

Research papers

Modelling and operational analysis of reversible hydroelectric solutions in island electricity systems: The case of Gran Canaria

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ABSTRACT

The island of Gran Canaria, with an annual energy demand of 3327,872.76 MWh, has completely isolated electricity system and is still highly dependent on fossil fuels, despite the progressive increase in the implementation of renewable energies, which in 2023 reached a coverage of 23%. The inherent variability in renewable sources requires large scale energy storage solutions to guarantee the stability of the electricity system and move towards its total decarbonization. This research covers two new energies proposals in Gran Canaria for reversible hydroelectric use for mass energy storage and their comparative analysis with the configuration currently proposed and under construction, and whose completion and commissioning is planned for 2030, the pumped-storage hydroelectric power plant “Chira-Soria” [Ch-S], with a capacity of 200 MW in turbined and 220 MW in pumped storage. The two proposals under investigation are:

- (a) an integrated solution connecting the Chira and Cueva de Las Niñas dams to achieve with such a connection as a larger upper reservoir, keeping Soria as a lower reservoir [(Ch + CN)-S]; and
- (b) the synchronized operation of two independent reversible hydropower plants: the existing Chira-Soria (Ch-S) and a new proposal called Cueva de Las Niñas-Soria (CN-S), forming the system [(Ch-S) + (CN-S)].

The objective is to address the technical, energy, environmental and economic performance of the three configurations through simulations and integration in the real system in 2023, hydraulic-energy analyses and climate impact estimates. The study also considers the ability of these infrastructures to integrate higher renewable penetration, provide critical grid services such as frequency regulation and reserve power and improve the resilience of the island electricity system. The results indicate that the third option [(Ch-S) + (CN-S)] achieves full decarbonization of the Gran Canaria electricity system, although it requires higher levels of investment and significantly more installed renewable power. This strategy represents a technically feasible solution for achieving a fully decarbonized and autonomous energy system under the evaluated conditions for the island.

1. Introduction

The energy system of the island of Gran Canaria, a geographically isolated enclave in the Atlantic, has historically been based on electricity generation using fossil fuels [1]. This dependence has resulted in a high carbon footprint [2,3], making it difficult to meet international decarbonization commitments [4–7], and exposing the island to geostrategic vulnerabilities and international energy market fluctuations [8,9].

In this context, the transition towards an energy system based on renewable sources has become a key objective in regional energy planning for the island [10–12]. Despite a notable increase in the integration of variable renewable energies (VRE), such as wind and solar, in 2023 these only managed to cover 23.27% of the total demand of 3327.87 GWh, of which 19.11% corresponded to wind energy and 4.16% to photovoltaic [9,13]. This still limited penetration, combined with its own intermittency [14,15], poses operational challenges for grid

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stability [16,17].

In 2023, more than 70% of installed power (906 MW of 1287 MW) came from non-renewable sources [9], in a system that still lacks large-scale energy storage infrastructures [17–20]. Against this backdrop, reversible hydropower storage is positioned as a strategic solution [21,22] to manage renewable surpluses and secure supply.

The Chira-Soria (Ch-S) pumped-storage hydropower plant, currently under construction, represents a major step in this direction, with a turbinized capacity of 200 MW and 220 MW in pumped mode [23,24].

However, recent studies have pointed out that, while Ch-S offers notable benefits such as improved frequency stability [14], the integration of renewables [25–27], and the reduction of operating costs, its capacity would not be sufficient to achieve full decarbonization [28].

In recent years, a growing body of literature has increasingly addressed the challenges associated with the decarbonization of isolated and island electricity systems, particularly focusing on the integration of variable renewable energy (VRE) sources and the role of large-scale energy storage. Several studies have explored optimal generation mixes and expansion planning strategies aimed at achieving high renewable penetration in island contexts such as Cape Verde and the Canary Islands, highlighting the importance of flexibility and storage technologies to ensure system reliability [5,6,11].

In parallel, extensive reviews have analyzed the role of energy storage systems in supporting renewable integration. Technologies such as batteries, hydrogen, and pumped hydro energy storage (PHES) have been widely evaluated in terms of technical performance, scalability, and economic feasibility [16,17,19]. Among these, PHES remains the most mature and cost-effective solution for large-scale, long-duration storage, particularly in geographically suitable regions [21,22].

More specifically, recent works have investigated the operation and optimization of pumped-storage systems under high renewable penetration scenarios, including their contribution to frequency control, system stability, and market operation [14,28]. In the case of island systems, studies have demonstrated that the integration of PHES can significantly reduce renewable curtailment and improve system resilience [23,24].

However, despite these advances, several important research gaps remain.

First, most existing studies focus on single-plant configurations or centralized storage solutions, without exploring the potential of multi-reservoir or multi-plant coordinated systems, which may offer enhanced operational flexibility and redundancy.

Second, although the role of PHES in renewable integration is well established, there is still limited research addressing its combined operation with complementary storage vectors, such as green hydrogen, within a unified system-level framework.

Third, many analyses are based on synthetic or projected demand and generation profiles, whereas fewer studies incorporate high-resolution real operational data to evaluate system performance under realistic conditions.

Finally, there is a lack of integrated multi-criteria assessments that simultaneously consider technical performance, environmental impact, economic feasibility, and system resilience in island contexts.

To address these research gaps, this paper presents a comprehensive modelling and operational analysis of alternative pumped-storage configurations in the isolated electricity system of Gran Canaria. The study evaluates both single and coordinated multi-plant solutions, incorporates real high-resolution operational data (2023), and explores the integration of green hydrogen as a complementary storage vector within a unified system-level framework. In addition, a multi-criteria assessment is applied to evaluate technical performance, environmental impact, economic feasibility, and system resilience.

Specifically, the potential of the Chira-Soria (Ch-S) system and its extended configurations is analyzed by incorporating the Cueva de Las Niñas dam as a complementary infrastructure. This additional facility acts as an upper reservoir, increasing storage capacity and enhancing

system flexibility. Two main configurations are considered:

- (a) an integrated system connecting the Chira and Cueva de Las Niñas dams [(Ch + CN)-S], significantly increasing the storage capacity of the upper reservoir and maintaining a single reversible hydraulic pumping jump.
- (b) a synchronized operation of two independent hydroelectric systems: Chira-Soria (Ch-S) and Cueva de Las Niñas-Soria (CN-S).

Using operational simulations based on real energy behavior in 2023 and technical analysis and operational research tools, this study evaluates the synergies generated by the incorporation of CN-S, its effect on emissions reduction, and its capacity to facilitate greater penetration of renewable energies. It also considers the use of possible renewable surpluses not managed by pumping to produce green hydrogen, thus consolidating a resilient, autonomous and climate-neutral island system. This work provides a robust scientific basis for energy planning in isolated systems, contributing to the development of resilient, autonomous, and climate-neutral energy models aligned with sustainability and energy security objectives.

1.1. Nomenclature

Ch-S	Chira–Soria pumped-storage configuration: upper reservoir (Ch) – lower reservoir (S)
CN-S	Cueva de las Niñas–Soria pumped-storage configuration: upper reservoir (CN) – lower reservoir (S)
(Ch + CN)-S	Integrated configuration with Chira and Cueva de las Niñas as upper reservoirs (Ch + CN) and a shared lower reservoir (S)
(Ch-S) + (CN-S)	Dual independent configuration: Chira–Soria system + Cueva de las Niñas–Soria system
PHES	Pumped Hydroelectric Energy Storage
LCOES	Levelized Cost of Stored Energy
CAPEX	Capital expenditure
OPEX	Operation and maintenance costs
REE	Red Eléctrica de España
MITERD	Spanish Ministry for Ecological Transition
GHG	Greenhouse gas emissions

2. Materials and methods

2.1. Energy context of Gran Canaria

The installed energy capacity on the island of Gran Canaria is made up of a diverse mix of conventional technologies, including four steam generators, five diesel engines, five gas turbines and a pair of combined cycle plants. The latter each integrates a dual gas turbine unit together with a steam turbine. Together, these thermal sources account for approximately 70.39% of the total installed capacity, equivalent to 906 MW. The remaining 29.61% (equivalent to 381 MW) corresponds to generation from renewable sources. The overall sum of available power on the island therefore amounts to 1287 MW.

During the year 2023, the total electricity production in Gran Canaria was 3327,872.76 MWh. Of this amount, 774,520.76 MWh (23.27%) came from renewable technologies, while conventional fossil-based systems contributed 2,553,388.26 MWh, i.e. 76.73% of the total generated. At present, the island's electricity system has no large-scale storage solutions.

The Chira-Soria pumped storage plant, currently under construction, is intended to be the first mass energy storage infrastructure on the island.

Fig. 1 represents an “annual average day” obtained by aggregating and averaging the hourly generation data over the 365 days of the year 2023. This approach provides a representative profile of the typical daily operation of the island's electricity system.

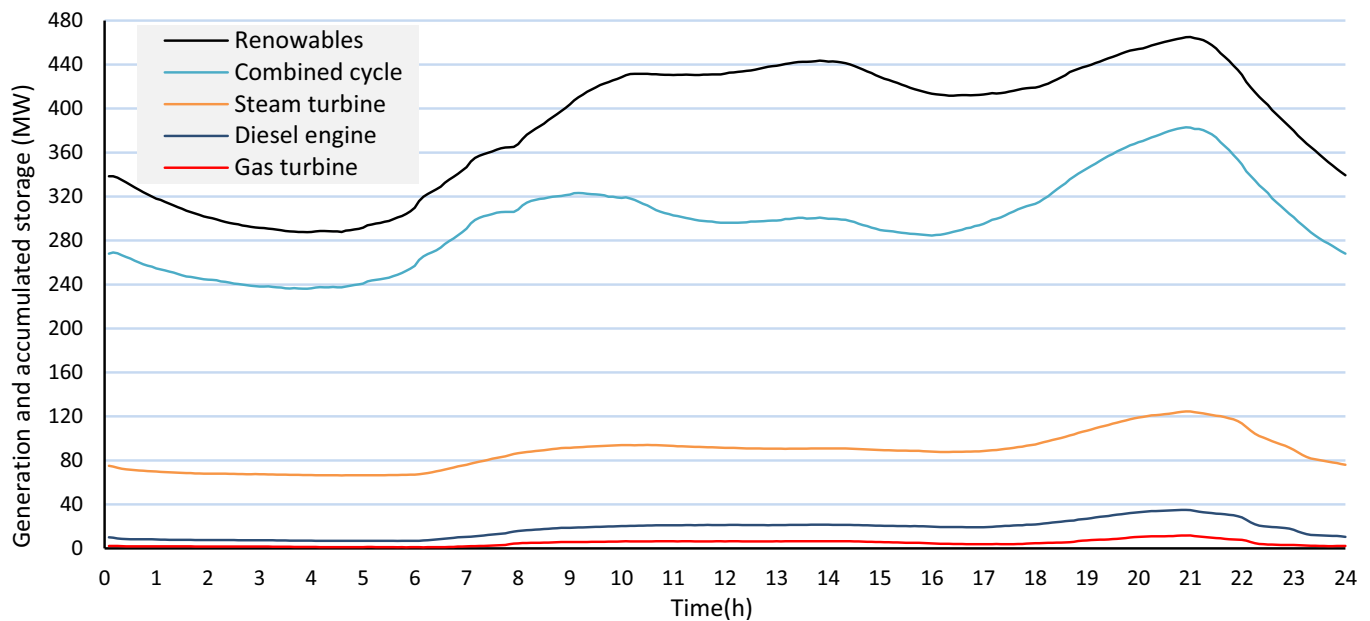


Fig. 1. Average daily generation and demand profile for Gran Canaria in 2023, based on the aggregation of 365 days of operation (annual average day).

It should be noted that Fig. 1 is presented in cumulative form, following the standard representation used by the Spanish system operator (REE). In this type of representation, the contribution of each generation source is accumulated over time. Therefore, the apparent dominance of renewable generation in the figure reflects its cumulative contribution and does not necessarily indicate higher instantaneous generation during all periods.

As a result, Fig. 1 does not capture specific extreme events, such as peak demand conditions. During such events, renewable generation may be significantly lower, and the system relies predominantly on conventional generation technologies, as discussed in the following analysis. This distinction highlights the difference between average system behavior and critical operating conditions.

The peak demand can be explained by the combined effect of several factors. Firstly, electricity consumption typically increases during evening hours due to residential and commercial activities. Secondly, renewable generation—particularly solar—was negligible at that time, while wind contribution was also very low. As a result, the system relied heavily on thermal generation units to meet demand, leading to a pronounced peak in fossil-based electricity production.

The curve obtained represents proportionally a fraction of 1/365 of the annual total, which makes it possible to verify that the daily energy values coincide with this proportion of the annual total. From this average profile, it is determined that the average annual power generated by the thermal (combustion) plants was 386.74 MW, as summarized in Table 1.

Among the most relevant energy milestones in 2023 was the highest daily demand ever recorded in the history of the island, reached on 9 October, when 1455.30 MWh were consumed. On the same day, two additional extreme values were also observed: a peak hourly demand of 558.80 MWh at 20:00 h and a historical maximum instantaneous power of 563.40 MW, recorded at 20:28 h.

The analysis of the day with the highest energy demand is key to understanding the immediate challenges facing the Gran Canaria

electricity system. This critical situation occurred on 9 October 2023, registering at 20:28 h a maximum instantaneous power of 563.70 MW. In contrast, the minimum value on the same day was 338.20 MW, recorded at 03:43 h. This new peak demand exceeds the previous historical maximum, reached on 17 August 2021 at 14:53, with 529.00 MW.

During this time of maximum demand on the grid, demand coverage was practically sustained by conventional generation. The contribution from renewable sources was marginal, with only 1.20 MW from wind power, representing just 0.21% of the total. The rest of the demand was supplied by fossil technologies: 37.10 MW from diesel units (6.61%), 28.20 MW from gas turbines (5.02%), 357.10 MW from combined cycle power plants (63.61%) and 137.80 MW from steam turbines (24.55%).

Fig. 2 is based on official data provided by the Spanish system operator (Red Eléctrica de España, REE) and illustrates the real operational response of the generation system during the peak demand event.

It shows the hourly response of the generation system, differentiating the contribution of renewable and non-renewable sources. The relevance of this day lies in the very low participation of renewable energy under critical conditions, highlighting the need for large-scale storage and surplus management solutions. In contrast, the reliance on combustion-based technologies results in significant greenhouse gas (GHG) emissions.

Table 2 presents fossil fuel consumption by generation technology and the associated greenhouse gas (GHG) emissions. It provides a breakdown of fuel use by technology, along with the corresponding emissions of carbon dioxide (CO₂), methane (CH₄), and nitrogen oxides (NO_x), expressed in CO₂-equivalent (CO₂-eq), offering a representative overview of the current energy situation in Gran Canaria.

The values presented in Table 2 are based on official data from the Canary Islands Energy Yearbook. Greenhouse gas emissions were estimated using standard emission factors in accordance with internationally recognized methodologies (e.g., IPCC guidelines).

During the year under analysis, the electricity generation system of

Table 1
Average daily consumption and annual consumption by technology in Gran Canaria 2023.

	Combined cycle	Steam turbine	Diesel engine	Gas turbine	Wind	Photovoltaic	Hydraulics	Total
GWh/ annual average day 2023	4.93	1.65	0.31	0.11	1.74	0.38	0.00	9.12
GWh/ year 2023	1799.26	602.76	111.40	39.88	636.15	138.37	0.00	3327.82

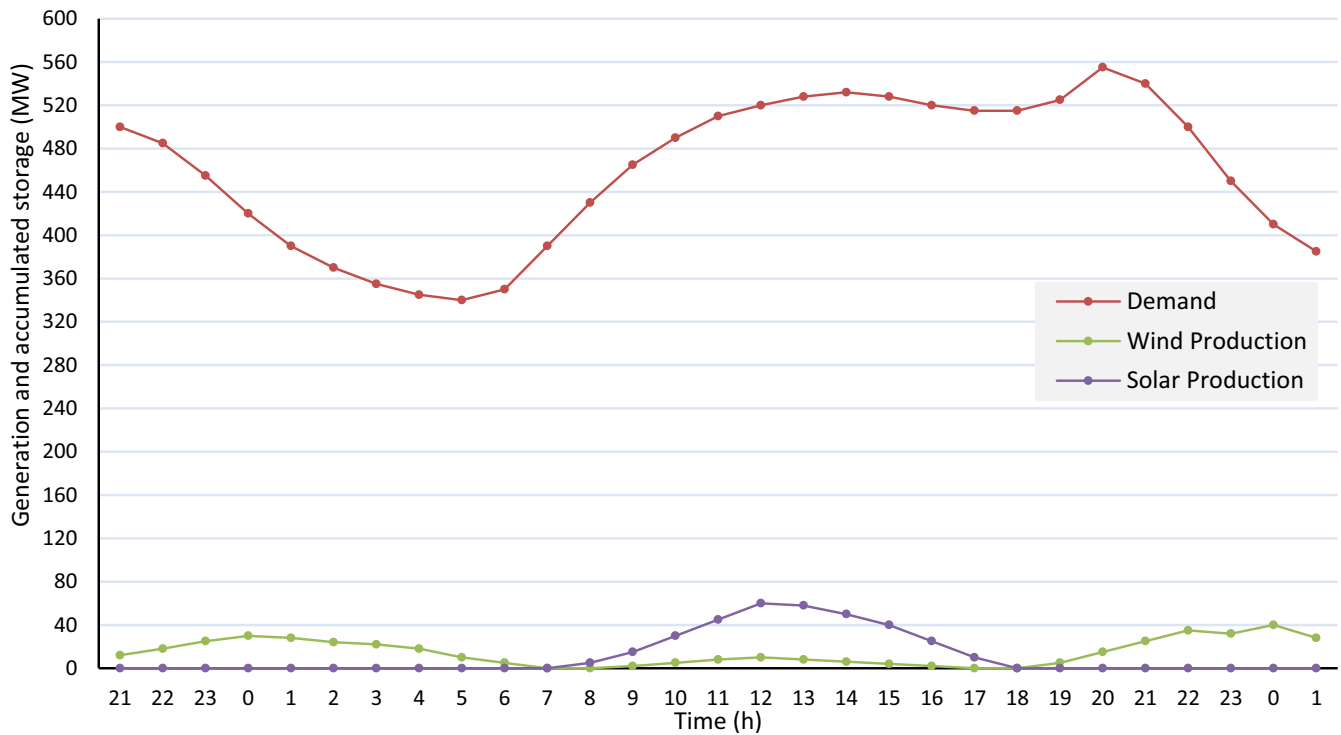


Fig. 2. Hourly generation profile during the day with the highest electricity demand in Gran Canaria, based on data from the Spanish system operator (REE), showing the contribution of renewable and non-renewable generation sources.

Table 2

Fuel consumption (t) and GHG emissions (tCO₂eq) in Gran Canaria (2023).

Type technology	Fuels			GHG	
	Fuel	Diesel	CO ₂	CH ₄	NOx
	(t)	(t)	(tCO ₂ eq)	(tCO ₂ eq)	(tCO ₂ eq)
STEAM TURBINE	160.119,0	129,0	524.382	427,0	1.260,0
DIESEL ENGINE	37.852,0	1.561,0	128.793	105,0	310,0
GAS TURBINE	0,0	21.781,0	68.710	58,0	172,0
COMBINED CYCLE	0,0	334.369,0	1.054.799	897,0	2.648,0
TOTAL	197.971,0	357.840,0	1.776.684,0	1.487,0	4.390,0

Source: Canary Islands Energy Yearbook.

Gran Canaria required a total volume of approximately 555,811 tons of fossil fuels, distributed mainly between fuel oil, diesel and natural gas. This consumption generated an estimated total emission of 1,782,561 tons of CO₂ equivalent (tCO₂eq). Considering the useful electrical energy supplied to users once transmission and distribution losses have been deducted, the average emission factor for the island electricity system is estimated at 0.536 tCO₂eq/MWh.

2.1.1. Future energy outlook with the incorporation of the pumped-storage hydropower plant Chira-Soria (Ch-S)

In order to properly contextualize the energy scenario for Gran Canaria, it is essential to highlight the expected role of the Chira-Soria (Ch-S) reversible hydroelectric power plant, which is scheduled to come on stream in 2030. This infrastructure will play a central role in the island's energy transition strategy by providing large-scale energy storage, an essential component for the efficient integration of intermittent renewables such as solar and wind.

Thanks to its reversible design, Ch-S will be able to operate in two modes: as a turbine power plant and as a pumping station, lifting water from the lower reservoir to the upper reservoir at times of renewable

surplus. This allows energy to be stored in the form of hydraulic potential and released at peak demand times.

Table 3 summarizes the main technical parameters of the balanced operation of Chira-Soria in its two operating modes (turbining and pumping), reflecting its capacity to dampen the variability of renewable generation and stabilize the island's electricity system.

The incorporation of the Chira-Soria (Ch-S) pumped-storage hydropower plant into the Gran Canaria electricity system will represent a significant advance on multiple strategic fronts. Its design and operational capabilities are aimed at addressing some of the main limitations of the island's current energy model. The integration of the Chira-Soria (Ch-S) system enables large-scale energy storage, frequency regulation capability, reduction in fossil-based generation, and improved system reliability under variable renewable conditions.

2.1.1.1. Large-scale energy storage capacity. Thanks to its pumped-reverse structure, the plant will allow the accumulation of excess energy produced by renewable sources such as solar and wind during periods of low demand. This stored energy can then be used when consumption is high or renewable generation is limited, thus acting as a dynamic back-up system for the grid.

2.1.1.2. Supporting grid stability. The fast operational response of Ch-S in both modes (turbined and pumped) will provide essential ancillary services such as frequency regulation and voltage control. This will allow damping of the variations inherent in renewable generation, helping to maintain the balance and quality of the electricity supply.

2.1.1.3. Reducing the use of fossil technologies. By facilitating greater penetration of clean energy, the plant will enable the progressive displacement of fossil fuel-based electricity production. As a result, the carbon footprint of the energy system will be reduced and dependence on imported, and price-volatile resources will be mitigated.

2.1.1.4. Strengthening energy security. The possibility of having

Table 3

Main technical parameters of the balanced operation of Chira-Soria.

Operating mode			Power	Energy/day	Flow rate	Displaced water volume
	Horas/día	%	MW	MWh	m ³ /s	m ³
Balance turbine	10.522	43.84%	200.00	2104.43	68.40	2,590,978.53
Balance pumping	13.478	56.16%	220.00	2965.12	53.40	2,590,978.52
Sum	24.000	100.00%				

instantaneous generation available in response to demand will increase system reliability, reducing vulnerability to failures, outages or consumption peaks. This is especially relevant in an island context where there are no external electricity interconnections.

2.1.1.5. Optimized use of renewable sources. With the possibility of storing renewable surpluses that are currently wasted due to grid constraints, it will be possible to maximize the performance of wind farms and photovoltaic plants. This will increase overall system efficiency and minimize clean energy losses.

From a quantitative perspective, the Chira-Soria (Ch-S) pumped-storage system provides a daily energy storage capacity of approximately 2965 MWh in pumping mode and a generation capacity of around 2104 MWh in turbine mode under balanced operation conditions. This corresponds to an average operational cycle with a pumping-to-generation ratio of approximately 56% to 44%, reflecting the round-trip efficiency of the storage cycle.

In terms of system impact, the integration of Ch-S reduces the reliance on thermal generation, contributing to a more stable and efficient generation profile and enabling a significant reduction in fossil-based generation and associated CO₂ emissions (approximately 23.3% compared to the current system).

Additionally, the system enables the effective absorption of renewable surpluses, requiring an estimated renewable capacity of approximately 483 MW (average) to sustain pumping operation under typical conditions. These results highlight the measurable contribution of Ch-S in enhancing renewable integration, improving system stability, and reducing emissions in the island electricity system.

Fig. 3 shows the average evolution of the energy performance of the Gran Canaria generating fleet, considering the future operational incorporation of the Chira-Soria reversible hydroelectric power plant. The figure compares the current combustion-based energy production with the projected combustion generation after the integration of the

Chira-Soria (Ch-S) pumped-storage system, and also includes the total energy production required to meet system demand, combining renewable and conventional sources.

This representation, constructed following the standard criteria of the Spanish electricity system, uses a cumulative format to reflect the contribution of each technology over time. The objective of this scenario is to illustrate a system configuration aimed at maximizing renewable integration, minimizing pollutant emissions, and improving the frequency stability of the island system. It should be noted that Fig. 3 focuses exclusively on combustion-based generation and does not represent the internal operation of the pumped-storage system. The balance between energy generation and pumping consumption is explicitly illustrated in Fig. 4.

The resulting profile shows a more balanced distribution between generation sources. In particular, the integration of the Chira-Soria plant allows production to be modulated by means of combustion technologies, transforming the thermal curve into two well-defined operating levels. These residual thermal generation steps are set at 299.50 MW (upper step) and 237.49 MW (lower step), representing the average power values necessary to cover the demand not covered by renewables or storage.

This adjustment results in an overall plant factor of 60.59% for fossil technologies, reflecting a more efficient and consistent operation. In addition, an appropriate operational balance is achieved between the turbine and pumping modes of the plant, with a ratio of 43.84% of energy generated in turbine mode and 56.16% of energy absorbed in pumping mode, in accordance with the energy balance principles of hydro storage.

For comparison, the current system without pumped-storage integration shows a significantly higher reliance on combustion-based generation, reflecting a less flexible and more carbon-intensive operation. The incorporation of Ch-S therefore enables a reduction in fossil fuel utilization and improves overall system stability.

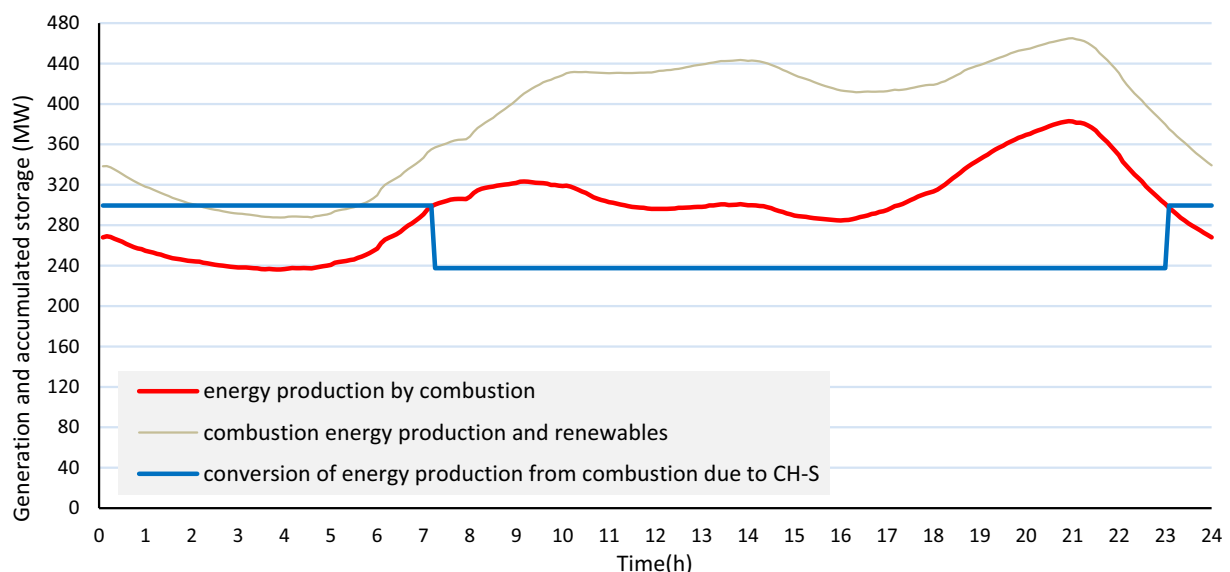


Fig. 3. Energy production through combustion due to the integration of the Chira-Soria pumped-storage hydroelectric power plant.

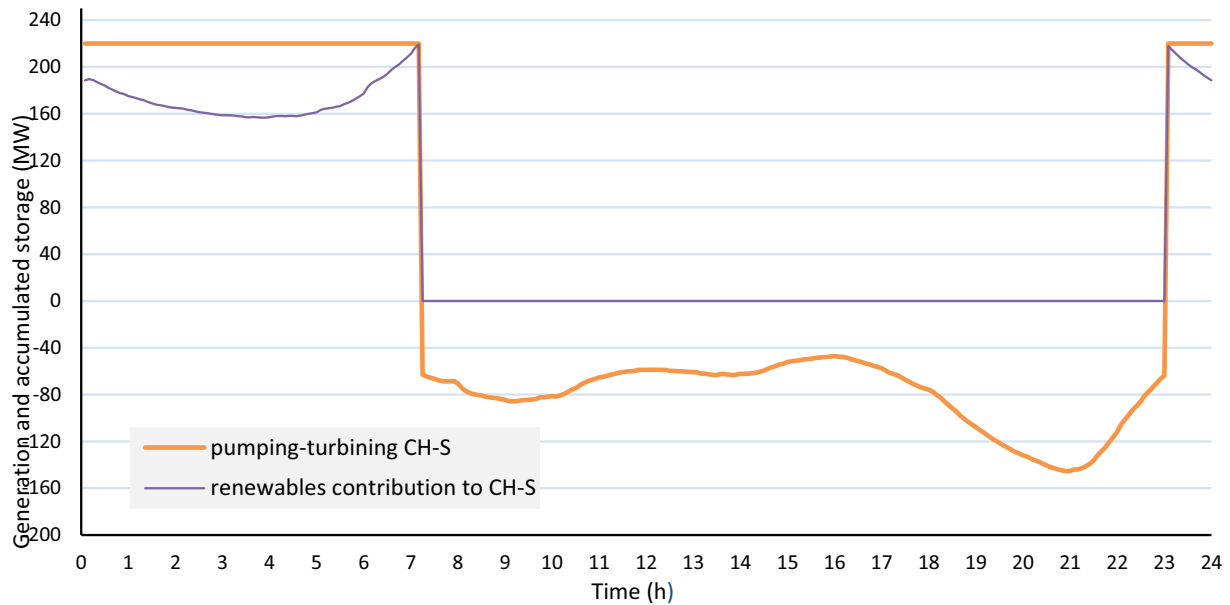


Fig. 4. Schematic of pumped and turbinized operation of the Chira-Soria reversible hydropower plant.

Fig. 4 complements this analysis by showing the detailed operating scheme of Chira-Soria in both modes of operation, illustrating its capacity to buffer renewable variations and allow dynamic management of the energy supply.

In order to achieve effective system integration with full operation of the Chira-Soria plant, it is essential to have sufficient support from renewable generation, particularly wind power. According to the simulations carried out, an average effective wind power output of 175.46 MW is required during pumping hours, with occasional peaks of up to 219.20 MW.

It should be noted that the current installed renewable capacity in Gran Canaria is approximately 330 MW. However, simulation results indicate that, in order to ensure optimal operation of the Chira-Soria (Ch-S) pumped-storage system, the available renewable capacity should reach approximately 635 MW, in line with the maximum renewable capacity required to sustain pumping demand under peak operating conditions.

Within this framework, the additional renewable capacity is primarily allocated to meet the pumping requirements of the Ch-S system. In particular, the most critical operating periods occur around 07:00 and 23:00, when the mismatch between renewable generation and system demand is more pronounced. During these periods, wind generation contributes to supplying the energy required for pumping.

Any surplus renewable energy not required for storage operation is subsequently injected into the grid, ensuring maximum utilization of available resources and minimizing curtailment.

Considering an availability factor of 34.5% (value observed for the wind regime in Gran Canaria during 2022), it is estimated that it will be necessary to install additional renewable capacity, beyond the existing one, in the order of 508.58 MW on average and up to 635.36 MW under peak pumping demand conditions.

However, if the average volume of unused renewable energy that can be redirected to the storage system is considered, these figures can be optimized. By incorporating such an adjustment, the net new need for additional renewable capacity is reduced to 483.13 MW as an annual average and 609.91 MW at times of peak pumping load.

This strategy not only enables increased utilization to be made of the wind potential already available but also transforms the Chira-Soria plant into a component of Gran Canaria's energy architecture. Beyond its function as a generating plant, the power plant acts as a key infrastructure for storage and grid stability, enabling an orderly, efficient and

climate-responsible energy transition.

By providing complementary services such as balancing supply and demand, frequency regulation and absorption of renewable surpluses, Chira-Soria is positioned as the central element of the new island energy model, capable of drastically reducing dependence on fossil fuels and moving towards a structural decarbonization of the system.

2.2. Methodology

The research is methodologically structured around a technical-operational evaluation of three reversible pumped hydropower storage configurations adapted to the island context of Gran Canaria. The methodology applied combines energy and hydraulic modelling, analysis of hourly system operation simulations, economic and environmental estimations, sensitivity analysis and multi-criteria comparison techniques. This integrated approach allows us to assess not only the technical performance of the different solutions proposed, but also their systemic impact, environmental sustainability and economic viability in the medium and long term.

2.2.1. Hydraulic configurations analyzed

The study analyses three structural alternatives that incorporate the Chira, Soria and Cueva de Las Niñas dams in different hydraulic connection schemes. These configurations represent different strategies for harnessing the available water resources for large-scale energy storage:

- Chira-Soria Hydroelectric Power Plant, {Ch-S}: base configuration currently under implementation. It operates with a pumping and turbine scheme between the Chira (upper) and Soria (lower) dams, with a nominal power of 200 MW in generation mode and 220 MW in pumping mode. This facility is designed to take advantage of renewable surpluses and contribute to the frequency stability of the system.
- Chira and Cueva de Las Niñas hydroelectric power plant - Soria, {(Ch + CN)-S}: integrated solution that hydraulically connects the Chira and Cueva de Las Niñas dams, forming a single upper reservoir with a larger useful volume. This enlargement makes it possible to increase the energy stored per pumping cycle, without modification the lower reservoir (Soria). The main objective is to maximize storage capacity without the need to duplicate generation infrastructures.

- c. Chira - Soria and Cueva de Las Niñas - Soria hydroelectric power plant, {(Ch-S) + (CN-S)}: consists of synchronized operation of two independent reversible hydroelectric dams. The first is Chira-Soria (as in the base configuration) and the second a new plant between Cueva de Las Niñas (as the upper reservoir) and Soria (lower), with its own hydraulic circuit and machinery. This configuration allows for greater operational flexibility and scalability, at the cost of a higher initial investment.

Each configuration was digitally represented based on existing topographic, bathymetric and reservoir capacity data, integrating actual turbine and pump efficiency parameters, head losses, and hydraulic operating constraints.

Fig. 5 illustrates the schematic layout of the three configurations, highlighting the hydraulic connections and key differences between the proposed schemes.

2.2.2. Hydrogen production modelling

In addition to pumped-storage operation, the model considers the use of surplus renewable energy for hydrogen production as a complementary energy management strategy. Hydrogen generation is activated when renewable production exceeds both system demand and the pumping capacity of the Chira-Soria (Ch-S) system.

In this context, surplus renewable energy not absorbed by the storage system is directed to an electrolysis unit, allowing its conversion into hydrogen. This approach ensures a hierarchical use of renewable resources, prioritizing grid supply and storage operation before hydrogen production.

The modelling approach for hydrogen production, including the electrolysis process, efficiency assumptions, and operational criteria, follows the methodology previously developed and validated in [29].

For the purposes of this study, hydrogen production is quantified based on the residual renewable surplus, providing an additional pathway for energy utilization and system flexibility.

2.2.3. Simulation tools and data used

To faithfully represent the behavior of each configuration under real operating conditions, various energy simulation and technical modelling tools were used:

- Energy data of the island system (2023): official hourly data on generation, demand, renewable curtailment, unmanaged discharges, and marginal prices of the Gran Canaria electricity system were used. The main sources were the system operator (REE) and the Government of the Canary Islands, complemented by open data from the Ministry for Ecological Transition (MITERD). The dataset was structured to provide a consistent hourly operational profile of the system. Renewable generation data (wind and photovoltaic) were

processed from hourly records and adapted to the simulation framework. This included aggregation and normalization procedures to ensure consistency with the system's operational profiles and to allow comparison between scenarios.

• Simulation software:

HOMER Grid and MATLAB-Simulink:

For hourly modelling of energy flows, interaction between renewable generation and storage, and performance analysis under different operating profiles.

PSS/E (Power System Simulator for Engineering):

For analyzing the effect of each configuration on grid stability, including frequency regulation capacity, power reserve, and reduction of the risk of disturbances due to excess renewable generation.

EPANET and GIS tools:

For hydraulic modelling, calculation of friction losses in pipelines, reservoir filling/emptying times, and estimation of net efficiencies.

2.2.4. Technical and multi-criteria evaluation criteria

The three configurations were evaluated using a set of key indicators to assess their technical, environmental and economic impact. These criteria were defined to be comparable and quantifiable:

- Useful energy storage capacity (GWh): maximum energy that can be stored considering the hydraulic capacities and losses of the system.
- Potential increase of renewable integration (%): additional percentage of renewable energy that can be managed thanks to the storage capacity.
- Estimated annual emissions reduction (tCO₂/year): calculated using emission factors of substituted fossil generation (according to IPCC methodology).
- Contribution to system stability: estimated through analysis of secondary and tertiary reserves managed by the plant, and capacity to contribute to grid services.
- LCOES (Levelized Cost of Stored Energy): levelized cost per MWh stored, calculated considering CAPEX, OPEX, useful life and overall efficiency.
- Additional environmental impact: qualitative analysis of water footprint, land occupation, impact on biodiversity and evaporation/seepage risks.
- Constructive feasibility and future scalability: considering access, required works, estimated construction times, and modular expansion possibilities.

Each indicator was weighed in a multi-criteria analysis using AHP (Analytic Hierarchy Process) techniques, with the collaboration of local experts in energy, environment and water infrastructure.

The weighting of the criteria was performed using the Analytic Hierarchy Process (AHP), based on pairwise comparisons carried out by a

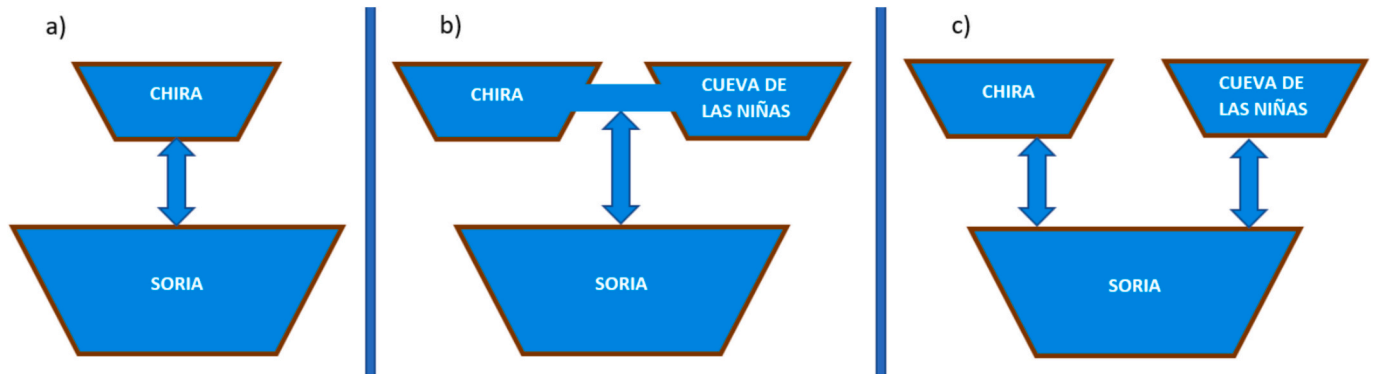


Fig. 5. Schematic representation of the pumped-storage configurations: (a) Chira-Soria (Ch-S) base configuration, (b) integrated system (Ch + CN)-S with a shared upper reservoir, (c) dual system (Ch-S) + (CN-S) with two independent plants connected to the Soria reservoir.

panel of experts in energy systems, hydraulic infrastructure, and environmental assessment. The consistency of the comparison matrix was verified to ensure the robustness of the weighting process. In particular, the “Construction Feasibility” criterion was derived considering several sub-factors, including the complexity of civil works, accessibility and terrain conditions, integration with existing infrastructure, and expected permitting and execution timelines. These sub-criteria were evaluated and aggregated within the AHP framework to obtain the final normalized score used in the multi-criteria analysis.

2.2.5. Sensitivity and uncertainty analysis

Given the variability of economic, technological and climatic conditions, a sensitivity analysis was incorporated to assess the robustness of the configurations to future scenarios:

- Variation in renewable availability: simulations with $\pm 20\%$ solar and wind generation to assess performance under different climatic conditions.
- Investment scenarios: increase (+15%) and reduction (−10%) of estimated CAPEX.
- Electricity demand projections: moderate and high growth scenarios for 2030 and 2035.
- Variation in CO₂ emission costs: considering their influence on system profitability.

This analysis makes it possible to determine critical feasibility points, identify cost-effectiveness thresholds, and define robust design margins.

In all cases, the impact of these variations is assessed using the defined system performance indicators, including renewable penetration, thermal generation reduction, CO₂ emissions, storage utilization, and system flexibility, together with economic performance metrics (e.g., levelized cost of energy).

2.2.6. Evaluation indicators

Each configuration is evaluated using a consistent set of indicators. Renewable curtailment refers to the portion of available renewable generation that cannot be utilized or stored. Operational flexibility reflects the system's ability to respond to hourly variability in demand and renewable generation. Emission reduction is calculated relative to the baseline system without storage. Storage utilization indicates the effective use of the storage capacity over time. These metrics are consistently applied across all scenarios to ensure comparability of results.

These indicators are summarized in Table 4.

The evaluation indicators are calculated as follows:

- Renewable penetration is defined as:

$$RP = \frac{E_{RES}}{E_{total}} \cdot 100 \quad (1)$$

Table 4

Evaluation indicators used in the analysis.

Indicator	Description	Unit
Renewable penetration	Share of total demand covered by renewable generation	%
Thermal generation reduction	Reduction in fossil-based electricity production	%
CO ₂ emissions reduction	Decrease in emissions compared to baseline	%
Storage utilization	Ratio between energy stored and energy generated	%
Renewable curtailment	Unused renewable energy	MWh
System flexibility	Ability to balance demand and generation	Qualitative/ quantitative

where E_{RES} is the energy generated from renewable sources and E_{total} is the total energy demand.

- Thermal generation reduction is calculated as:

$$TGR = \frac{E_{thermal,base} - E_{thermal,scenario}}{E_{thermal,base}} \cdot 100 \quad (2)$$

- CO₂ emissions reduction is defined as:

$$CO_2^{red} = \frac{Em_{base} - Em_{scenario}}{Em_{base}} \cdot 100 \quad (3)$$

- Storage utilization is expressed as:

$$SU = \frac{E_{discharged}}{E_{stored}} \quad (4)$$

- Renewable curtailment is calculated as:

$$RC = E_{available} - E_{used} \quad (5)$$

System flexibility is evaluated based on the system's ability to balance supply and demand, considering ramping capability and response to variability in renewable generation.

2.3. Hydraulic and energy modelling

The hydraulic and energy modelling of the proposed configurations was based on a detailed characterization of their operating parameters, storage capacities, balancing behavior (turbining and pumping), as well as their impact on emission reduction. The simulation was carried out on an hourly basis using the operation of the island system during the year 2023 and allows a precise quantification of the technical contribution of each alternative towards the decarbonization of the Gran Canaria electricity system.

The hydraulic parameters of the system were defined based on the original engineering design project of the Chira-Soria pumped-storage plant, provided by the Cabildo de Gran Canaria. These data include reservoir capacities, hydraulic head, pipeline characteristics, and operational constraints, ensuring a realistic and engineering-based representation of the system.

Although a fully operational pumped-storage system is not yet available on the island, the model combines real system-operation data with validated engineering design parameters. This ensures consistency between simulated scenarios and actual system behavior, providing a reliable technical assessment of the proposed configurations under realistic operating conditions.

Nevertheless, the results should be interpreted within the context of simulation-based analysis, as direct empirical validation against an operating local facility is not currently feasible.

The analysis is based on hourly operational data from the year 2023, which provides a detailed and representative snapshot of the system behavior. However, inter-annual variability in hydrological and climatic conditions may affect renewable generation and storage performance. Future work should extend the analysis to multiple representative years (e.g., dry, wet, and typical scenarios) to further evaluate system resilience under varying conditions.

The simulation framework is based on hourly time resolution using real operational data from 2023. The dispatch strategy prioritizes renewable generation, followed by pumped-storage hydropower for

short-term balancing, and hydrogen storage as a long-duration backup during extended periods of low renewable availability. Operational constraints include reservoir capacities, hydraulic head, system efficiencies, and technical limits derived from engineering design data. This modelling approach ensures consistency with actual system operation and supports the reproducibility of the results.

For clarity, a distinction is made between input assumptions and model outputs. Input parameters include renewable generation profiles, hourly demand data, system constraints, and operational assumptions used to define the simulation framework. Model outputs correspond to the resulting system performance indicators, including energy managed, operational flexibility, emission reduction, and storage utilization. This distinction avoids ambiguity and improves the transparency of the modelling approach.

From a system stability perspective, the proposed configurations contribute to frequency regulation through the fast response capability of pumped-storage hydropower and coordinated storage operation. Although detailed dynamic indicators such as RoCoF or frequency nadir are not explicitly calculated, system stability is assessed through operational proxies, including reserve margins, dispatch flexibility, and response capability.

Pumped-storage plants provide rapid power adjustments, contributing to primary frequency control and supporting system inertia. In addition, the redundancy of the (Ch-S) + (CN-S) configuration enhances system robustness by ensuring available reserve capacity under variable renewable conditions.

2.3.1. Operating parameters: balancing turbine operation

Operation in generation mode represents the phase of electricity generation from the water stored in the upper reservoir. For all configurations, the use of binary Francis type reversible turbine-pump groups has been considered, with unit powers of 33.33 MW per unit (in total 6 turbines per plant).

The main operating parameters for turbine mode are summarized in Table 5.

The (Ch + CN)-S configuration significantly increases the maximum continuous energy available due to the expansion of the upper storage volume, improving system autonomy during periods of low renewable generation.

2.3.2. Operational parameters: balancing pumping

The pumping phase consists of raising water from the lower reservoir (Soria) to the upper reservoir using renewable surplus or low-cost energy. An estimated power of 220 MW in pumping mode per plant has been estimated, with an efficiency of around 85%.

The main operating parameters for pumping mode are summarized in Table 6.

The combined configuration [(Ch-S) + (CN-S)] has the highest energy storage and restitution capacity but also requires more renewable energy to operate at full load: up to 1292.17 MW renewable.

2.3.3. Hydraulic and structural capacity

The energy efficiency of the installations depends on the combination of peak flow, head and volume transferred.

Table 5
Main operating parameters in turbine mode for the analyzed configurations.

Parameter	Ch-S	(Ch + CN)-S	(Ch-S) + (CN-S)
Total Turbine Power (MW)	200.00	200.00	400.00 (200.00 + 200.00)
Energy/day (MWh)	2104.43	2104.43	4208.79
Max. continuous energy (MWh)	3313.84	6733.27	6528.37
Maximum continuous hours (h)	16.57	33.67	32.64

Table 6
Main operating parameters in pumping mode for the analyzed configurations.

Parameter	Ch-S	(Ch + CN)-S	(Ch-S) + (CN-S)
Total pumping power (MW)	220.00	220.00	440.00 (220.00 + 220.00)
Energy/day (MWh)	2965.12	2965.12	5.930.33
Max. continuous energy (MWh)	4669.16	9487.10	9.198.70
Maximum continuous hours (h)	21.22	43.2	41.81

The main hydraulic and structural parameters are summarized in Table 7.

The equilibrium volume represents the normal operating volume, compatible with the daily pumping and turbinning cycles. The increase in useful volume in (Ch + CN)-S and (Ch-S) + (CN-S) improves daily energy autonomy and resilience to extreme events.

2.3.4. Impact on emissions and decarbonization

The main objective of the system is the elimination of the use of fossil generation, resulting in significant reductions in greenhouse gas emissions.

The estimated emission reductions for each configuration are summarized in Table 8.

Only the coordinated operation of both plants in parallel allows a total reduction in emissions to be achieved, thanks to the complete coverage of electricity demand by turbines + green H₂ in unmanageable peaks.

2.3.5. Conclusion of the modelling

The results of the hydraulic and energy modelling confirm the following:

- Ch-S alone represents a significant advance in renewable storage, but its impact is limited against full decarbonization targets.
- (Ch + CN)-S improves system efficiency without duplicating electromechanical infrastructure and is a viable intermediate option with lower capital cost.
- (Ch-S) + (CN-S), through synchronized and redundant operation, achieves full zero-emission coverage, managing 100% of demand through renewables and storage and using green hydrogen as a backup vector.

The role and indicative sizing of the hydrogen system as a long-duration backup solution are further detailed below to assess the feasibility of the fully renewable configuration.

2.3.6. Hydrogen system integration and operation under low-renewable conditions

To reinforce the feasibility of the fully renewable configuration [(Ch-S) + (CN-S)], a complementary green hydrogen system has been incorporated as a long-duration energy storage solution. In this approach, excess renewable electricity that cannot be absorbed by pumped-storage hydropower during periods of high generation is redirected to an electrolyzer system for hydrogen production. The electrolyzer capacity is estimated to be in the range of 150–250 MW,

Table 7
Hydraulic and structural parameters of the analyzed configurations.

Parameter	Ch-S	(Ch + CN)-S	(Ch-S) + (CN-S)
Racking volume (m ³)	4,080,000	4,210,000	8,290,000
Equilibrium volume (m ³)	2,590,978	2,756,029	5,347,008
Water head (m)	343.00	327.00	~340 (average)
Pipe diameter (m)	4.00	4.13	4.00 (average)

Table 8

Estimated annual CO₂ emissions and reduction levels for the analyzed configurations.

Configuration	Expected emissions (tCO _{2eq} /year)	Reduction (%)
Ch-S	1.720.164,09	23,32%
(Ch + CN)-S	1.720.164,09	23,32%
(Ch-S) + (CN-S)	0 (100% renewable system)	100%

depending on renewable surplus availability and system operating conditions.

From an operational perspective, pumped-storage hydropower acts as the primary balancing technology, managing daily and short-term fluctuations due to its high efficiency and rapid response. In contrast, the hydrogen system operates as a strategic backup designed to supply energy during prolonged “Dunkelflaute” events, defined as extended periods of low wind and solar availability. During these events, when hydro storage approaches its minimum operational levels, stored hydrogen is reconverted into electricity, ensuring continuous demand coverage and enhancing overall system resilience (Table 9).

3. Results and discussion

This chapter presents the results obtained after the hydraulic and energy modelling of the three proposed configurations of reversible hydroelectric power plants for the island of Gran Canaria. Their performance is analyzed in terms of energy generation and storage, renewable integration capacity, greenhouse gas emission reductions, additional renewable power requirements and technical feasibility. The discussion compares quantitatively and qualitatively the alternatives Chira-Soria (Ch-S), (Ch + CN)-S, and (Ch-S) + (CN-S), assessing their suitability as strategic solutions for the decarbonization of the island's electricity system.

3.1. Energy performance and daily operating capacity

One of the main indicators evaluated was the energy generated in turbine mode per day, as a representation of the real capacity of the facilities to cover manageable demand from hydro storage.

- In the Ch-S configuration, currently under construction, an average daily turbinized energy of 2104.43 MWh is achieved, limited by a total power of 200 MW and 6 turbine-pump groups.
- The (Ch + CN)-S variant, which uses the Chira and Cueva de Las Niñas dams as a combined upper reservoir, maintains the same daily energy values, as it retains the same installed power.
- In contrast, the (Ch-S) + (CN-S) option - based on the synchronized operation of two independent power plants doubles the daily energy managed, reaching 4208.79 MWh/day, thanks to a total power of 400 MW (two blocks of 200 MW).

This increase has direct implications for the autonomy of the system, the capacity to adapt to demand peaks, and the flexibility to operate

Table 9

Indicative role and sizing parameters of the hydrogen system in the (Ch-S) + (CN-S) configuration.

Parameter	Value/Description
Electrolyzer capacity	150–250 MW (conversion of excess renewable electricity into hydrogen)
Hydrogen storage capacity	Long-duration energy reserve for extreme events
Reconversion system capacity	Electricity generation from stored hydrogen
Operational role	Backup system after renewables and pumped hydropower

asynchronously depending on the availability of renewable resources. By operating in tandem, both plants can cover scenarios of high demand or low renewable generation without resorting to thermal generation.

3.2. Maximum continuous energy and operational resilience

Maximum continuous available energy refers to the ability of each configuration to operate without interruption in turbine mode until its useful storage volume is exhausted. The results show:

- Ch-S can operate continuously for 16.57 h, delivering a total of 3313.84 MWh before needing a new recharge by pumping.
- (Ch + CN)-S substantially improves this autonomy, reaching 33.67 h of continuous operation and a total energy of 6733.27 MWh, thanks to the increase in the useful volume of the upper reservoir.
- (Ch-S) + (CN-S) achieves a combined continuous energy of 6528.37 MWh, although distributed between two independent jumps that can alternate or operate in parallel.

This result is relevant for to ensure the resilience of the system in emergency situations or low renewable generation, such as days with unfavorable weather conditions. The existence of two independent jumps not only increases the overall storage capacity, but also introduces operational redundancy, allowing one plant to make up for the inactivity of the other.

3.3. Pumping power and daily energy consumption

The pumping mode represents the energy consumption of the system to store water in the upper reservoir. Although this process does not generate energy directly, it is crucial for absorbing renewable surpluses and avoiding spills.

- All individual configurations (Ch-S or CN-S) have a pumping power of 220 MW and an overall cycle efficiency of 75% (pumping + turbinizing).
- The combined (Ch-S) + (CN-S) configuration requires 440 MW of pumping power, which implies a higher daily energy consumption to fully recharge both reservoirs: 5930.33 MWh/day.

This value defines the minimum installed renewable power required to operate the system on a sustained basis. In particular, the following are required:

- 725 MW renewable in individual configurations.
- 1292.17 MW in the case of (Ch-S) + (CN-S), which represents a significant but feasible increase considering the wind and photovoltaic potential of the island.

3.4. Reduction of greenhouse gas emissions

The most relevant effect from an environmental perspective is the ability of the configurations to reduce CO₂ emissions from the use of thermal generation. The study estimates the following reductions.

Table 10

Estimated annual CO₂ emissions and reduction levels for the analyzed configurations, based on the replacement of thermal generation by renewable energy and storage.

Configuration	Current emissions (tCO _{2eq} /year)	Estimated emissions	Reduction (%)
Ch-S	2.243.202,21	1.720.164,09	23,32%
(Ch + CN)-S	2.243.202,21	1.720.164,09	23,32%
(Ch-S) + (CN-S)	2.243.202,21	0	100%

The estimated greenhouse gas emissions for each configuration are summarized in Table 10.

Only the last configuration makes it possible to achieve a totally carbon-free electricity system, thanks to Complete coverage of demand by turbines (daily turbinning of 4208 MWh).

Use of unpumped renewable surplus to produce green hydrogen, used as back-up energy (2.04% of annual demand).

This result places the Gran Canaria Island system as a reference model for total decarbonization in isolated environments, demonstrating that a combination of synchronized hydro storage and H₂ production can completely cover demand without resorting to fossil fuels.

3.5. Renewable requirements and system size

To achieve these results, a correctly dimensioned renewable system is necessary. The study establishes that, with an average capacity factor of 36.76%, it is required to install:

- 1292.17 MW of renewables to feed both direct consumption and pumping cycles and hydrogen production.

This power can be distributed between new solar (in the south) and wind (onshore and offshore) installations, which is compatible with the administrative authorizations in force on the island.

Fig. 6 illustrates how the (Ch-S) + (CN-S) configuration doubles the managed energy and completely eliminates emissions:

Table 11 compares the three reversible hydro configurations, together with a graph illustrating the daily energy generated (turbinning) and the associated emissions in each case. This allows a clear visualization of the energy yield versus environmental impact:

- The Ch-S and (Ch + CN)-S configurations generate similar daily energy (~2100 MWh), but do not achieve full decarbonization (they maintain ~1.72 MtCO₂/year).
- The combined (Ch-S) + (CN-S) configuration doubles the daily generation capacity (~4200 MWh) and achieves a 100% emission reduction, enabling a fully renewable island system.

3.6. Qualitative and multi-criteria analysis

Beyond the numerical values, each configuration has qualitative advantages and limitations:

- Ch-S: more mature solution and implementation. Low incremental cost but limited decarbonization capacity.
- (Ch + CN)-S: improves energy autonomy without duplicating equipment, being an alternative with a lower investment cost and less constructive impact.
- (Ch-S) + (CN-S): the only option that allows the strategic objective of zero emissions to be met, but requires greater investment, more installed renewable power and more complex operational management.

In a weighted multi-criteria analysis (based on Canary Islands Government energy planning criteria), the third option obtains the best overall score by maximizing sustainability, energy independence, system security and long-term environmental viability.

3.7. Visual multi-criteria analysis

To clearly and comparatively summarize the main technical, operational and strategic attributes of the three reversible pumped hydro-power storage configurations analyzed, a multi-criteria radar graph was drawn up. This type of representation allows for the simultaneous evaluation of several critical factors in energy planning decision-making, particularly in island contexts where resilience, sustainability and viability are essential.

The six criteria evaluated were as follows:

- Managed daily energy (MWh): reflects the capacity of each system to meet electricity demand continuously from stored energy.
- Operating autonomy (hours): represents the maximum duration for which the system can operate in turbine mode without the need for refueling by pumping.
- CO₂ emission reduction (%): indicates the relative contribution of each configuration to the decarbonization of the system.

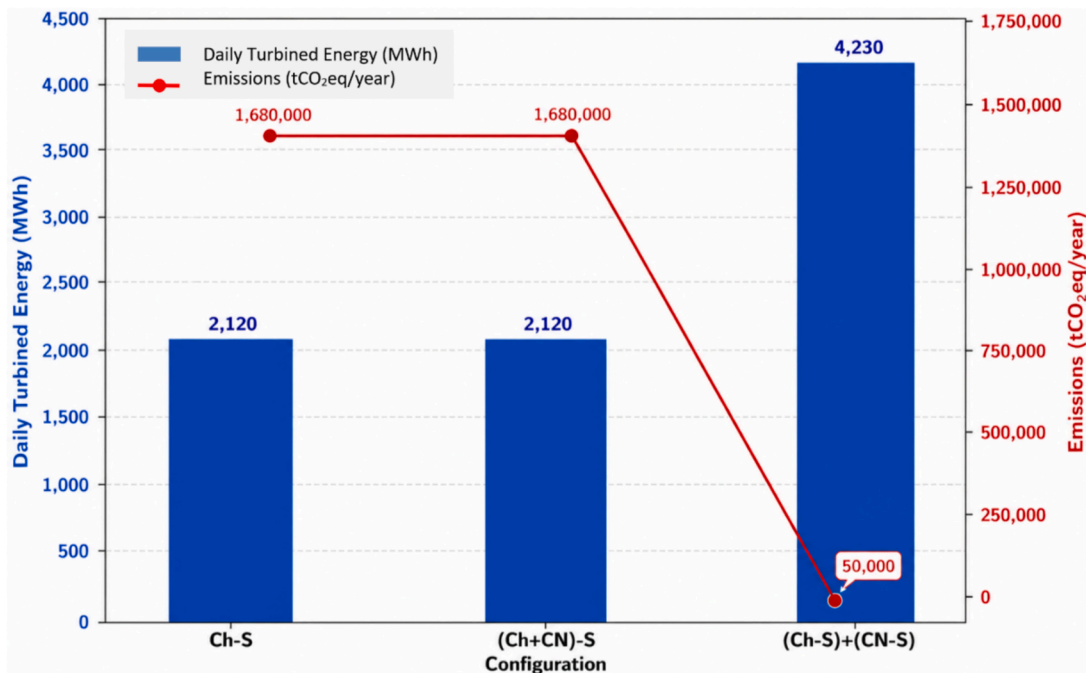


Fig. 6. Energy comparison and emissions comparison of the different configurations.

Table 11
Comparison of the main technical parameters of the balanced operation of the three configurations.

Section	Parameter	Unit	Ch-S	(Ch + CN)-S	Ch-S	CN-S	SUMA
Equilibrium turbination	Hours/day	h/day	10.52	10.52	10.52	10.52	21.04
			0.43842	0.43842	0.43842	0.43841	0.87683
	Maximum continuous hours	h	16.57	33.67	16.57	16.07	32.64
	Flow rate	m ³ /s	68.40	68.40	68.40	72.76	
	Turbines	No.	6.00	6.00	6.00	6.00	12.00
	Unit power	MW	33.333	33.333	33.333	33.333	33.333
	Power	MW	200.00	200.00	200.00	200.00	400.00
	Energy/day	MWh	2104.43	2104.43	2104.43	2104.35	4208.79
	Max continuous energy	MWh	3313.84	6733.27	3313.84	3214.53	6528.37
	Hours/day	h/day	13.48	13.48	13.48	13.48	26.96
Equilibrium pumping			0.56158	0.56158	0.56158	0.56159	1.12317
	Maximum continuous hours	h	21.22	43.12	21.22	20.59	41.81
	Flow rate	m3/s	53.40	53.40	53.40	56.80	
	Turbines	Ud	6.00	6.00	6.00	6.00	12.00
	Unit power	MW	36.667	36.667	36.667	36.667	36.667
	Power	MW	220.00	220.00	220.00	220.00	440.00
	Energy/day	MWh	2965.12	2965.12	2965.12	2965.21	5930.33
	Max continuous energy	MWh	4669.16	9487.10	4669.16	4529.54	9198.70
	Year 2023	tCO2/year	2,243,202.21				
	Forecast 2023	tCO2/year	1,720,164.09	1,720,164.09			
Emissions	Decrease	%	23.32%	23.32%	100%	100%	100%
	Renewable power required	MW	725	725	1292.17	1292.17	1292.17
General	Racking volume	m ³	4,080,000	8,290,000	4,080,000	4,210,000	8,290,000
	Equilibrium volume	m ³	2,590,978.52	2,590,978.52	2,590,978.52	2,756,029.30	5,347,007.82
	Waterfall	m	343	343	343	327	
	Pipe diameter	m	4.00	4.00	4.00	4.13	

- IV. Renewable power required (MW): estimates the level of renewable infrastructure required to operate the plant in a self-sufficient and sustainable manner.
- V. Operational flexibility: measures the system's ability to adapt to hourly demand variability and different weather scenarios, especially in double-jump configurations.

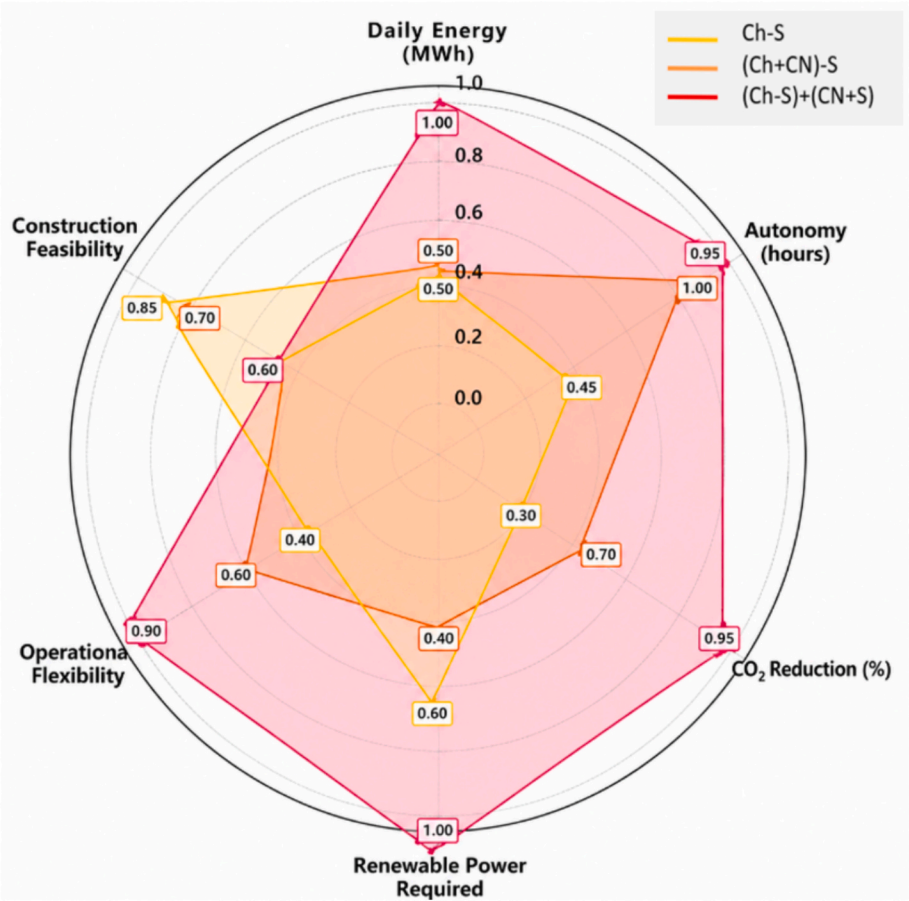


Fig. 7. Multi-criteria comparison of the three reversible hydropower configurations using normalized indicators (0–1 scale) based on AHP weighting. Numerical values are included to enhance the transparency of the comparative assessment.

VI. Constructive feasibility: assesses the ease of technical implementation, including civil works requirements, integration of existing infrastructures and execution times.

The values were normalized on a scale of 0 to 1 to facilitate relative comparison, and the result is shown in Fig. 7.

For improved transparency, numerical values have been incorporated into Fig. 7, allowing a clearer interpretation of the relative performance of each configuration. The “Construction Feasibility” scores reflect the relative complexity of implementation, where lower values indicate higher technical and administrative difficulty.

Table 12 summarizes the main evaluation indicators for the analyzed configurations, providing a comparative overview of their technical, environmental, and operational performance. Quantitative indicators are complemented with normalized qualitative assessments to reflect operational characteristics that cannot be directly expressed numerically.

These results highlight the significant improvement in system performance achieved by the dual configuration (Ch-S) + (CN-S), particularly in terms of renewable integration, emissions reduction, and operational flexibility.

- The (Ch-S) + (CN-S) configuration clearly dominates in the first five criteria: it offers the highest daily energy managed, the highest operational flexibility and is the only option able to achieve a total emission reduction (100%). Its ability to operate two independent hops makes it a particularly robust and adaptable solution for high renewable variability scenarios.
- The (Ch + CN)-S alternative, while maintaining the same installed power as Ch-S, significantly improves the autonomy of the system thanks to the increase in useful storage volume. This positions it as a solid intermediate option, especially in contexts with budgetary or constructive constraints.
- The Ch-S baseload configuration, currently under construction, represents a substantial improvement over the current scenario without storage. However, its contribution to decarbonization is limited (23.3%) and it lacks the capacity to ensure full renewable coverage.

It should be noted that the criterion “Renewable power required” is represented inversely to its requirement: a higher value in the graph implies a higher system coverage from renewables (not a lower requirement). Likewise, the lower score for “constructive feasibility” for (Ch-S) + (CN-S) reflects its higher technical and administrative complexity, which should be taken into account in the planning process.

Overall, the multi-criteria analysis reaffirms that, although more demanding in terms of investment and development, the (Ch-S) + (CN-S) option constitutes the most efficient, resilient and climate-neutral alternative from a technical and operational perspective to achieve an autonomous energy system in Gran Canaria.

3.8. Sensitivity of LCOES to CAPEX increase

To evaluate the economic robustness of the recommended configuration [(Ch-S) + (CN-S)], a sensitivity analysis was conducted considering a + 15% increase in CAPEX, reflecting potential uncertainties associated with construction costs and financing conditions (Table 13).

Table 12
Evaluation indicators for the analyzed configurations.

Configuration	Renewable penetration (%)	Thermal generation reduction (%)	CO ₂ emissions reduction (%)	Storage utilization (%)	Renewable curtailment	System flexibility
Ch-S	46–50	23.32	23.32	75	Reduced	Medium
(Ch + CN)-S	46–50	23.32	23.32	75–80	Reduced	Medium–High
(Ch-S) + (CN-S)	100	100	100	75–85	Minimal	Very high

Table 13

Sensitivity of the Levelized Cost of Stored Energy (LCOES) to a + 15% increase in CAPEX for the (Ch-S) + (CN-S) configuration.

Scenario	CAPEX variation	LCOES (€/MWh)
Base case	0%	145
High-cost scenario	+15%	167

This corresponds to an increase of approximately 15.2% in LCOES. Despite this variation, the configuration remains competitive compared to other large-scale storage technologies, particularly considering its contribution to system decarbonization.

In addition to the economic assessment, the sensitivity analysis evaluates the impact of the considered scenarios on the main system performance indicators. Variations in renewable availability primarily affect renewable penetration and curtailment levels, while demand growth scenarios influence storage utilization and thermal generation requirements. Changes in CO₂ emission costs mainly impact the economic performance of the configurations.

Overall, the results indicate that the proposed configurations remain robust across the evaluated scenarios, maintaining consistent improvements in renewable integration and emissions reduction compared to the baseline system.

4. Conclusions

This study has presented a comprehensive technical and operational assessment of three pumped-storage hydropower configurations for the isolated electricity system of Gran Canaria, integrating real operational data from 2023, hydraulic modelling, and multi-criteria analysis.

The results demonstrate that the incorporation of large-scale storage significantly improves system performance by increasing renewable integration, reducing reliance on fossil-based generation, and enhancing operational flexibility. While the Chira-Soria (Ch-S) configuration provides a relevant improvement over the current system, its impact remains limited in terms of achieving full decarbonization. The extended configuration (Ch + CN)-S improves storage capacity and operational autonomy without increasing installed power, representing a balanced intermediate solution.

The dual configuration (Ch-S) + (CN-S) enables full coverage of electricity demand through renewable energy and storage, achieving complete decarbonization under the simulated conditions. This configuration also increases system resilience by combining short-term storage (pumped hydro) with long-duration backup through hydrogen, ensuring supply during extended periods of low renewable generation.

From a system perspective, the results highlight the importance of coordinated operation between multiple storage technologies and sufficient renewable capacity to ensure stable and reliable operation in isolated grids. The integration of hydrogen as a complementary storage vector further extends the system's capability to manage long-term variability.

Overall, the proposed modelling framework provides a consistent methodology for evaluating storage-based solutions in island systems, combining technical performance, environmental impact, and operational feasibility. The results confirm that fully renewable and decarbonized island energy systems are technically achievable, although they require significant expansion of renewable capacity and careful system

planning.

Future work should focus on detailed economic assessment, multi-year climatic variability, and socio-environmental analysis to further support decision-making and implementation strategies.

CRedit authorship contribution statement

Juan Carlos Lozano Medina: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Federico León Zerpa:** Writing – review & editing, Writing – original draft, Validation, Software, Project administration, Investigation, Formal analysis, Conceptualization. **Alejandro Ramos Martín:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Funding acquisition, Data curation, Conceptualization. **Carlos Alberto Mendieta Pino:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition, Formal analysis.

Future line of research

It is recommended to deepen socio-environmental impact studies, comparative economic analyses (CAPEX/OPEX), as well as governance models for a phased implementation of the dual system [(Ch-S) + (CN-S)], including public-private participation schemes and European financing mechanisms.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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