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Massive energy storage using H_2 to support the optimal and efficient integration of a pumped hydroelectric power plant

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ABSTRACT

In Gran Canaria, the integration of renewable technologies is being investigated to address intermittency in power generation. The future Chira-Soria pumped-storage hydroelectric power plant (PHES), planned for 2030, will be key in harnessing the island's hydro potential. In addition, hydrogen storage is being explored as a viable solution. This method uses electrolysis of water to produce hydrogen during energy surplus, storing it to generate electricity when there is low renewable production. This approach mitigates intermittency, stabilizes the energy system and reduces dependence on fossil fuels. The combination of the Chira-Soria PHES with hydrogen storage will ensure a sustainable and reliable energy supply, contributing to the transition to a cleaner and more resilient energy matrix. The studies seek to optimize this technology, maximizing its efficiency to promote the sustainable development of Gran Canaria and reduce greenhouse gas (GHG) emissions.

1. Introduction

The rush to move toward decarbonization [1] and expand the presence of renewable energy [2,3] has generated a consensus among experts and leaders in the energy field [4–6]. These imperative manifests itself particularly acutely in the context of the Canary Islands [7,8], with a special focus on Gran Canaria [9,10], where four crucial challenges are delineated that will require innovative and strategic responses in the coming years [11–14].

The first of these challenges lies in the need to meet the growing electricity demand [15,16]. By 2023, a demand of 3321 GWh is projected in Gran Canaria [17], which calls for a gradual transition of current energy production plants towards more efficient technologies [18]. This process includes the elaboration of a meticulous plan to replace obsolete units, while ensuring the capacity to cover the expected increase in electricity demand [19]. The projected installed capacity for 2023 is estimated at 1287 MW, which underscores the need for adaptation and modernization of the island's energy system.

On the other hand, the obsolescence of the current energy system represents a significant risk of collapse, which requires a partial renewal of the infrastructure in Gran Canaria [19]. Most of the energy facilities on the island are over 30 years old and do not meet current technological standards in terms of efficiency and emissions. This scenario directly affects the cost of electricity and CO_2 emissions, especially considering the high dependence of 70.40% on imported fossil fuels in 2023. Therefore, the need for an urgent technological upgrade becomes evident to ensure the stability and sustainability of the energy supply. Furthermore, increasing renewable energy penetration in Gran Canaria is imperative to mitigate environmental impact and promote long-term sustainability [9,10,20]. Although renewable energy penetration on the island currently stands at 29.60%, there is still a long way to go [17]. Government initiatives aimed at encouraging the installation of wind farms and solar panels reflect a growing environmental awareness and active search for clean and re-renewable alternatives [21]. However, the adoption of CO_2 neutral systems emerges, such as [22,23], as a complementary and necessary strategy to achieve decarbonization goals [10, 24,25].

Finally, the optimization and integration of the Chira-Soria pumped-storage hydroelectric power plant [26,27] into the energy system of Gran Canaria represents a significant step [28] towards system stabilization and resilience [29–31]. This power plant plays a crucial role in providing energy storage [32–34] by pumping water to high altitudes, which allows the generation of electricity during de-mand peaks and the efficient utilization of available renewable energy [28]. The successful

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integration of this technology will not only contribute to reducing dependence on fossil fuels but will also strengthen the system's responsiveness to fluctuations in renewable generation [15].

In summary, the energy challenges facing Gran Canaria in the coming years demand a comprehensive and collaborative approach that combines technological modernization, the promotion of renewable energies, and the implementation of innovative energy storage solutions [35]. Only through a coordinated and committed effort, Gran Canaria will be able to ensure a sustainable, reliable and environmentally friendly energy supply for future generations [36]. The detailed analysis of the existing and future system of Gran Canaria will consider the incorporation of the Chira-Soria pumped hydroelectric power plant, as well as the proposed hydrogen (H_2)-based alternative mass storage [37, 38]. This massive storage of green H_2 will occur massively when the pumped hydro plant operates in turbine mode and to a lesser extent also in pumped mode if there is wind capacity left over [38]. The process involves converting renewable energy into hydrogen [39], storing the hydrogen produced for later use in fuel cells [40] or other conversion processes [41,42].

The fundamental purpose of this study and sizing of alternative storage using H_2 is not only to take full advantage of the available renewable energy capacity without generating environmentally harmful discharges, but also to ensure an optimal and efficient integration of the Chira-Soria pumped-storage hydroelectric power plant into the energy landscape of Gran Canaria [43]. This integration seeks not only to improve the stability of the island's electricity system, but also to maximize efficiency in energy management. In addition, this innovative approach aims to contribute significantly to the reduction of greenhouse gas emissions, thus consolidating the island's commitment to the fight against climate change. By implementing cleaner and more efficient energy storage strategies, it is expected to move towards a more sustainable and resilient energy model, providing a solid framework for the economic and social development of Gran Canaria in harmony with its natural environment.

When proposing a methodology for the analysis of energy generation systems at both continental and island level, and particularly in the Canary Islands, several authors have opted for the Hybrid Optimization of Multiple Energy Resources (HOMER) model. This software, which was developed by the National Renewable Energy Laboratory (NREL), estimates the best energy system, the economic investment and the levelized cost of energy (LCE), among others, and considers different energy sources. For the different alternatives or scenarios in island environments, it is necessary to consider the existing systems responsible for non-renewable sources, as well as the use of alternative fuels (both fossil and renewable) and their impact on the level of emissions. In addition, it is necessary to consider the fact that generation systems already in use must be compatible with renewable generation systems in order to meet the existing energy demand. Furthermore, the integration of new technologies, such as the pumped-storage hydroelectric power plant (PHES) of Chira-Soria, in Gran Canaria, the optimization of H_2 production, as well as multiple factors and variables specific to this installation, must be considered. Consequently, a methodological alternative is required that includes all of the above considerations.

1.1. Overall situation of energy production in 2022 and 2023 in Gran Canaria

Energy production in Gran Canaria in 2022 and 2023 is based on a diverse mix of technologies, including steam turbines, diesel units, gas turbines and combined cycles [19].

In 2022, these installations accounted for 70.40% of the total installed capacity, which amounted to 906.00 MW, while the remaining 29.60%, equivalent to 381.00 MW, came from renewable sources. Overall, the total installed capacity on the island reached 1287.00 MW [44].

By 2023, total energy demand rose to 3321 GWh, which represents an annual average of 379.10 MW [17], marking a historical milestone. On October 9 of that year, the historical maximum daily energy demand was recorded in the Canary Islands, with a demand of 1455.3 MWh [17], coinciding with the maximum peak recorded in Gran Canaria of 558.80 MWh at 20:00 h. This detailed analysis of the day of maximum energy demand is crucial to anticipate and prepare for extreme situations that could become more frequent in the future. It is relevant to note that this day was characterized by a low contribution of renewable energies, which underlines the importance of diversifying and further strengthening the island's energy mix. During this period of maximum demand, a total of 563.40 MW was covered, with 298.43 MW coming from renewable sources and 354,43 MW from non-renewable sources. This analysis highlights the need to continue investing in sustainable technologies and in infrastructures that promote the integration of clean energies in the energy system of Gran Canaria.

Fig. 1 shows the representation of the average demand differentiated by the days of the week and the annual average for the year 2023 (379.10 MW) as well as the annual average for the year 2022 (350.91 MW).

1.2. H_2 energy storage

Storage of energy from renewable sources using hydrogen (H_2) offers a promising solution to address the challenges of intermittent and variability inherent in renewable generation. The algorithm-based approach to efficiently manage this process is described:

Renewable generation management: Renewable generation management begins with the collection of detailed data on energy production from renewable sources, such as wind and solar energy. This data includes information on wind speed, solar radiation, solar panel and wind turbine capacity, among other relevant factors. Once collected, this data is subjected to extensive analysis to understand power generation patterns over time. This involves the use of forecasting and forecasting techniques to predict the availability of renewable energy over future periods, which can vary from hours to days or weeks, depending on the time scale required. During this management process, a number of variables are taken into account, such as historical weather conditions, seasonal changes, geographical location of renewable resources, and any other factors that may affect energy production. Accurate prediction of the availability of renewable energy is essential for effective planning of power system operation, allowing operators to anticipate and proactively manage the integration of renewable energy into the power grid. This facilitates informed decision-making on generation scheduling, energy storage and demand management, thus contributing to the stability and efficiency of the system as a whole.

Energy surplus identification: A data analysis algorithm is used to identify periods when renewable energy generation exceeds instantaneous energy demand. During these surplus periods, instead of wasting the surplus energy, it is channeled into hydrogen production.

Electrolysis for hydrogen production: Surplus electrical energy is used to power electrolyzes, devices that decompose water (H_2O) into hydrogen (H_2) and oxygen (O_2) through a process of electrolysis.

Hydrogen storage: The hydrogen produced is stored in tanks or in the form of metal hydrides for future use. These storage systems allow large amounts of energy to be stored during periods of surplus for later use when renewable generation is not sufficient to meet demand.

Hydrogen-to-energy conversion: When energy demand exceeds available renewable generation, stored hydrogen is used. This can be used in fuel cells to produce electricity and heat efficiently and cleanly, without greenhouse gas emissions.

System optimization: Optimization algorithms are used to determine the optimal time to produce, store and use hydrogen, thus maximizing system efficiency and minimizing operating costs.

Integration with the power grid: The hydrogen storage system integrates with the existing power grid, acting as a flexible infrastructure that can provide backup services and stability to the system,

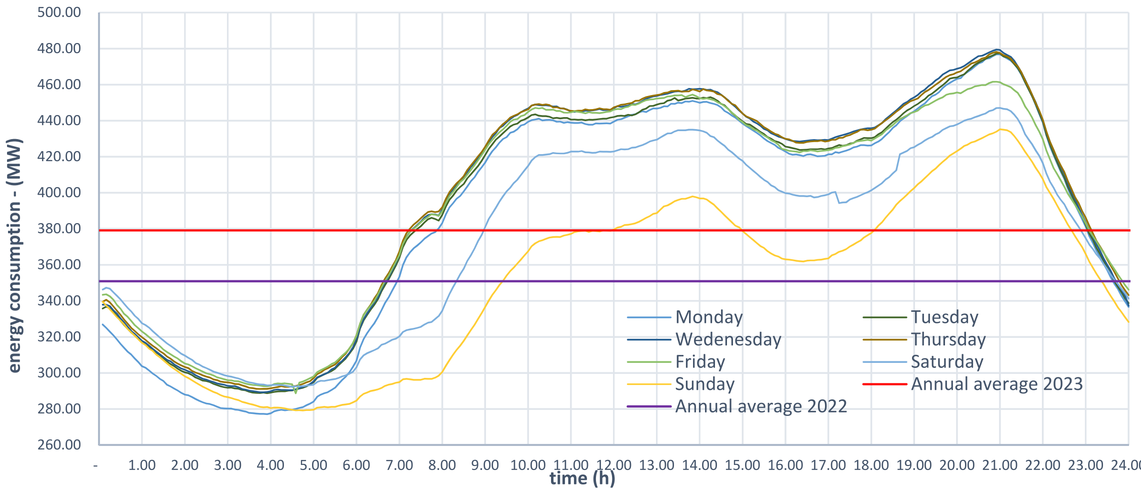

Fig. 1. Average annual consumption differentiated days of the week in 2023 and average annual consumption 2022 and 2023.

contributing to the management of energy supply and demand.

This algorithm-based approach provides a systematic methodology to efficiently harness surplus energy from renewable sources through hydrogen production and storage, thus contributing to the transition to a more sustainable and resilient energy system.

2. Materials and methods

2.1. Methodology

The methodology followed for the system analysis, study and proposal for the production and storage of hydrogen from surplus energy from renewable sources, given the future energy situation with the incorporation of the Chira-Soria pumped-storage hydroelectric power plant, must be a precise methodology that combines knowledge of the different technologies and data analysis. The methodological approach used, which has involved the development of a specific algorithm to guide the process, can be divided into several key stages:

Data collection: The first stage involves the collection of data on renewable energy production in each region or area. This includes data on wind, solar or other available renewable energy generation.

Analysis of renewable energy availability: A detailed analysis of the availability of renewable energy during specific periods is performed, considering factors such as climatic and seasonal variability.

Identification of energy surpluses: Using data analysis techniques, periods in which renewable energy generation exceeds current energy demand are identified. These periods are known as “energy surpluses”.

Selection of hydrogen production technology: Proton exchange membrane electrolysis (PEM) is the most suitable technology for producing hydrogen from available surplus energy. This technology is more efficient, uses a solid membrane that allows a higher current density, resulting in more efficient hydrogen production, although it is more expensive than alkaline, and offers more flexibility by better coupling with fluctuating renewable energies such as solar and wind.

System optimization: An optimization model is developed to determine the optimal amount of renewable energy to divert to hydrogen production based on energy demand and other relevant factors.

Economic and environmental feasibility assessment: An economic and environmental feasibility analysis is performed to evaluate the cost and environmental impact of hydrogen production from surplus renewable energy.

Implementation and monitoring: Once the algorithm have been developed and the results evaluated, the hydrogen production system is implemented. Subsequently, a continuous monitoring process is established to adjust the system as needed and optimize its performance.

This algorithm-based approach provides a systematic structure to investigate and exploit the potential of hydrogen production from surplus renewable energy, thus contributing to the transition to a more sustainable and efficient energy system. It is show schematically in Fig. 2.

2.2. Pumped storage hydroelectric power plant (PHES). Analysis

The Chira-Soria pumped storage hydroelectric power plant project, located on the island of Gran Canaria, Spain, represents a strategic energy infrastructure in the transition to a more sustainable electricity system. This plant is part of a broader effort to increase the penetration of renewable energies in the Canary Islands’ energy mix, thus improving the stability and efficiency of the local electricity system. Its commissioning is scheduled for 2030. As for its technical characteristics, we highlight the following in brief:

2.2.1. Main components

The Chira-Soria pumped-storage hydroelectric power plant project consists of several key components:

- Reservoirs:

Chira Reservoir: Located at an altitude of approximately 875 m above sea level, it has considerable water storage capacity.

Soria Reservoir: Located at a lower altitude, approximately 600 m above sea level. It also has a significant water storage capacity.

- Tunnels and Forced Conduits:

The system includes tunnels and forces conduits that connect the two reservoirs, allowing the controlled flow of water between them. The total length of the tunnels exceeds 2 km and are designed to withstand high water pressures.

- Hydroelectric power plant:

The power plant contains several reversible turbines that can operate in both generator and pumping mode. The installed capacity is 200 MW, which allows for significant power production during periods of high

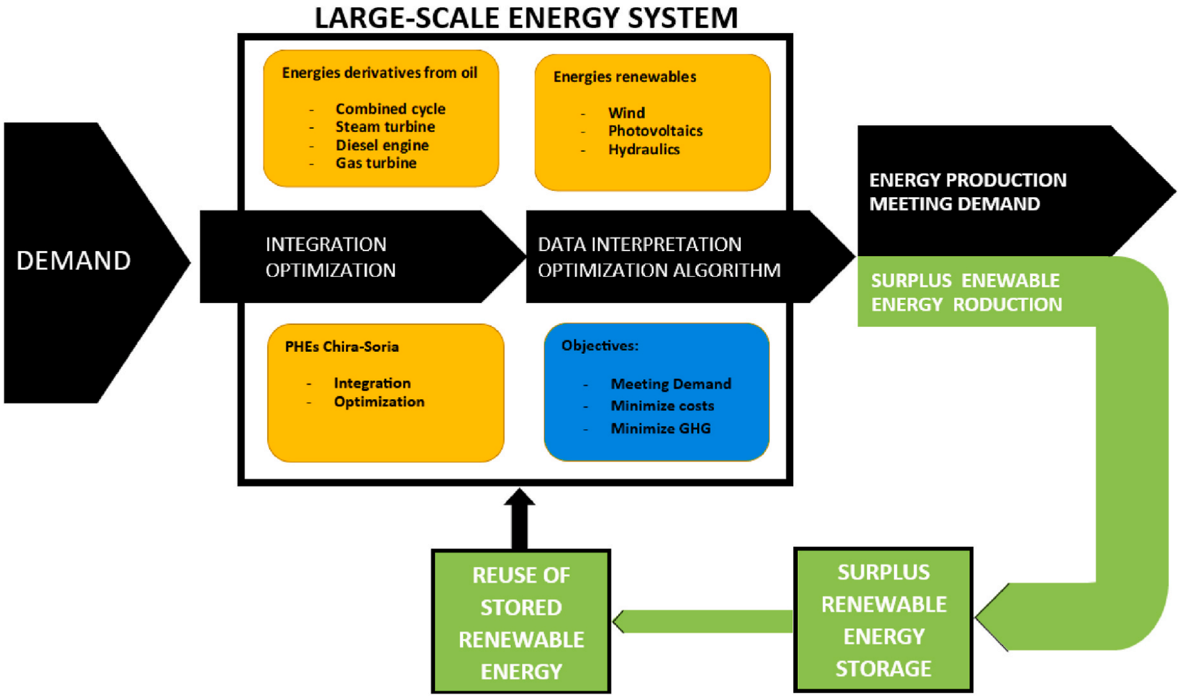

Fig. 2. Methodology.

demand.

- Substation and Transmission Lines:

An electrical substation facilitates the integration of generated power into the local electrical system. Transmission lines connect the plant to the power grid, ensuring efficient energy distribution.

2.2.2. System operation

The operation of the Chira-Soria Pumped Storage Hydropower Plant is based on the principle of Pumped Storage Hydropower (PSH). During times of low electricity demand, when there is excess production of renewable energy (mainly solar and wind), the system uses this excess energy to pump water from the lower reservoir (Soria) to the upper reservoir (Chira). During periods of high demand, water is released from the upper reservoir to the lower reservoir, passing through the turbines and generating electricity.

2.2.3. Technical benefits

- Energy Storage:

Acts as a giant battery, storing energy in the form of potential water during periods of excess renewable production.

- Frequency Regulation:

Improves grid stability by providing ancillary services such as frequency regulation and the ability to respond quickly to variations in demand.

- CO_2 Emissions Reduction:

By facilitating greater integration of renewable energy, it contributes to the reduction of greenhouse gas emissions.

- Improved System Efficiency:

Optimizes the use of existing infrastructure and reduces the need to turn on fossil power plants at times of high demand.

2.2.4. Project analysis. Environmental impact

The environmental impact of the project has been carefully assessed:

- Impact on Flora and Fauna:

Measures have been implemented to minimize the impact on the local ecosystem, including relocation of sensitive species and creation of conservation areas.

Water Management:

- Water management is critical to avoid overexploitation of water resources and ensure the sustainability of the system.
- CO_2 Emissions:

The power plant will help reduce CO_2 emissions by enabling greater integration of renewable energy sources.

- Noise and Vibration:

Measures have been taken to mitigate noise and vibration during construction and operation, including the use of advanced technologies and the installation of acoustic barriers.

The Chira-Soria pumped-storage hydroelectric power plant project, with its energy storage and generation capacity, not only supports the transition to a higher proportion of renewable energy, but also provides greater stability and security to Gran Canaria's electricity system. The combination of its technical, economic and environmental benefits makes Chira-Soria a key project on the road to a cleaner and more resilient energy future.

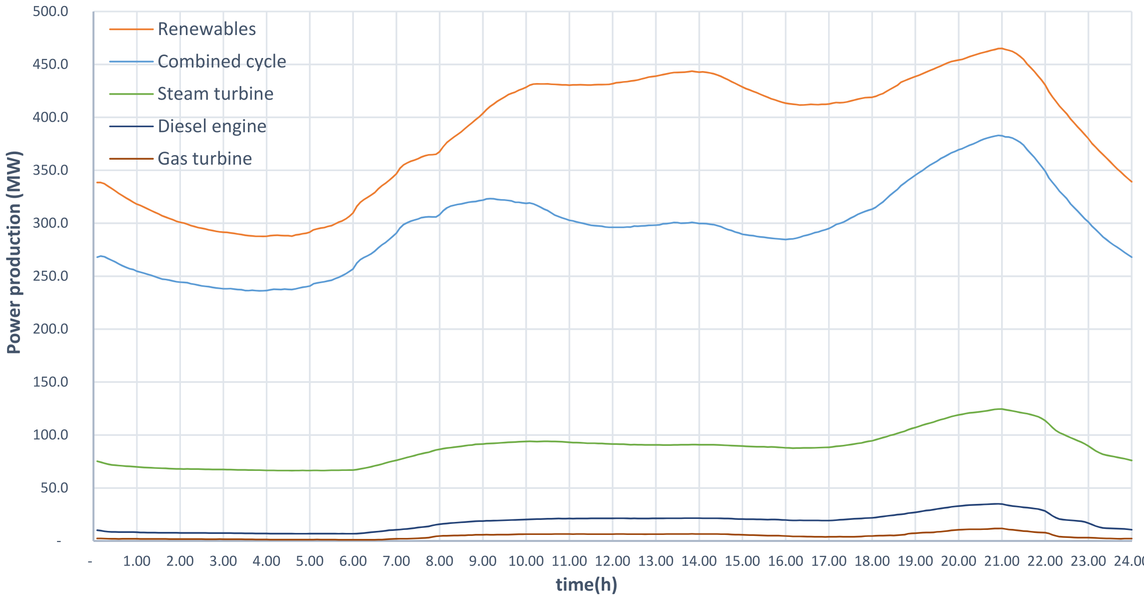

Fig. 3. Average daily demand response curve for Gran Canaria in the year 2023.

2.3. Estimation of the average demand curve for the study and estimation of the integration of the Chira-Soria pumped-storage hydroelectric power plant in the energy system of Gran Canaria in the year 2023

In order to analyze the energy situation for the year 2023 as a whole and to serve as a basis for studying the integration of the Chira-Soria pumped-storage hydroelectric power plant into the system, the average energy performance curve of the producing equipment is needed. For this purpose, the 365 days of the year 2023 are analyzed and the annual average of these 365 days is established, which will be called the "annual average day". Following the standards of representation of the Spanish electrical grid, the cumulative representation would be as shown in Fig. 3.

This representation has been obtained from real data, published by the production company, with readings every 5 min 365 days a year. Represents energetically 1/365th of the year 2023. Resulting and coinciding the data of the average day with 1/365 part of the annual data. From this curve it is obtained that the average annual power of the combustion production equipment is 386,74 MW, and its production is established in Table 1.

2.4. Estimated renewable energy discharges 2023

In the Canary Islands, and due to the lack of storage in the Canary Islands electricity system, there are spills of renewable energy. These were estimated for the year 2023, as shown in Table 2, as a % of demand.

This represents an accumulated annual average of 6.58% (25.45 MW) of discharges.

2.5. Estimation of average daily emissions by production equipment in the energy system of Gran Canaria in the year 2023

To analyze the emissions and their effects or modifications with the integration of the Chi-ra-Soria pumped-storage hydroelectric power plant into the system, the average emissions curve of the producing equipment is needed. For this purpose, the 365 days of the year 2023 are analyzed and the annual average of these 365 days is established, which will be called the "average annual day of emissions". It would be as shown in Fig. 4.

This curve represents energetically 1/365th of the year 2023 and has been obtained from real data, published by the production company, with readings every 5 min 365 days a year. Resulting and coinciding the data of the average day with 1/365 part of the annual data. From this curve it is obtained that the average annual power of the combustion production equipment is 386.74 MW, and its production is established in the following Table 3.

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	4.91	1.65	0.31	0.11	1.74	0.38	0.00	9.10
GWh/year 2023	1793.25	602.76	111.40	39.88	636.15	138.37	0.00	3321.82

Table 2
Renewable energy spillage in Gran Canaria 2023.

	January	February	March	April	May	June	July	August	September	October	November	December	Running total
Wind	3.85%	0.70%	8.50%	11.18%	15.44%	0.33%	8.72%	8.63%	2.73%	0.73%	6.39%	2.76%	7.27%
Photovoltaic	0.51%	0.06%	1.47%	5.84%	8.39%	0.01%	6.59%	6.04%	1.23%	0.14%	3.11%	0.52%	3.08%
Total	3.41%	0.51%	7.38%	10.16%	14.46%	0.25%	8.51%	8.33%	2.47%	0.55%	5.86%	2.24%	6.58%

Source: Red Eléctrica de España

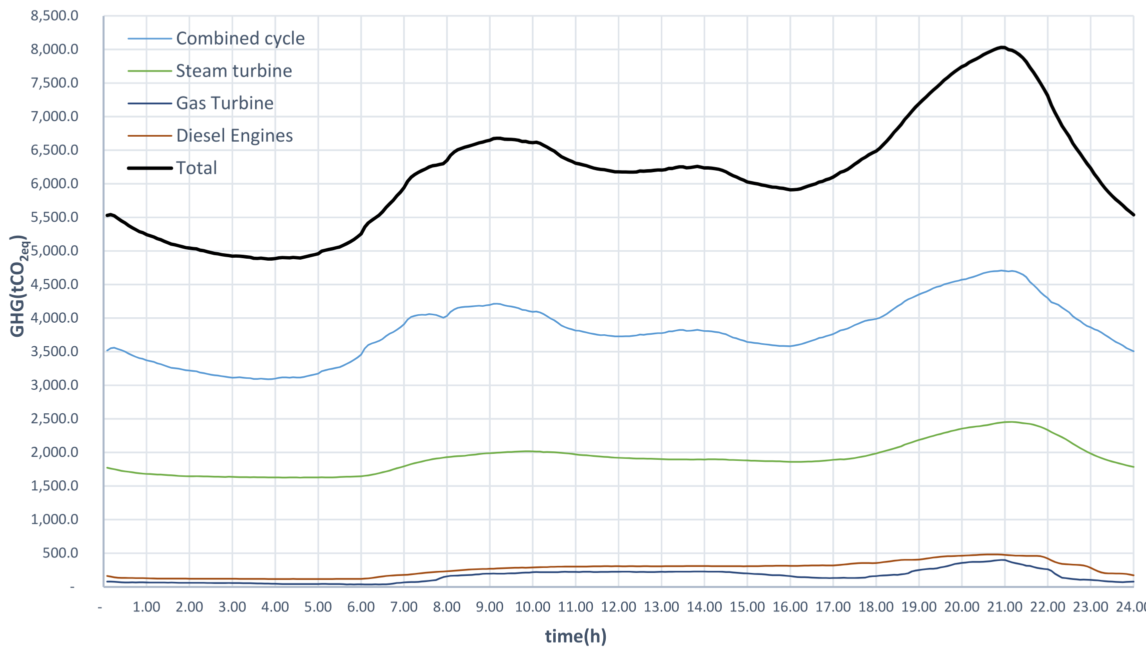

Fig. 4. Gran Canaria average daily GHG emissions curve for the year 2023.

2.6. Integration of Chira-Soria into the Gran Canaria energy system

2.6.1. Consequences on energy production with the integration into the energy system of Gran Canaria in the year 2023

This is a theoretical integration that seeks to minimize emissions and stabilize the frequency with the maximum use of renewables (assuming that there is no deficit of renewables for such use), in the average annual day studied, which represents the year 2023. This integration of the Chira-Soria pumped-storage hydroelectric power plant is shown in Fig. 5 and the operation of the Chira-Soria pumped-storage hydroelectric power plant is shown in Fig. 6.

With this optimization and integration, the production curve through combustion has been flattened, being defined in two steps, these steps represent the average annual demand to be covered by the combustion equipment due to the integration of the Chira-Soria pumped-storage hydroelectric power plant, the highest at 299.50 MW and the lowest at 237.49 MW, establishing a plant factor of 60.59% and also complying with the Pumping-Turbine balance (43.84% turbine and 56.16% pumping).

For this ideal integration it is necessary to have an average annual power in the pumping period of 175.46 MW of wind and 219.20 MW, which leads, taking as data the availability factor for 12-month operations in the year 2022, (34.5%) to an additional installation in renewable power to the existing one of 508.58 MW on average and 635.36 MW on time. From this amount, it would be necessary to subtract the accumulated average renewable discharges, redefining the additional installation in renewable power to the existing one and establishing the new renewable needs at 483.13 MW on average and 609.91 MW on time.

The following graph defines the annual pumping and turbining averages.

2.6.2. Consequences on emissions with the integration in the energy system of Gran Canaria in the year 2023

The following graph for the average annual day in 2023, Fig. 7, shows the total emissions produced and compares them with those produced with the integration of the Chira-Soria pumped-storage hydroelectric power plant for the same year.

The average daily emissions in 2023 were 6145.61 tCO_{2eq}/day, which means 2,243,202.21 tCO_{2eq}/year. 202.21 tCO_{2eq}/year and with the incorporation of the Chira-Soria Hydroelectric Pumping Plant, which increases emissions in the pumping phase, but decreases in the turbine phase, the net result would be a decrease in emissions of 1432.98 tCO_{2eq}/day, or 523,038.12 tCO_{2eq}/year, which represents a decrease of 23.32%.

2.6.3. Summary of integration

Table 4 is attached, a summary table of the three operating proposals, all of them complying with the necessary and argued guidelines, for an average useful installed power of 211.23 MW:

Table 5 shows a summary table of the most significant parameters of the integration of the Chira-Soria Pumping Hydroelectric Power Plant, highlighting the reduction in emissions due to its integration.

For this ideal integration it is necessary to have an average annual power in the pumping period of 175.46 MW of wind power, from this amount it would be necessary to subtract the accumulated average renewable discharges, which means an accumulated annual average of 6.58% (25.45 MW) of discharges, establishing the need for power used at 133.82 MW. As for the installed power of renewables and the new needs, it would be necessary to increase the existing ones by 483.13 MW on average and, occasionally, by 609.91 MW, which brings us to an average of 788.62 MW.

Extrapolating the average annual data per year, the annual data

Table 3
Average daily and annual emissions by technology in Gran Canaria 2023.

	Combined cycle	Steam turbine	Diesel engine	Gas turbine	Wind	Photovoltaic	Hydraulics	Total
$ktCO_{2eq}$/annual average day 2023	3.804	1.9159	0.267	0.158	0.00	0.00	0.00	6.145
$ktCO_{2eq}$/year 2023	1388.767	699.226	97.495	57.712	0.00	0.00	0.00	2243.202

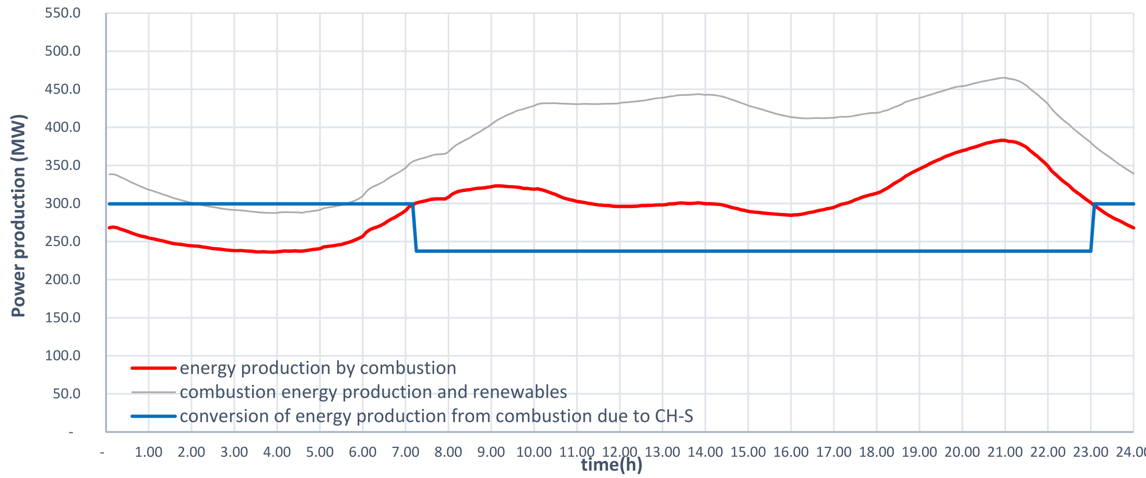

Fig. 5. Flattening of the energy production curve through combustion due to the integration of the Chira-Soria pumped-storage hydroelectric power plant. Average year 2023.

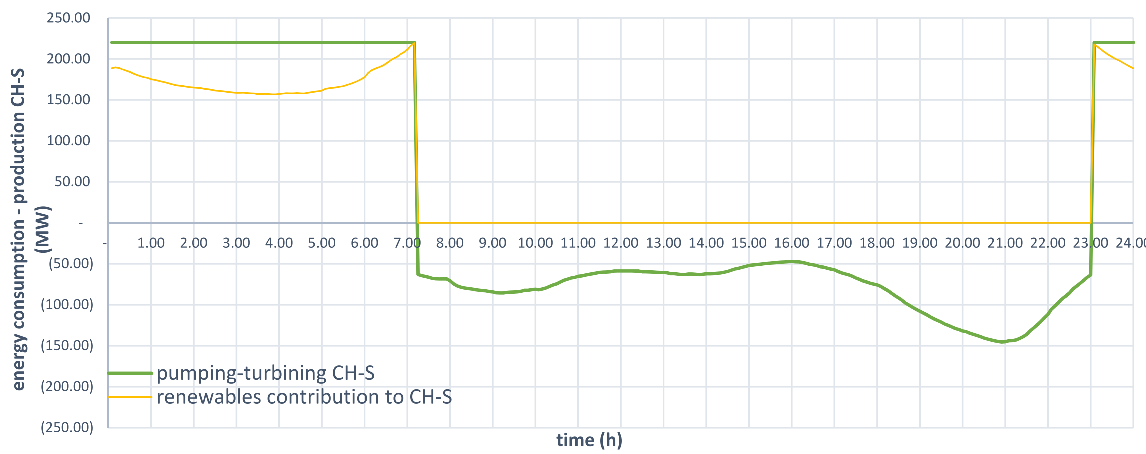

Fig. 6. Pumping and turbining of Chira-Soria Hydroelectric Pumping Station. Average year 2023.

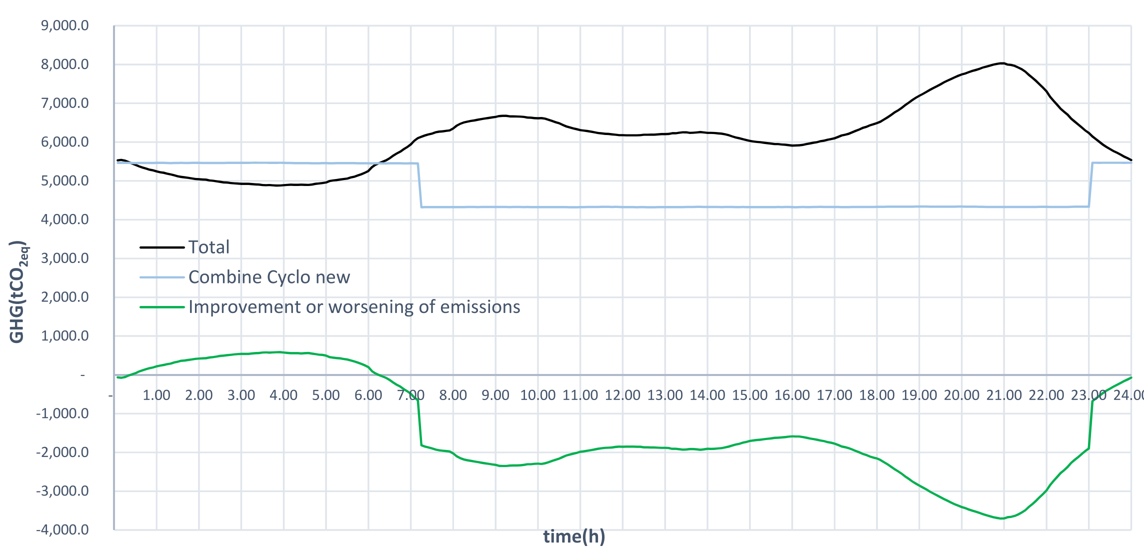

Fig. 7. Comparison of tCO_{2eq}/MWh emissions with and without the integration of the Chira-Soria pumped-storage hydroelectric power plant. Average daily emissions in 2023.

Table 4
Energy integration data Chira-Soria Pumping Hydroelectric Power Station.

	Daily production (GWh)			Average power used (MW)			Factor of Availability	Hours use		Power Necessary Renewable (MW)		Production flat		Production Flat with renewable discharges 2023	
	pumping	turbine	sum	pumping	turbine	sum		pumping	turbine	media	maximum	loud	casualty	loud	casualty
Day	1.79	1.27	3.07	74.86	53.13	127.99	60.59%	8.17	15.83	483.13	609.91	299.50	237.49	299.50	237.49
Year	655.78	465.42	1121.21	74.86	53.13	127.99	60.59%	2980.33	5799.17	483.13	609.91	299.50	237.49	299.50	237.49

would be as follows. For the case of increased utilization of renewable energy in 483.13 MW, Table 6 results.

3. Results and discussion

3.1. Availability of surplus renewable energy

As a result of the integration of the Chira-Soria hydroelectric pumping station into the energy system of Gran Canaria, a surplus of renewable energy is obtained in the turbine phase.

As already mentioned, for the ideal integration it is necessary to have an average annual power in the pumping period of 175.46 MW of wind power and 219.20 MW, which leads, taking as data the availability factor for 12 months operation in the year 2022, (34.5%) to an additional installation in renewable power to the existing one of 508.58 MW on average and 635.36 MW on time. From this amount, it would be necessary to subtract the accumulated average renewable discharges, redefining the additional installation in renewable power to the existing one and establishing the new renewable needs at 483.13 MW on average and 609.91 MW on time.

The following graph, Fig. 8, defines the average demand covered by combustion, the annual averages of pumping and turbining that are integrated in this demand, the demand covered by renewables and the increase in renewables.

Fig. 9 describes the behavior in terms of power in the pumping and turbine zone of the Chira-Soria Pumped Storage Hydroelectric Power Plant. Average year 2023 detailing the need for renewables in pumping and new renewable production.

Average year 2023 detailing the need for renewables in pumping and new renewable production. As a result, the surplus energy from wind energy is 4962.97 MWh/day and 1,811,482.96 MWh/year.

3.2. Conversion to H_2: energy consumption in the conversion, compression and treatment of water

In this section we proceed to justify the results on the conversion of the surplus renewable energy to H_2, the energy consumption in the conversion, the H_2 compression and the water treatment. The conditions of the conversion process are as follows:

- The conversion of H_2 from H_2O by PEM electrolysis is 111 g H_2 per 1000 g H20. This means that for every kg of H_2, 9.009009 kg of H_2O are needed.
- Energy required, PEM electrolysis: The energy required to obtain 1 kg of H_2 is 50.0–65.7 KWh/Kg H_2.
- H_2 mass storage pressure: Between 60 bar and 70 bar. This range has been chosen because storage at pressures of 30–100 bar is more energy efficient, as the compression energy is lower than at higher pressures, but requires more physical space on the surface, which is not a disadvantage in Gran Canaria.
- Energy required for compression (compression efficiency 65%): The energy required to store 1 kg H_2 at a pressure of 60 bar is 2.40 KWh/Kg H_2, and for a pressure of 70 bar it is 2.54 KWh/Kg H_2.
- Water treatment: The energy required to treat the raw water to obtain a treated product suitable for electrolysis is:

Desalination: 2.4×10^{-3} KWh/Kg of treated water (reverse osmosis desalination).

Purification: 1.4×10^{-3} KWh/Kg of treated water (purification plants).

The total energy required is as follows.

With desalinated water: 62.5216 KWh/KgH_2

With treated water: 62.5126 KWh/KgH_2

And the amount of H_2 obtained by both methods:

With desalinated water: 1,811,482.96 × 103 KWh/year/62.5216 KWh/KgH_2 = 28,973,714.04 Kg H_2/year.

Table 5
GHG data with the Chira-Soria Pumping Hydroelectric Power Plant energy integration. Day.

	Average daily production (MWh)		Average daily power Used (MW)		Installed power (MW)		GHG daily average (tCO_{2eq})	
	2023	2023 - CH–S	2023	2023 - CH–S	2023	2023 - CH–S	2023	2023 - CH–S
Combined cycle	4913.02	6206.24	204.71	258.59	433.10	433.10	3804.69	4712.78
Steam turbine	1651.40	–	68.81	–	259.60	–	1915.69	–
Gas turbine	109.26	–	4.55	–	147.00	–	158.12	–
Diesel engines	305.22	–	12.72	–	66.55	–	267.11	–
Wind	1742.89	3211.67	72.62	133.82	305.49	788.62	0.00	–
Solar	379.11	386.64	15.80	16.11	73.16	73.16	0.00	0.00
Suma	9100.91	9804.55	379.20	408.52	1284.90	1294.88	6145.61	4712.78

Table 6
GHG data with energy integration Chira-Soria Pumping Hydroelectric Power Plant. Year.

	Average annual production (GWh)		Average annual power Used (GW)		Installed power (GW)		GHG Annual Average ($ktCO_{2eq}$)	
	2023	2023 - CH–S	2023	2023 - CH–S	2023	2023 - CH–S	2023	2023 - CH–S
Combined cycle	1793.253	2265.277	74.718	94.385	433.10	433.10	1388.767	1720.164
Steam turbine	602.761	–	25.115	–	259.60	–	699.226	–
Gas turbine	39.8810	–	1.661	–	147.00	–	57.712	–
Diesel engines	111.,406	–	4.641	–	66.55	–	97.495	–
Wind	636.155	1172.259	26.056	48.844	305.49	788.62	–	–
Solar	138.373	141.123	5.765	5.880	73.16	73.16	–	–
Suma	3321.827	3578.660	111.903	149.109	1284.90	1294.88	2243.202	1720.164

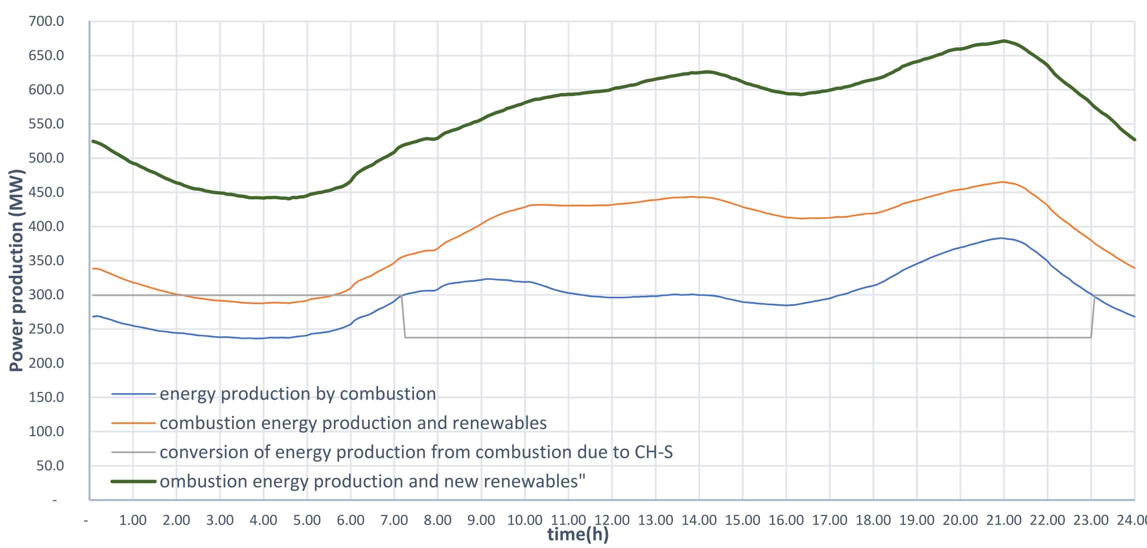

Fig. 8. Flattening of the energy production curve through combustion due to the integration of the Chira-Soria pumped-storage hydroelectric power plant. Average year 2023.

With treated water: 1,811,482.96 × 103 KWh/year/62.5126 KWh/KgH$_2$ = 28,977,885.42 Kg H$_2$/year.

3.3. Impact on electricity production from H_2 combustion

For this section, the two thermal power plants in Gran Canaria are considered to have an efficiency with a weighted average value of 50% (the Juan Grande power cycles operate at 51%).

$$\eta = \frac{N_{electric}}{m_f/t + H_p} \; ; \; W_{electric} = \eta \cdot m_f \cdot H_p$$

With desalinated water: $W_{electric}$ = 482.939,499 MWh/year.

With treated water: $W_{electric}$ = 483.009,028 MWh/year.

This results in an efficiency:

$$\text{With desalinated water} : \% = \frac{482.939,499 \text{ MWh/year}}{1.811.482,96 \text{ MWh/year}} = 26,660\%$$

$$\text{With treated water} : \% = \frac{483.009,028 \text{ MWh/year}}{1.811.482,96 \text{ MWh/year}} = 26,664\%$$

3.4. Impact on GHG emissions from H_2 combustion

GHG emissions from H_2 combustion are calculated.
The lower calorific value (L.C.P.) are:
L.C.P. (H_2) = 120.011,00 kJ/kg.
L.C.P. (fuel-oil) = 41.239,98 kJ/kg.
To equalize the energy it takes 2.91 times, the mass of H_2 in fuel oil.
The mass of H_2 obtained by both methods is:

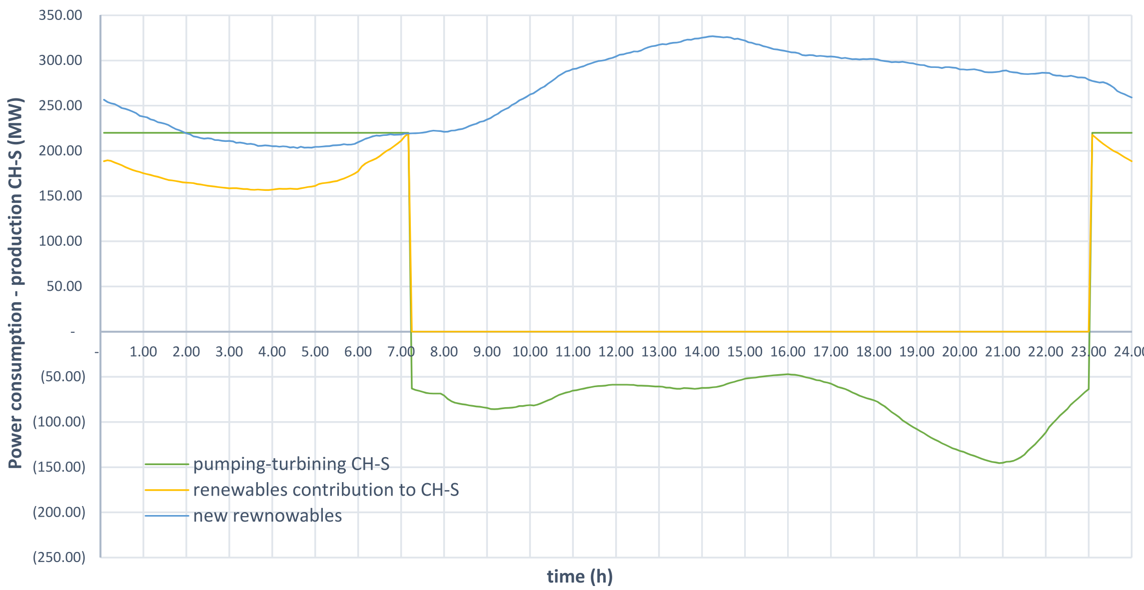

Fig. 9. Pumping and turbining of Chira-Soria Hydroelectric Pumping Plant.

With desalinated water : 28.973, 71 t_{H_2} / *year*

With treated water : 28.977, 88 t_{H_2} / *year*

The equivalent fuel oil mass in each case:

With desalinated water : 84.315, 37 $t_{fuel-oil}$ / *year*

With treated water : 84.327, 51 $t_{fuel-oil}$ / *year*

Being the fuel oil emission factor 3365 $\frac{t_{CO_{2eq}}/year}{t_{fuel-oil}}$, the tCO_{2eq}/year that are no longer emitted due to the use of H_2 are obtained:

$$\text{With desalinated water : } 84.315,37\ \frac{t_{fuel-oil}}{year}\ \text{x}\ 3,365\ \frac{t_{CO_{2eq}}/year}{t_{fuel-oil}} = 283.721,23\ t_{CO_{2eq}}$$

$$\text{With treated water : } 84.327,51\ \frac{t_{fuel-oil}}{year}\ \text{x}\ 3,365\ \frac{t_{CO_{2eq}}/year}{t_{fuel-oil}} = 283.762,93\ t_{CO_{2eq}}$$

3.5. *Almacenamiento del H_2*

The number of storage tanks at 60 bar required is calculated. The most unfavorable quantity to be stored daily is purified water:

Mass to be stored = 28.977,88 t_{H_2}/*year* = 79,39 t_{H_2}/*día* = 79.391,47 Kg_{H_2}/*day*.

The density of H_2 at 60 bar being 4.975 kg/m^3, the total cubic capacity of the tanks is obtained:

Compressed H_2 volume: 15.958,08 m^3.

For tanks with a capacity of 135 m^3/unit, 119 tanks are required.

4. Summary of applied methods

The following graph, Fig. 10, shows the surplus energy of the energy system resulting from the optimal integration of the Ch-S pumped-storage hydroelectric power plant.

As a summary, it is indicated that the emissions produced in 2023 [45], with the incorporation of Ch-S were 1,720,164.09 tCO_{2eq} and with hydrogen storage they would be 1,436,402.00 tCO_{2eq} [19,28]. When discounting the emissions that are no longer emitted due to the substitution of fuel oil for H_2 in the combustion processes, 283,762.93 tCO_{2eq} are no longer emitted.

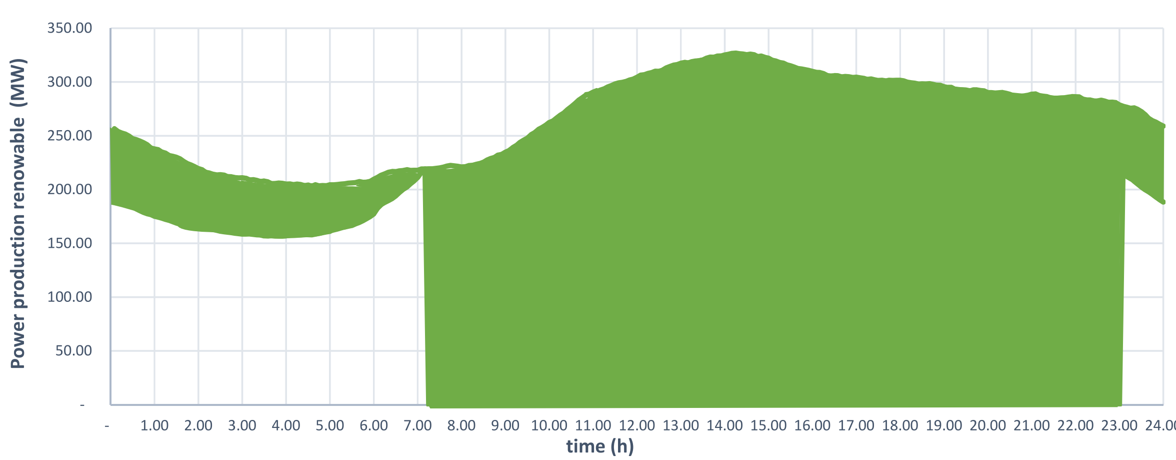

Fig. 10. Wind energy available for conversion to H_2.

Table 7
Emission summary and necessary renewables year.

	Installed power by renewables (MW)	Power effectively used (MW)	Renewable Production (MWh)	GHG (tCO_{2eq})	Cumulative decrease (%)
2023	378.65	32,272.06	774,529.35	2,245,225.21	
2023 with Ch-S	861.78	54,724.30	1,313,383.15	1,720,164.09	23.39%
2023 with Ch-S and H_2 storage	861.78	75,478.46	3,124,866.11	1,436,402.00	36.02%

In the case of the use of H_2, the useful production of renewable energy went from 1,313,383.15 MWh to 1,811,482.96 MWh due to the use in the turbine time slot, resulting in a total of 3,124,866.11 MWh [46], a summary of the results is shown in Table 7.

5. Conclusions

During the process of analysing the implications of H_2 energy storage of surplus renewable energy for the integration of the Chira-Soria hydroelectric pumping station into the energy production system in Gran Canaria, major benefits would be achieved:

Once the Chira-Soria hydroelectric pumping station has been integrated, the addition of the H_2 energy storage system for renewable energy surpluses will reduce atmospheric emissions by 12.36% compared to the already integrated system. If we compare it with the energy system without integration, it represents 36.02%.

For this we must consider that 1,811,482.96 MWh/year have been used, which has resulted in a conversion to H_2 of 28,977.88 tH_2/year, equivalent to 79,391.47 KgH_2/day, and in volume of compressed H_2 it would be 15,958.08 m^3/day.

On the other hand, there is an increase in energy use of 1,811,482.96 MWh per year, which represents an increase in capacity of 137.9%.

Proton exchange membrane electrolysis (PEM) is the most suitable technology for producing hydrogen from the surplus energy available from the surplus renewable production at the Chira-Soria pumped-storage hydroelectric power plant. With this technology, more efficient hydrogen production has been achieved and offers more flexibility to better couple with fluctuating renewable energies such as wind power.

The technological proposal and the contribution of H_2 storage to the energy system of Gran Canaria is an indisputable solution for differentiation in the response to demand in Gran Canaria, as well as maximizing the reduction of emissions and optimizing the island's natural resources.

The technological solutions and proposals that have been presented in this research study represent a broad improvement, quantitative and qualitative, in the energy system of Gran Canaria, all of them without limitations or uncertainties.

It is advisable to immediately initiate the necessary procedures at an organizational level for the implementation of the H_2 conversion and storage process as set out in the proposed model, and for it to become a reality in the short term. All this will bring Gran Canaria broad energy and environmental benefits.

CRediT authorship contribution statement

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

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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.

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