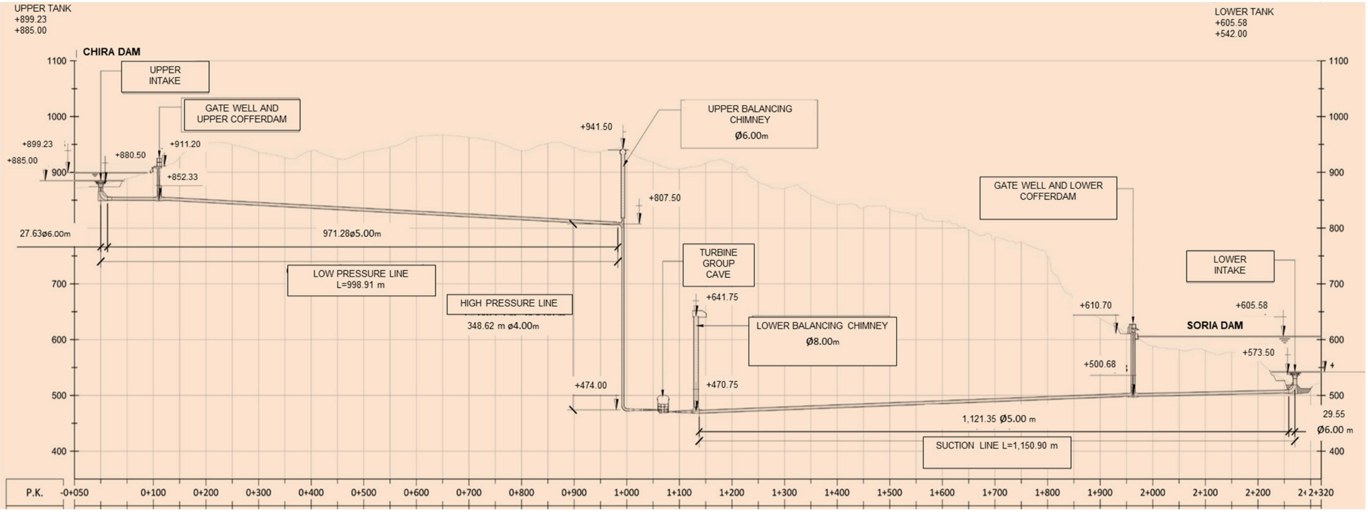

Figure 5. Hydraulic system of Chira-Soria PHE [31].

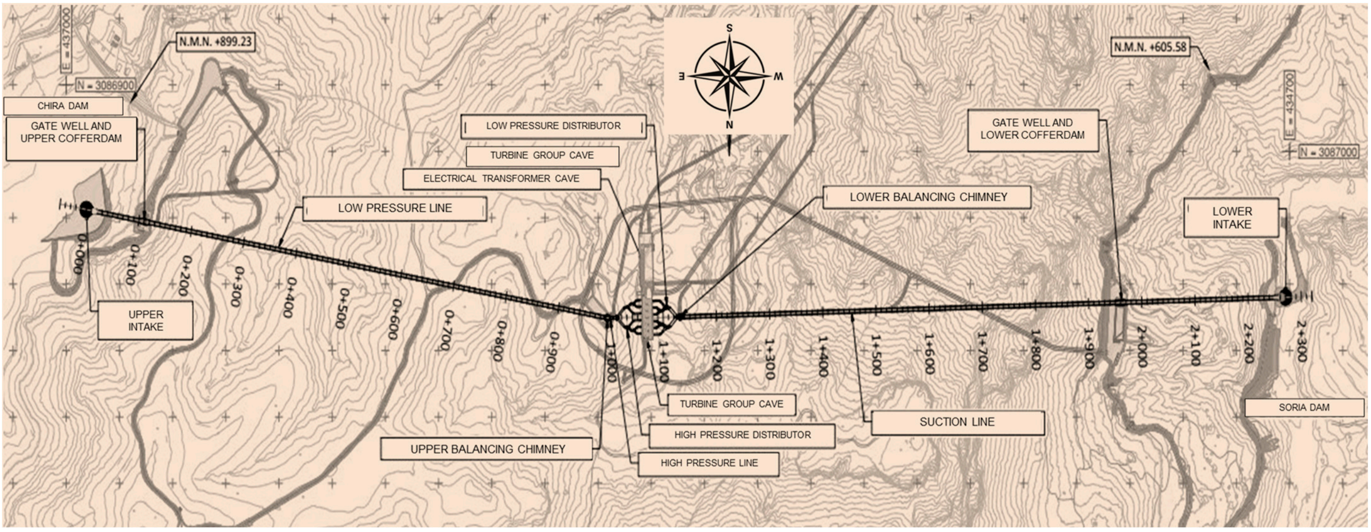

Figure 6. Layout of the circuit followed by the water (hydraulic circuit) [31].

Table 3 provides details on the turbomachinery used in the Chira-Soria pumped-storage hydroelectric station, including their performance characteristics for both generation and pumping modes.

Table 3. Turbine operation mode.

Mode of Operation	Units	Hours of Work	Power per Unit	Power Total	Caudal	Water Volume	Energy Day
	Ud	hours	MW	MW	m^3/s	m^3	MWh
(T1) Turbining	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

Source: Chira-Soria PHE Project.

The Soria reservoir has a capacity of 32.30 hm^3, while the Chira reservoir holds 5.64 hm^3 of water. The maximum water transfer capacity between the two dams is 4.08 hm^3. The water in these reservoirs is sourced from rainfall collected in several ravines.

To maintain the reservoir water levels within the required range, the reverse osmosis plant that processes seawater produces 0.007 hm^3 of water per day. This amount is insignificant compared to the volumes used in power generation and pumping activities: 3.94 hm^3 in 16 h for generation and 1.54 hm^3 in 8 h for pumping.

- Stabilization of the water resource

An in-depth analysis was carried out to evaluate the water supply requirements for industrial purposes associated with the Soria reservoir and its hydroelectric facility. Ensuring adequate water inflows is crucial for maintaining the hydroelectric system's ability to function at optimal capacity during its operational lifespan.

To estimate the water production needs for industrial use, three distinct calculations were performed. The first calculation quantified the reservoir's annual water losses due to evaporation and seepage, amounting to 1.63 hm^3 per year. The second assessment incorporated potential climate change effects, referencing targets from the Paris Climate Agreement, which seeks to restrict global temperature rise to 1.5 °C by 2100. Under these conditions, annual water losses could increase to approximately 1.68 hm^3. To counterbalance these deficits, the required production capacity of the seawater reverse osmosis (SWRO) plant is estimated at 1.80 hm^3 per year. Any excess water generated by the SWRO plant will additionally serve the nearby town of Arguineguín, as illustrated in Figure 7.

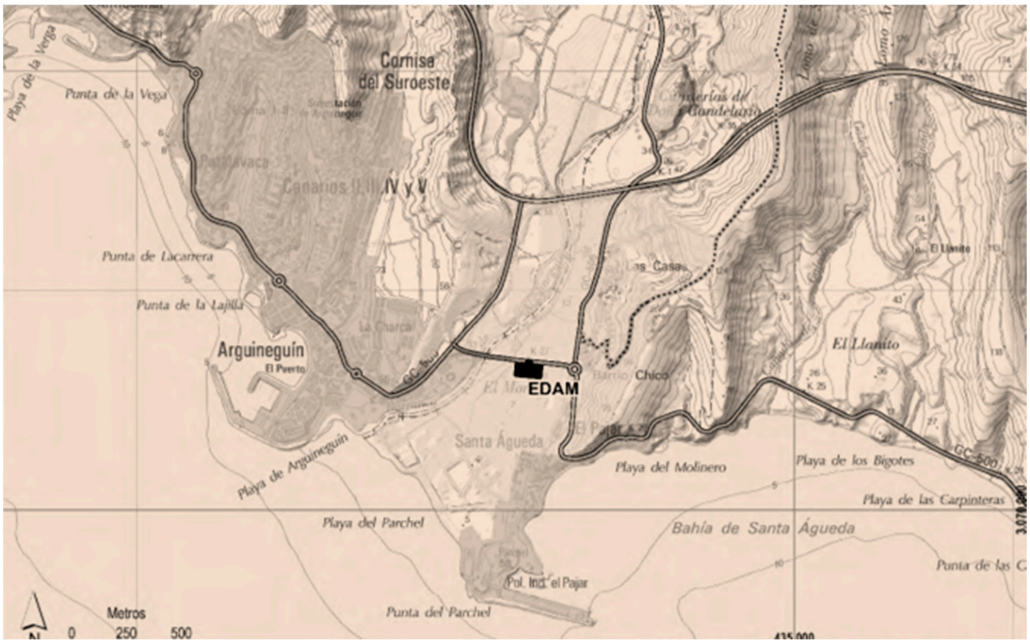

Figure 7. Arguineguín. SWRO Situation.

2.3.3. Functional Description

The plant will operate in pumping mode during periods of energy surplus, mainly caused by excessive nondispatchable generation (primarily wind) or low electricity demand. Without this approach, large thermal power plants might be forced to run inefficiently or below their technical minimum. During periods of high energy demand, the plant will switch to turbine mode, substituting energy that would otherwise be generated by costlier and environmentally impactful thermal technologies.

The plant follows a daily operational cycle as follows:

Pumping Mode: During off-peak hours (typically from midnight to 7:00 am), the turbomachinery consumes electricity to pump water from Soria (lower basin) to Chira (upper basin). This mode of operation uses excess renewable energy produced during the night, avoiding waste. Additionally, it helps thermal plants maintain optimal efficiency during low-demand hours, reducing overall CO_2 emissions. Pumping also eliminates the need for expensive shutdown and restart cycles of thermal units. In cases of surplus wind energy, pumping can artificially boost demand, improving energy integration.

Turbine Mode: In peak demand hours (usually between 9:00 am and 11:00 pm), with key peaks between 10:00 am and 1:00 pm and 7:00 pm to 9:00 pm), the turbomachines generate electricity by transferring water from the upper basin to the lower basin. The turbine replaces more expensive technologies, such as gas turbines powered by diesel, throughout the year.

In addition, the hydropower plant's rapid response capabilities allow it to react quickly to grid or system failures, and power can be restored within 10 to 20 min due to its flexibility, making it the main recovery system in the grid.

The facility has a maximum of 200 MW for turbines and a maximum of 220 MW for firefighters, with a total energy storage capacity of 3.2 GWh in 16 h of turbining. The maximum volume of water that can be moved between the two reservoirs is 4.08 hm^3. Sedimentation studies show that the water transfer capacity will remain unaffected by sediment accumulation for at least 50 years, ensuring an initial operational lifespan of five decades before dredging becomes necessary.

2.3.4. Advantages and Disadvantages

- Balancing of pumping turbine

As discussed earlier, the plant's units will alternate between pumping and turbine modes throughout the day. This section examines the electricity demand associated with each mode during different hours of operation, along with the corresponding volumes of water pumped and turbined, as presented in Table 4.

Table 4. Hydraulic balance in pumping and turbine operation.

Mode of Operation	Operation Time		Power Total	Energy Day	Caudal	Water Volume
	h/day	%	MW	MWh	m/s^3	m^3
Balance turbine	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
Total	24.000	100.00%				

Maintaining water levels is crucial to ensure uninterrupted turbining operations. Therefore, it is essential to achieve a balance between water pumping and turbining within the designated operational periods, preventing any risk of exceeding the transfer capacity. Table 4 highlights the system's hydraulic limitations, providing a reference for determining the maximum energy capacity achievable under these constraints.

If the turbines operate for 43.84% of the day (equivalent to 10 h and 31 min), pumping must take place for the remaining 56.16% (around 13 h and 28 min). This operational pattern results in an energy generation of 2104.43 MWh per day from turbining, while the energy required for pumping reaches 2965.12 MWh per day.

- Analysis of renewable and power energy production

As previously highlighted, Chira-Soria PHE is designed to optimize the integration of renewable energy sources, minimizing potential energy discharges and supporting the growth and deployment of these technologies. At present, there are several new renewable projects with a combined potential capacity of 725.00 MW. However, only 400.97 MW have received Final Registration confirmation.

Table 5 outlines the projected growth in renewable energy production based on 2021 data for average operating hours of renewable technologies.

Table 5. Expected growth in renewable energy.

Type Renewable	Chira-Soria Project Estimate	Year 2021	Year 2023	Final Registration
	GWh Year	GWh Year	GW Year	GW Year
Wind	1829.62	641.99	955.57	1001.58
Photovoltaic	148.90	52.24	77.76	85.85
Total	1978.53	694.23	1033.34	1087.44

- Analysis of the new availability of power in the island's electricity system

From the previous study, energy production facilities are defined in Table 6. Installed capacity has grown by 13.53%, and renewable energies now account for 30.73% of total installed capacity.

Table 6. New power availability in Gran Canaria's electricity system (MW).

Origin Energy		Installed Power	
		MW	%
Energies derived from oil	Steam turbine	280.00	18.94%
	Diesel engine	84.00	5.68%
	Gas turbine	173.45	11.73%
	Combined cycle	461.73	31.23%
	Cogeneration	24.88	1.68%
	Subtotal	1024.06	69.72%
Energies produced by renewables	Wind	205.24	13.88%
	Photovoltaics	49.15	3.32%
	Hydraulics	200.00	13.53%
	Subtotal	454.39	30.73%
Total		1478.45	100.00%

- Analysis of the new energy production and demand of the island's electricity system

The implementation of the Chira-Soria PHE project introduces significant considerations regarding energy demand and production. The facility will require water to be transferred from Soria to Chira, causing an estimated daily energy demand increase of 2.96 GWh, which scales up to approximately 1082.26 GWh annually under full pumping capacity. This demand corresponds to 56.16% of the annual average operational hours, raising the total yearly demand from 3350.09 GWh to a potential maximum of 4432.36 GWh.

On the energy production side, the turbine process is expected to generate an average of 2.10 GWh per day, translating to about 768.11 GWh annually when operating at maximum turbine capacity. This accounts for 43.84% of the annual operational time. As a result, the addition of the Chira-Soria hydroelectric pumping station would increase annual electricity production from 3350.09 GWh to a maximum of 4118.21 GWh. However, this would still result in an annual energy shortfall of approximately 314.15 GWh. Table 7 shows the impact of Chira-Soria PHEs on energy demand and production.

Table 7. Impact of Chira-Soria PHEs on energy demand and production.

Analysis of the new demand depending on the % of the pumping operation.							
Percentage pumping operation (%)	56.16%	50.00%	40.00%	30.00%	20.00%	10.00%	0.00%
Pumping (h/day)	13.48	12.00	9.60	7.20	4.80	2.40	0.00
Increase demand (GWh year)	1082.26	963.60	770.88	578.16	385.44	192.72	0.00
Pre-existing demand (GWh year)	3350.09	3350.09	3350.09	3350.09	3350.09	3350.09	3350.09
Sum (GWh year)	4432.36	4313.69	4120.97	3928.25	3735.53	3542.81	3350.09
Analysis of the new energy production depending on the % of the turbine operation.							
Percentage turbine operation (%)	43.84%	39.04%	31.23%	23.42%	15.61%	7.81%	0.00%
Turbine (h/day)	10.52	9.37	7.49	5.62	3.75	1.87	0.00
Production increase (GWh year)	768.11	683.89	547.11	410.33	273.55	136.77	0.00
Pre-existing production (GWh year)	3350.09	3350.09	3350.09	3350.09	3350.09	3350.09	3350.09
Sum (GWh year)	4118.21	4033.98	3897.20	3760.43	3623.65	3486.87	3350.09
Net energy. Difference. (GWh year).	−314.15	−279.70	−223.76	−167.82	−111.88	−55.94	0.00

- New power needs from renewables

In order to cope with the updated energy production requirements and meet the growing demand, two key scenarios are analyzed:

Balancing Pumping and Turbining Differences: This scenario estimates the additional wind energy needed to compensate for the energy gap between water pumping and electricity generation through turbining.

Fully Meeting Pumping Energy Needs: This scenario evaluates the wind energy required to completely cover the energy consumed during the pumping process.

For both scenarios, wind energy requirements are determined using various capacity factors. As previously noted, the average annual wind power capacity factor stands at 36.8%, which corresponds to approximately 8.8 h per day or 3220.00 equivalent operational hours per year. This first scenario, described in Table 8, a wind power capacity of 97.6 MW would be required to bridge the net energy gap between pumping consumption and turbine generation. This estimation assumes pumping operates 56.1% of the time and turbining 43.9%, using a wind capacity factor of 36.78% (8.8 h per day), consistent with the 2021 average performance.

Table 8. New power needs from renewables to cover the difference in demand.

Percentage pumping performance (%)		56.1%	50.0%	40.0%	30.0%	20.0%	10.0%	0.0%
Hours pumping operation per day (h/day)		13.5	12.0	9.6	7.2	4.8	2.4	0.0
Capacity factor wind	Equivalent operating	Power (MW)						
25.0%	6.0	143.4	127.7	102.2	76.6	51.0	25.5	0.0
29.2%	7.0	123.0	109.5	87.6	65.7	43.8	21.9	0.0
33.3%	8.0	107.6	95.8	76.6	57.5	38.3	19.1	0.0
35.7%	8.6	100.4	89.4	71.5	53.6	35.8	17.9	0.0
36.8%	8.8	97.6	86.9	69.5	52.1	34.7	17.4	0.0
37.5%	9.0	95.6	85.1	68.1	51.0	34.0	17.0	0.0
41.7%	10.0	86.1	76.6	61.3	46.0	30.6	15.3	0.0
45.8%	11.0	78.2	69.7	55.7	41.8	27.9	13.9	0.0

The second scenario, described in Table 9, is shown.

It is about achieving full coverage of pumping energy requirements over the maximum operational duration of 56.1% of the time, which would necessitate a wind power capacity of 336.1 MW. This calculation also relies on the same wind capacity factor of 36.8% (8.8 h per day), aligning with the 2021 benchmark.

It is essential to compare installed wind power capacity and energy production with the operational hours of pumping to ensure synchronization. Table 10 shows that the highest pumping capacity corresponds to 21 h and 13 min of continuous operation.

Table 9. New power needs from renewables to cover exclusively the increase in pumping demand.

Percentage pumping performance (%)		56.1%	50.0%	40.0%	30.0%	20.0%	10.0%	0.0%
Hours pumping operation per day (h/day)		13.5	12.0	9.6	7.2	4.8	2.4	0.0
Capacity factor wind	Equivalent operating	Power (MW)						
25.0%	6.0	494.2	440.0	352.0	264.0	176.0	88.0	0.0
29.2%	7.0	423.5	377.1	301.7	226.3	150.9	75.4	0.0
33.3%	8.0	370.6	330.0	264.0	198.0	132.0	66.0	0.0
35.7%	8.6	346.0	308.0	246.4	184.8	123.2	61.6	0.0
36.8%	8.8	336.1	299.2	239.4	179.5	119.7	59.8	0.0
37.5%	9.0	329.5	293.3	234.7	176.0	117.3	58.7	0.0
41.7%	10.0	296.5	264.0	211.2	158.4	105.6	52.8	0.0
45.8%	11.0	269.6	240.0	192.0	144.0	96.0	48.0	0.0

Table 10. Turbine and maximum pumping.

Mode	**Operation**		**Caudal**	**Volume of Water**
	Time	**%**	**m^3/s**	**hm^3**
Balance turbining	16 h 34 min	43.9%	68.4	4.08
Balance pumping	21 h 13 min	56.1%	53.4	4.08
Sum		100.0%		

Under these conditions, working pumping operations for 21 h and 13 min would require a wind power capacity of 529.3 MW, translating to an annual energy demand of approximately 1703.87 GWh, assuming a wind capacity factor of 36.8% (8.8 h per day), as detailed in Table 11.

Table 11. 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	Equivalent operating	Power (MW)	
25.0%	6.0	494.2	778.2
29.2%	7.0	423.5	667.0
33.3%	8.0	370.6	583.6
35.7%	8.6	346.0	544.8
36.8%	8.8	336.1	529.3
37.5%	9.0	329.5	518.8
41.7%	10.0	296.5	466.9
45.8%	11.0	269.6	424.5

- Analysis of working water volumes

In order to reach an annual energy output of 768,118.23 MWh through the turbine, the frequency of water replacement in the reservoir can be approximated as follows:

Total Replacement Duration: Draining the reservoir takes 16 h and 34 min, while refilling requires 21 h and 13 min. This sums up to a complete water renewal cycle lasting 37 h and 47 min.

Yearly Cycles Needed: Achieving the turbine's maximum annual energy capacity demands approximately 231.8 full water replacement cycles per year.

2.3.5. Efficiency Comparison with Other Modern Energy Storage Technologies

The Chira-Soria pumped hydroelectric plant is an efficient technology for mass energy storage, but its performance varies compared to other modern storage technologies:

- Energy efficiency

Chira-Soria (pumped hydroelectric plant): It has a full-cycle efficiency of between 70% and 80%. It is highly efficient for large-scale and long-term storage.

Lithium-ion batteries: Efficiency of 85% to 95%, but with greater degradation in the long term. Suitable for short-term storage and fast-response applications.

Flow batteries: Efficient around 65% to 75%, but can be scaled for extended storage with less degradation.

Green hydrogen: Efficiency of around 30% to 50% due to losses in electrolysis and conversion to electricity.

- Scalability and storage capacity

Chira-Soria: High storage capacity (several GWh), ideal for island or national electricity systems.

Lithium-ion batteries: Limited by cost and energy density; best suited for decentralized applications.

Flow batteries: Good scalability, but with low energy density.

Green hydrogen: Excellent capacity for seasonal storage, although with low efficiency.

- Response Time and Storage Duration

Chira-Soria: Fast response time (seconds to minutes) and long storage (days).

Lithium-ion batteries: Almost instantaneous response, but limited duration (hours).

Flow batteries: Good duration (hours to days) and quick response.

Green hydrogen: Long-term storage (months), but with a slow response in the conversion.

2.4. Connection of the Chira-Soria Hydroelectric Power Plant with the Energy Infrastructure of Gran Canaria

2.4.1. Contribution to the Current Energy System

The day with the highest demand and, therefore, the highest electricity production of 2021, 17 August 2021, indicates that the contribution of wind energy remains relatively stable throughout the 24-h period (see Figure 8). On average, 119.2 MW of the total installed capacity of 205.2 MW are used, with a peak hourly average of 147.5 MW and the lowest hourly average of 91.1 MW. This stable pattern, shown in Figure 8, illustrates that wind energy production remains within a stable range during the day; these figures are considered typical due to the generally constant nature of wind energy production in the different months of the year; moreover, this trend is maintained each year. As you can see, the installed wind capacity is much lower than what is ideally needed. Therefore, there is no immediate concern regarding excess wind energy generating waste. In addition, it should be noted that the study of climate change foresees that due to this factor, there will be changes in the dynamics of the wind, making it gustier, variable in component, and with large gaps of wind deficiency. All this means that in order to cover the wind demand necessary for the Chira-Soria project, the power must be further increased through the installation of wind turbines.

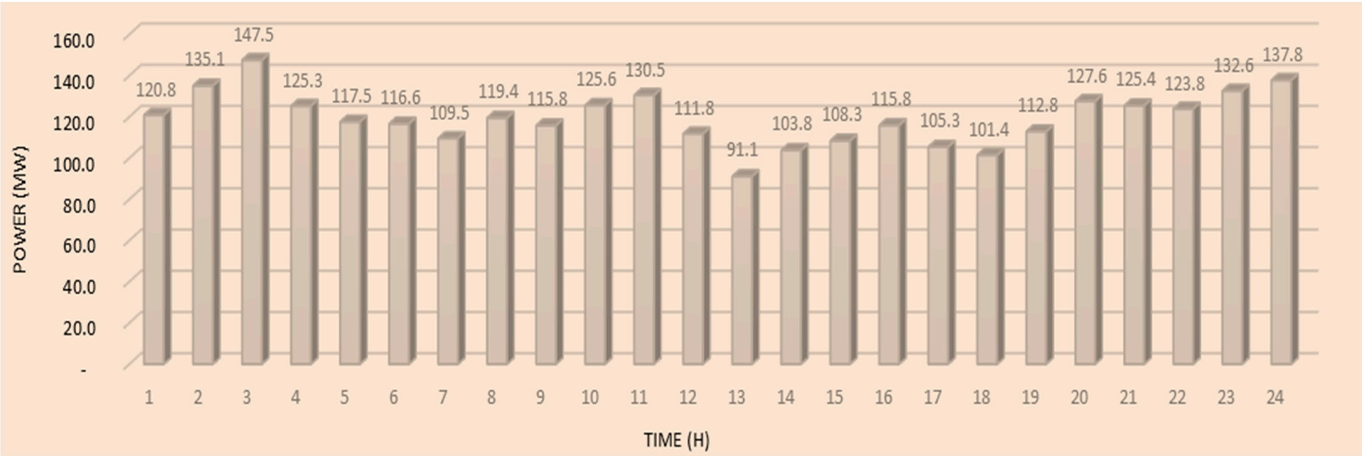

Figure 8. Wind power the day with the highest demand (MW) [18].

To fulfill the pumping needs of the Chira-Soria hydroelectric plants (refer to Table 11), an additional 529.3 MW of wind energy would be required, based on a capacity factor of 36.8% (8.8 h daily). With only 205.2 MW of wind power currently installed, integrating the Chira-Soria plants would necessitate a reduction in the installed capacity and energy production from the existing system. As more wind power capacity is added and approaches the target, the Chira-Soria plants will more effectively meet their design goals.

Another analysis focused on integration optimization focuses on daily variations in energy production, as shown in Figure 9. It examines weekly fluctuations in energy production and demand to identify potential dips on days of lower industrial activity. By using excess energy from combustion during these periods of low demand, it could be directed towards pumping. This strategy would help to meet the minimum technical requirements of the equipment, in particular of the combined cycle units.

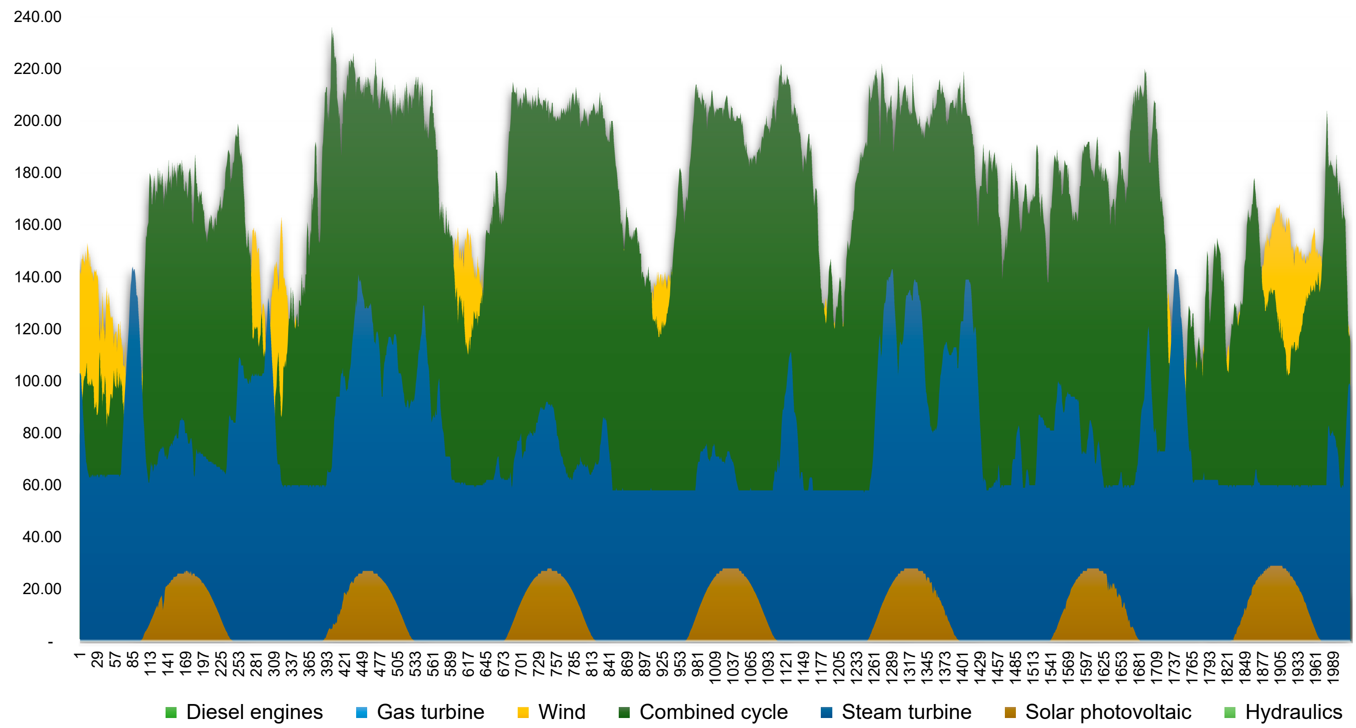

Figure 9. Production the day with the highest demand (MW) [18].

In the period of low demand (energy storage). When there is an excess of electricity on the grid (for example, at night or on days of high solar or wind production), this energy is used to pump water from a lower reservoir to an upper reservoir. This process consumes electricity but allows energy to be stored in the form of elevated water. You can see the result in Figure 10.

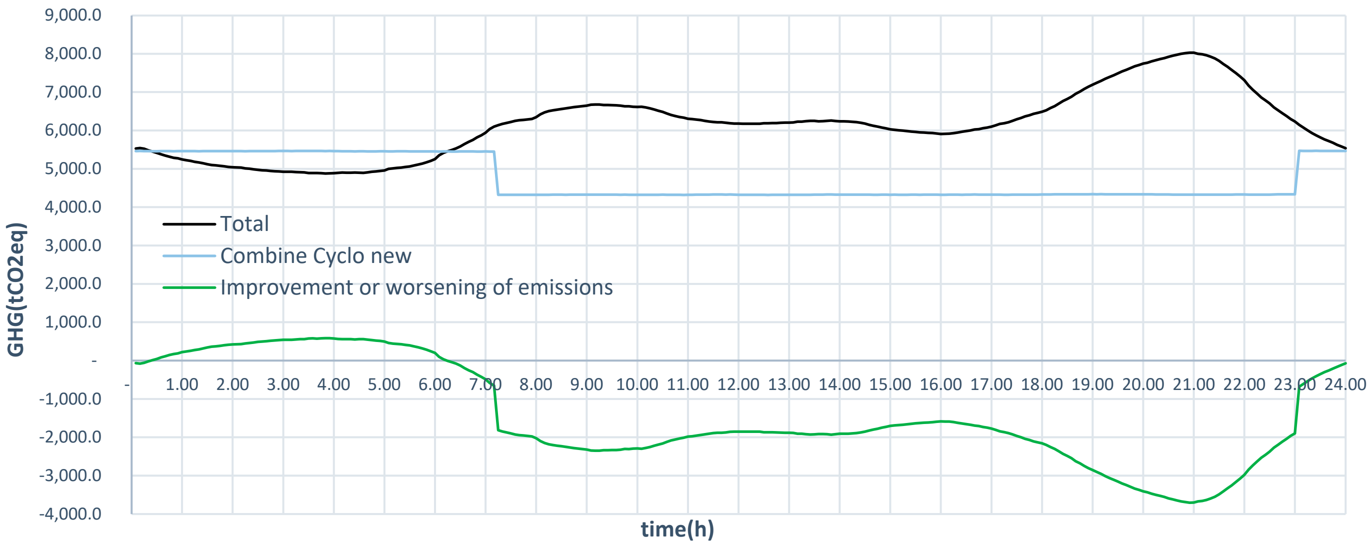

Figure 10. Comparison of the average daily emissions in the current energy production and the estimate with the incorporation of Chira-Soria (average annual day).

This approach could act as an effective interim solution until wind power can fully meet the plant's demand, especially on off-peak days, making better use of available energy resources.

2.4.2. Involvement in the Evolving Energy System of Gran Canaria

The Chira-Soria PHEs project has been developed to meet specific energy demands. Based on the study findings, reaching the targeted results will require an extra 529.3 MW of wind energy, increasing the total installed wind capacity to 734.5 MW. The updated power capacity, as shown in Table 12, totals 2007.7 MW, with 48.99% of this coming from renewable sources. This table reflects the combined energy generation, which includes both the hydro turbine output and the new wind power installations.

Table 12. Capacity study (MW).

Origin Energy		Installed Power	
		MW	%
Energies derived from oil	Steam turbine	280.00	13.95%
	Diesel engine	84.00	4.18%
	Gas turbine	173.45	8.64%
	Combined cycle	461.73	23.00%
	Cogeneration	24.88	1.24%
	Subtotal	1024.06	51.01%
Energies produced by renewables	Wind	734.51	36.58%
	Photovoltaics	49.15	2.45%
	Hydraulics	200.00	9.96%
	Subtotal	983.66	48.99%
Total		2007.72	100.00%

Furthermore, Table 13 introduces a new energy demand tied to the pumping operations of the plant. This scenario results in an additional 1389.72 GWh per year compared to the current renewable overproduction situation. The added generation can help reduce dependence on non-renewable sources, which currently meet 2661.45 GWh of demand, and support the pumping activities. As a result, this would lead to a 47.78% reduction in polluting power and emissions while increasing the share of renewable energy production to 71.31%.

Table 13. Global increase production and demand (MWh).

Type Technology	Powers	Actual Situation	Increased Energy Production	Increased Energy Demand	Equilibrium	
	MW	GW	GW	GWh	GWh	%
Current nonrenewable generation	1024.06	2661.45	2661.45	2661.45	1271.72	28.69%
Current photovoltaic renewable generation	49.15	55.82	55.82	55.82	55.82	1.26%
Current wind renewable generation	205.24	632.81	632.81	632.81	632.81	14.28%
Generation by new wind renewables	529.27	-	1703.87	-	1703.87	38.44%
Hydro turbine generation	200.00	-	768.11	-	768.11	17.33%
Demand pumping	−220.00	-	-	1,082,269.50	-	-
		3350.09	5822.09	4432.36	4432.36	100.00%

3. Results and Discussions

During the evaluation of integrating the Chira-Soria PHEs into Gran Canaria's energy grid and maintaining stable water levels in the reservoirs to ensure consistent operation, the following findings were observed:

3.1. Installation Features

Efficiency of Hydraulic Turbomachinery: Performance of turbo hydraulic machines: The turbo hydraulic machines used in pumping mode exhibit lower performance compared to turbines. They require more power for lower hydraulic consumption, resulting in a deficit of 20.00 MW and a reduced pumping flow compared to turbines. Consequently, more time and energy are needed to restore the normal operating levels of the reservoirs. Specifically, out of a maximum of 24.00 h of operation, 13.50 h is needed for pumping versus 10.50 h for turbinating. This imbalance leads to an annual energy deficit of 314.15 GWh.

Reservoir Storage and Energy Output: The Chira reservoir, with a total capacity of 5,640,000.00 m^3, supports a maximum transferable volume of 4,080,000.00 m^3. This limitation constrains the energy output capacity of the power plant. To maximize energy production, continuous energy generation would need to run for 16.00 h and 34.00 min, yielding 3.31 GWh. Achieving this would require compensatory pumping for 21.00 h and 15.00 min, consuming 4.66 GWh.

3.2. Water Resource Stabilization

A comprehensive study on industrial water supply requirements for the Soria reservoir and its associated hydroelectric plant highlights the critical need to maintain sufficient water inflow for optimal system functionality. The analysis included three assessments to quantify annual water losses caused by evaporation and seepage, totaling approximately 1.63 hm^3 per year. Under a climate change projection targeting a temperature increase of no more than 1.5 °C by 2100, these losses are anticipated to rise slightly to 1,680,000.00 m^3 annually.

To determine the average annual industrial water demand, a simulation covering the years 1972 to 2019 was conducted. The results, summarized in Table 14, present water consumption trends based on annual and seasonal fluctuations. This data-driven approach supports accurate planning to address future water resource needs, ensuring long-term sustainability in the face of evolving climate conditions.

Table 14. Analysis of the evolution of reservoirs from 1972 to 2019.

Situation	Characteristic	Annual Average Industrial Water Requirement in Chira (m^3/Year)
Lousy	Linked to a 10% probability of occurrence over the useful life.	1,574,872.91
Medium	Linked to a 50% probability of occurrence during the useful life.	1,104,571.81
More likely	Linked to a 90% probability of occurrence during the useful life.	615,389.27

Source: PHEs Project Chira-Soria.

Finally, a study was carried out to estimate the time needed to accumulate a water volume of 5 hm^3, as required by the Concession, within a maximum period of 60 months (5 years). The findings are summarized below:

- Without natural contributions: If the Soria reservoir relies exclusively on industrial water produced by the reverse osmosis (RO) plant, it would require approximately 43 months to reach the specified volume. The total water flow necessary for this process would amount to 6,396,160.62 m^3.
- With 20% contribution from natural sources: In scenarios where 20% of the water volume is naturally sourced, the estimated filling times are as follows:
    a. Low probability scenario (5% likelihood): 24 months.
    b. Average probability scenario (50% likelihood): 38 months.
    c. High probability scenario (100% likelihood): 43 months.

Table 15 outlines the key capacity specifications of the seawater reverse osmosis plant utilized in this analysis.

Table 15. 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	11,644.50m^3/day

Source: Chira-Soria Hydroelectric Pumping Plant Project.

3.3. Integration of Renewable Energy

- Projected renewable energy capacity: The Chira-Soria PHE project estimates an installed renewable energy capacity of approximately 725 MW.
- The necessary increase in renewable energy: To effectively restore water levels in the Chira reservoir, an additional 529.22 MW of renewable power might be needed, bringing the total capacity to around 734.51 MW. This requirement arises from the analysis, considering an operational timeframe of 21 h and 15 min, primarily dependent on wind energy.
- The proportion of installed wind capacity: With the total renewable capacity reaching 734.51 MW, wind energy installations would account for roughly 49% of the island's total energy capacity.
- Yearly energy generation: Achieving an annual energy production of up to 768,118.23 MWh per turbine would necessitate approximately 231.8 annual cycles of the reservoir's maximum transfer volume.

3.4. Benefits for the Energy System

The finalized installation of the PHEs, with capacities ranging from 725.00 MW to 734.51 MW, would deliver significant advantages:

- Maximized renewable energy integration, preventing excess energy losses and promoting further expansion of renewable installations.
- Enhanced reliability and security of the electrical supply.
    a. Improved frequency stabilization, which becomes more challenging with increased integration of variable renewable sources.
    b. Greater flexibility in the grid, allowing for more efficient responses to unexpected fluctuations.
- Reduced operational costs for the electrical system.
- Lower dependence on external energy sources.

3.5. Impact on Greenhouse Gas (GHG) Emissions

Figure 10 illustrates a comparison of the average daily emissions existing in the current energy production and the estimate with the incorporation of Chira-Soria.

It has been determined that average daily greenhouse gas emissions reach 6145.61 tCO_2eq, translating to an annual total of 2,243,202.21 tCO_2eq. With the integration of the Chira-Soria pumped hydroelectric power plant, emissions rise during the pumping phase but are significantly reduced during the turbine phase. The overall outcome is a net daily reduction of 1432.98 tCO_2eq, which corresponds to an annual decrease of 523,038.12 tCO_2eq, representing a 23.32% drop in total emissions.

A summary table, Table 16, outlining the main parameters associated with the integration of the Chira-Soria pumped hydroelectric power plant is presented, emphasizing the substantial emission reductions achieved through its operation.

Table 16. Results obtained from GHG production per year with the integration of PHEs.

	Producción Media Anual (GWh)		Average Annual Power Used (GW)		Installed Power (MW)		GHG Annual Average (tCO_{2eq})	
	2023	2023—CH-S	2023	2023—CH-S	2023	2023—CH-S	2023	2023—CH-S
Combined cycle	1793.25	2265.27	74.71	94.38	433.10	433.10	1,388,767.77	1,720,164.09
Steam turbine	602.76	-	25.11	-	259.60	-	699,226.41	-
Gas turbine	39.88	-	1.66	-	147.00	-	57,712.66	-
Diesel engines	111.40	-	4.64	-	66.55	-	97,495.37	-
Wind	636.15	1172.25	2653.33	48.84	305.49	788.62	-	-
Solar	138.37	141.12	5.76	5.88	73.16	73.16	-	-
Total	3321.82	3578.66	138.40	149.10	1284.90	1294.88	2,243,202.21	1,720,164.09

For optimal integration, an average annual wind power capacity of approximately 175.46 MW is necessary during the pumping phase. From this figure, it is essential to deduct the average renewable discharge losses, which account for about 6.58% (25.45 MW) of the annual average output. This adjustment results in a net power demand of around 133.82 MW.

Regarding installed renewable capacity, there is a need for an average increase of 483.13 MW, with occasional peaks reaching up to 609.91 MW. Consequently, the total required renewable capacity averages approximately 788.62 MW.

When scaling these estimates to an annual level, the yearly requirements can be outlined as follows.

3.6. Challenges

The Chira-Soria PHE project presents several challenges for the energy system. Designed to work in synergy with wind energy, the facility aims to optimize resource utilization. The primary challenges are as follows:

- Wind energy production shortfall: To compensate for current gaps in wind energy production, Gran Canaria's wind capacity must eventually reach 725 MW. At present, the Chira-Soria pumped hydroelectric power plant requires an additional 529.27 MW of wind energy to support its pumping operations effectively.
- Interim solutions: Until wind energy production achieves the target of 725 MW, the plant can prioritize pumping during periods of low energy demand. This strategy helps maintain the technical minimum requirements of the combined cycle power plants and addresses the current wind power shortfall, which limits the plant's full operational efficiency.
- Power capacity deficit: If the Chira-Soria PHEs are commissioned immediately, the island's electricity system will face a power deficit of approximately 97.56 MW. As additional wind power capacity approaches either the required 529.27 MW or the projected 734.51 MW, the Chira-Soria facility will gradually meet its intended operational goals.

4. Summary of Applied Methods

4.1. Hydraulic Stabilization Requirements

A comprehensive simulation was performed to assess hydraulic stabilization needs, and the findings are presented in Figures 11 and 12. This illustration shows water consumption scenarios derived from annual and seasonal variations observed throughout the analysis period.

From the analysis of the time required to accumulate 5 hm^3 of water, under the assumption that 20% of the natural inflow reaches the Soria reservoir as specified in the Concession, the filling process presents the following scenarios:

If the reservoir were to rely entirely on industrial water generated by the ROS plant, without contributions from natural inflows, it would take approximately 43 months to accumulate the target volume of 5 hm^3, requiring a total flow of 6,396,160.62 m^3.

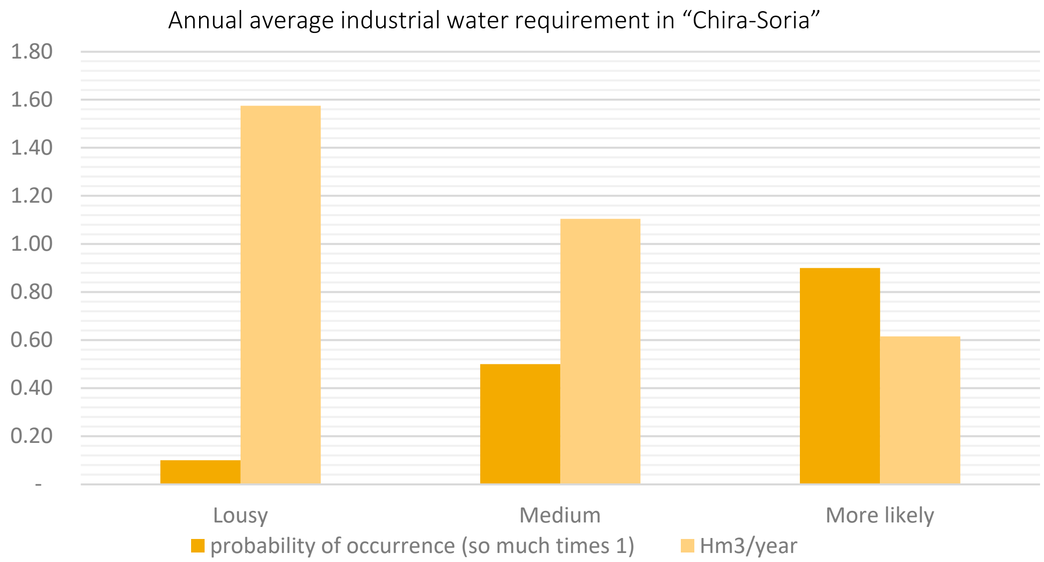

Figure 11. Analysis of the evolution of emalses from 1972 to 2019.

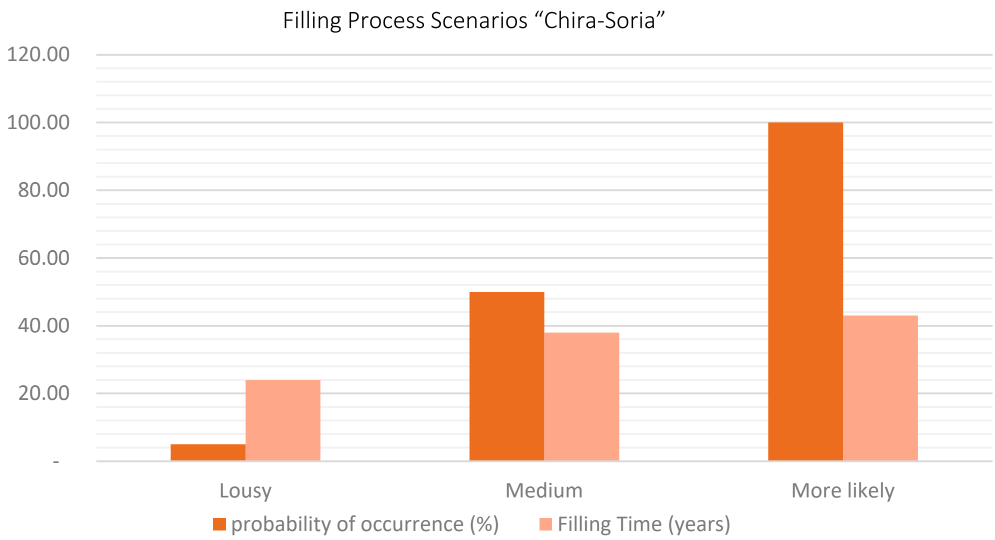

Figure 12. Estimation of volumetric recharge time of reservoirs.

4.2. Wind Power Requirements

To sustain pumping operations for the maximum feasible duration, estimated at 56.16% of the time, a wind power capacity of approximately 336.11 MW would be necessary. This estimate is based on a wind capacity factor of 36.76%, corresponding to an average of 8.82 h of operation per day, reflecting the performance levels recorded in 2021, as shown in Table 9.

These results are further illustrated in Figure 13, which provides a comparative overview of additional operational parameters.

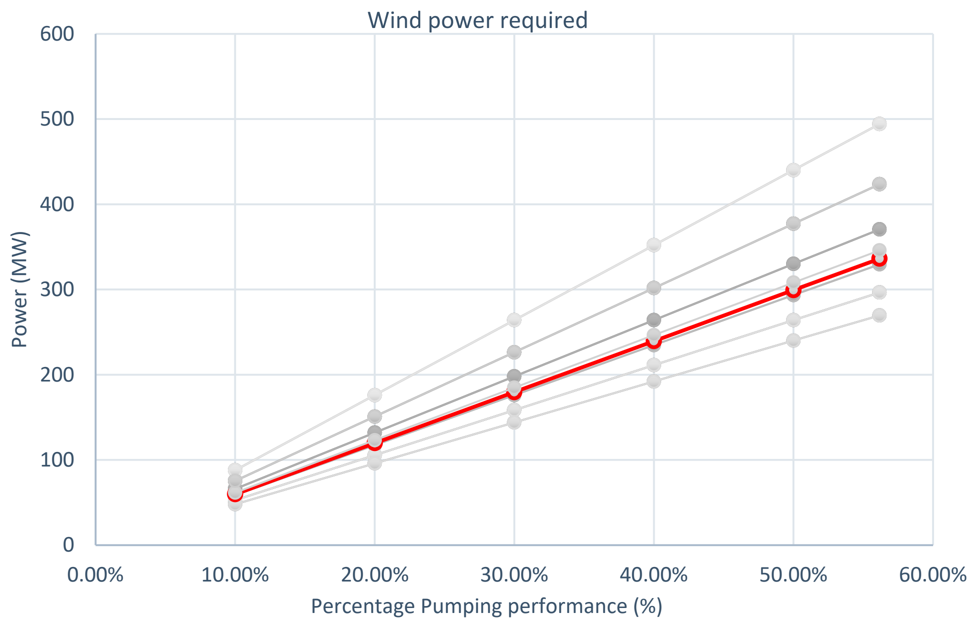

Figure 13. Wind capacity increase analysis.

5. Conclusions

1. Performance of Turbohydraulic Machines: Turbohydraulic machines operating in pumping mode demonstrate lower efficiency compared to their performance in turbine mode. They require higher energy input to move smaller water volumes, resulting in a power deficit of 20 MW and reduced pumping capacity. In scenarios of continuous turbine operation lasting 16 h and 34 min, the system generates 3313.84 MWh.

However, restoring water levels through pumping demands 21 h and 15 min and consumes 4669.16 MWh, creating an energy shortfall of 1355.32 MWh.

2. Annual Reservoir Renewals for Maximum Output: Maximizing energy production requires approximately 231.8 complete renewals of the reservoir's maximum transferable water volume each year.
3. Advantages of the PHE System: Integrating pumped hydroelectric energy storage (PHES) will optimize renewable energy usage, minimizing otherwise unavoidable energy spills. This integration promotes the expansion of renewable infrastructure while enhancing the stability and reliability of the electrical grid.
4. Reduction of Greenhouse Gas Emissions: The implementation of the PHE system is projected to significantly cut greenhouse gas emissions, achieving a net daily reduction of 1432.98 tCO_{2eq}, equivalent to 523,038.12 tCO_{2eq} annually. This reduction corresponds to a 23.32% decrease in overall emissions.

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