

Power Storage With Pumped-hydro Storage Systems in the Island of Crete, Greece. A SWOT Analysis

Vourdoubas John

Consultant Engineer, 107B El. Venizelou Str., 73132, Chania, Crete, Greece

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Abstract

The deployment of pumped-hydro storage systems in the island of Crete, Greece, allows the higher integration of the abundant renewable energies of the island into the electric grid. Pumped-hydro storage (PHS) is broadly used worldwide for energy storage, having many advantages compared with other technologies. The clean energy transition in the island requires the higher use of solar and wind energy for power generation, while power storage is necessary for integrating intermittent energy sources, like solar and wind energy, into the grid. A Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis regarding the development of pumped-hydro storage systems in Crete has been conducted. The strengths, weaknesses, opportunities and threats of the technology have been analyzed. The main strengths include the maturity and reliability of the technology, the good geomorphological characteristics of the island for its adoption, the improvement in grid characteristics, the high domestic value of these systems, their long life-span, their high storage capacity and their low capital cost- \$/kWh. SWOT's weaknesses include high investment costs, geographic and water limitations, environmental concerns, integration complexities, and competition from other power storage options. The current work could be useful to local authorities and policy makers, to energy companies and investors as well as to the operator of the electric grid.

Keywords: Crete-Greece, mechanical energy, power storage, pumped-hydro, renewable energies, SWOT analysis

1. Introduction

The clean energy transition and the mitigation of climate change require the integration of renewable energies in the energy systems. Taking into account the intermittent nature of solar and wind energy, power storage is necessary to integrate them smoothly into power systems (Andrijanovits et al, 2012; De Carne et al, 2024). Several power storage technologies have been developed and used worldwide (Aghmadi et al, 2024; Rehman et al, 2015). Pumped-hydro storage is a mature, reliable and well-known power storage technology with many global applications (Jurasz et al, 2017; Tiwari et al, 2023; Tsiknakou, 2022). It has been already used in remote and isolated islands assisting the integration of solar and wind energy into their power systems (Cruz-Perez et al, 2024), (Papathanasiou et al, 2025), (Vourdoubas, 2022), (Briongos et

al, 2023), (Sousa et al, 2022). The island of Crete, Greece, is located in eastern Mediterranean region having abundant solar and wind energy resources. The development of PHS systems in the island could help in the higher integration of solar and wind energy into its grid. SWOT analysis is a valuable strategic tool that helps organizations to understand their internal capabilities and external environment making rational decisions (Nazarko et al, 2017), (Puyt et al, 2023), (Karadzhov, 2025).

The aim of the current work is to investigate the development of power storage in Crete with pumped-hydro systems using SWOT analysis.

The text is structured as follows: After the literature review the power system in Crete is described and the power storage technologies are stated. Next, the PHS technology is analyzed and the planned PHS system in Amari, Rethymno, Crete is mentioned. After that, the SWOT method is presented, and a SWOT analysis of storing power with PHS systems in Crete is conducted. The text ends with discussion of the findings, the conclusions drawn and the citation of the references used.

The text is innovative since there are not similar published studies related with SWOT analysis of power storage systems in Crete. It fills a gap regarding the SWOT analysis of deploying PHS systems in the island. The work could be useful to policy makers, to power companies, to local and regional authorities as well as to island's grid operator.

2. Literature survey

The literature survey is separated in three sections, including: a) SWOT analysis, b) energy storage technologies, and c) pumped-hydro energy storage systems.

2.1 SWOT analysis

A SWOT analysis regarding the benefits of hydropower in four Archipelagos has been conducted (Cruz-Perez et al, 2024). The authors studied the opportunities for developing PHS systems in Azores, Madeira, Canary Islands, and Cape Verde. They mentioned that PHS systems play a significant role in the green transition of these islands, while Madeira hosts the world's first underground PHS system. The use of SWOT analysis in modern business has been studied (Chakrabarty, 2024). The author stated that while SWOT analysis remains valuable due to its simplicity, it faces significant limitations in today's dynamic market environments. It was suggested that the future of SWOT analysis lies in its evolution in a real-time process that adapts to changing market conditions. The application of SWOT analysis in the public management of technology has been investigated (Nazarko et al, 2017). The authors proposed an improvement of the conventional SWOT analysis in the context of technological foresight. They suggested the assessment of factors' significance in two time perspectives, the current state and the hypothetical future horizon. The origins of SWOT analysis have been explored (Puyt et al, 2023). The authors stated that the origins of SWOT analysis have been enigmatic until now.

They mentioned that in the past, during a firm's planning process the managers were analyzing the issues as Satisfactory, Opportunities, Faults and Threats (SWOT). Later this methodology was revised and relabeled as SWOT. The improvement of SWOT analysis has been examined (Karadzhev, 2025). The author stated that SWOT analysis should include a quantitative approach, collaborative methodologies and ongoing updates. It was also proposed that the analysis should engage diverse stakeholders, external consultants and collect and analyze comprehensive data. A SWOT analysis of PHS systems has been conducted (Abdellatif et al, 2026). The authors stated that the strengths of PHS systems include their huge storage capacity, the long operational life and the ability to balance the grid while they have various drawbacks including the high upfront cost, environmental and regional restrictions and long development times. They mentioned that they have several challenges, such as the emerging power storage technologies, evolving regulations and water scarcity due to climate change. The importance and the adoption of PHS systems conducting a SWOT analysis have been studied (Bosnjakovic et al, 2025). The authors compared the PHS systems with battery storage in terms of technical, economic and ecological aspects. They mentioned that PHS systems play a key role for long-term energy storage and grid stabilization while battery storage can be used for short-term storage and fast frequency response.

2.2 Energy storage technologies

The energy storage technologies have been reviewed (Cole et al, 2005). The authors stated that currently only PHS, compressed air storage and electric batteries are technically and commercially viable. They have conducted a SWOT analysis of several energy storage systems, while they mentioned that the characteristics of PHS systems are: a) installed power 200-2,000 MW, b) response time 12 min, c) efficiency around 70-75%, and d) life time around 50 years. The long-term energy storage technologies for renewable energy systems, conducting a comparative SWOT analysis, have been explored (Andrijanovits et al, 2012). The authors stated that the strengths of PHS systems include: a) their high capacity, b) the low cost per kWh, and c) the minor needs for electronics and converters. They also mentioned that a threat of these systems is the possibility of obsolescence when distributed generation will be preferred while their weaknesses include their centralized storage and their geographical restrictions. The energy storage systems used in high-power applications have been assessed (Aghmadi et al, 2024). The authors studied several high-power storage technologies including supercapacitors, superconducting magnetic energy storage, flywheels and lithium-ion batteries characterized for their high energy density. The energy storage systems have been classified (Kandhasamy et al, 2024). The authors stated that these systems are categorized according to the physical form energy stored such as thermal, electrical, electrochemical, chemical and mechanical. They mentioned that each energy system is characterized by its energy density, efficiency, charge and discharge power and the response time. The role of energy storage systems in secure energy supply has been studied (De Carne et al, 2024). The authors stated that energy storage systems are fundamental for insuring the energy supply and the voltage power quality to customers. They compared several energy storage systems according to several characteristics such as: specific energy, energy efficiency, lifetime, discharge time, average capital cost and self-discharge time.

The energy storage systems have been reviewed (Mahadevan et al, 2025). The authors critically assessed several power storage systems storing energy as mechanical, electrical, electrochemical, chemical and thermal energy. They concluded that hydrogen storage is the most promising energy storage technology. Several energy storage systems have been assessed (Tiwari et al, 2023). The authors analyzed the state of the art of energy storage technologies, comparing their characteristics. They mentioned that a single storage system cannot meet alone all the energy storage requirements while a good mix among various energy storage systems should give the best results. The current developments in energy storage technologies have been studied (Liu et al, 2025). The authors stated that the energy storage technologies are crucial in the clean energy transition and the achievement of the carbon neutrality goals. They evaluated the advantages and drawbacks of each energy storage technology indicating its potential applications and prospects. The energy storage technologies reviewing the existing literature have been assessed (Elalfy et al, 2024). The authors have compared several energy storage methods according to their capacity, lifetime, capital cost, strength and weakness. They also studied the integration between various energy storage systems.

2.3 Pumped-hydro storage systems

The pumped-hydro energy storage has been studied (Rehman et al, 2015). The authors stated that PHS is the most suitable technology for small autonomous island grids and massive energy storage while their energy efficiency varies in the range of 70-80% or even higher. They also mentioned that the typical size of the PHS systems worldwide is in the range of 1,000-1,500 MW, while in some cases they could reach at 2,000-3,000 MW. The technology trends, value chains and markets of PHS systems in EU have been reported (Quaranta et al, 2025). The authors stated that hydropower provides grid stability and dispatchable power generation as well as additional water supply and grid services. They also mentioned that PHS holds more than 90% of energy storage in EU while traditional hydroelectricity has a share at around 10% of the EU's total electricity generation. The technology development, trends, value chains and markets of PHS in EU have been reported (Quaranta et al, 2023). The authors stated that approximately 270 PHS systems exist worldwide with total turbine capacity at 175 GW, while 160 PHS systems operate in Europe with an overall turbine capacity at 55 GW. They also mentioned that the PHS plants in most countries operate with efficiencies in the range of 70-75%. The hybrid solar, wind and PHS plants in Poland using mathematical modelling have been investigated (Jurasz et al, 2017). The authors stated that a hybrid solar-wind-PHS system can cover almost 40% of the energy demand in the country with a 25% increase in the energy cost. A PHS system in Türkiye has been analyzed (Saltuk, 2023). The author studied the planned PHS system at Gokcekaya dam examining two scenarios including a PHS system and a hybrid solar photovoltaic (solar-PV) and PHS system. It was stated that the estimated payback period in the examined scenarios varies in the range of 8.66 to 18.05 years, depending on the assumptions made. The role of PHS systems in a net-zero economy has been examined (Tsiknakou, 2022). The author stated that PHS systems have high domestic value in National and European levels. It was mentioned that two PHS systems owned by Public Power Company with total capacity 700 MW operate in Greece since 1990s while two more PHS projects owned by Terna Energy are planned in the country.

The power storage in pumped-hydro and hydrogen systems focusing on Kefalonia island, Greece has been compared (Papathanasiou et al, 2025). The authors examined which energy storage method meets better the water and energy shortages in the island. They concluded that PHS is more efficient for short-to-medium-term needs while hydrogen storage is better for long-duration storage. The water-energy autonomy in remote islands using a hybrid system consisted of wind farms, Solar-PVs, PHS and hydrogen storage systems has been explored (Papathanasiou et al, 2025). The authors stated that the hybrid energy system studied can meet the energy and water requirements, via water desalination, in remote islands. They mentioned that a combination of renewable energies and energy storage systems can provide sufficient water and energy resources in remote islands. The development of an energy system based on renewable energies in Karpathos island, Greece has been studied (Vourdoubas, 2022). The author stated that Karpathos island, Greece has similar characteristics with El Hierro island, Spain which has installed a sustainable hybrid energy system based on wind farms and PHS storage. It was mentioned that a similar hybrid energy system can be installed in Karpathos island indicating that local renewable energies can meet the most of the energy needs in non-interconnected Greek islands. The feasibility of using combined wind power, solar-PV and PHS in Greece has been investigated (Dianellou et al, 2021). The authors stated that the morphology of the country favors the development of PHS systems while the low cost of wind turbines and solar-PV systems allows their broad expansion in Greece. The use of renewable energies in El Hierro island, Spain has been explored (Briongos et al, 2023). The authors stated that the power system in the island comprises a wind farm, a PHS system and a diesel generator while the share of renewable energies in the energy mix is around 50%. They mentioned that by adding solar-PV installations combined with electric batteries the share of renewable energies in the energy mix of the island could be significantly increased. The PSH systems have been reviewed (Papadakis et al, 2023). The authors stated that PHS systems have high power and energy storage capacity, long-life time, high efficiency and low-response time. They mentioned that PHS systems consist of a mature and proven power storage technology integrating renewable energies into the grid system increasing its stability. The contribution of PHS systems in increasing the penetration of renewable energies into the power system has been studied (Blakers et al, 2025). The authors stated that massive deployment of solar-PV and wind power installations require the development of energy storage systems. They mentioned that there is a vast potential for developing PHS systems which are characterized by low capital cost (\$ per kWh). The underground PHS system in Madeira island, Portugal has been studied (Sousa et al, 2022). The authors stated that this is the first underground PHS plant worldwide, while the height difference between the two reservoirs is 450 meters. They mentioned that the volume of the reservoir is 40,000 M³ while the maximum power is 24 MW. The possibility of using floating solar photovoltaic panels on water reservoirs in the island of Crete has been explored (Vourdoubas, 2022). The author stated that the installation of floating solar photovoltaics on the surface of two large water reservoirs in Crete, covering 10% of their surface, could generate 252.77 GWh/year corresponding at around 8.3% of the annual electricity generation in the island.

3. The Power System of the Island of Crete

The island of Crete has one of the most distinctive power systems in Greece due to its geographic isolation, high energy demand, and strong potential for renewable energy production. For many years, the grid of Crete operated as an electrically isolated system, relying heavily on local power generation to meet the needs of its population, tourism sector, and industry. Later, Crete has invested in renewable energy sources. The island has abundant wind and solar energy potential, making it ideal for renewable power generation. Today, wind farms and photovoltaic installations contribute at around 25% of Crete's electricity production. These renewable energy sources reduce fossil fuels consumption, greenhouse gas emissions, lower operating costs, and enhance energy sustainability. However, their intermittent nature also introduces challenges for grid stability, requiring advanced control systems and backup generation. A major milestone in Crete's power system development was the construction of electrical interconnections with mainland Greece, an endeavor that is under finalization. The two interconnection projects, completed in phases, link Crete to the national transmission system via two submarine electric connections. This development significantly improved the island's energy security, reduced reliance on local fossil-fuel plants, and enabled greater integration of renewable energies. Despite these advances, challenges remain. Managing peak demand, integrating higher shares of renewable energies, and upgrading distribution networks are ongoing priorities. Energy storage solutions, such as batteries and PHS systems, are being explored to further enhance integration of renewable energies, grid flexibility and reliability. Through renewable energy development and grid interconnections, Crete is going to become a model for energy transition in island regions, balancing reliability, environmental protection, and economic efficiency.

4. Power Storage technologies

As the global demand for energy continues to rise and intermittent renewable energy sources such as solar and wind energy become more widespread, effective power storage has become increasingly important. To ensure a stable and reliable energy supply, various power storage methods have been developed. The main methods of power storage include mechanical storage, electrochemical storage, thermal storage, electrical storage and chemical storage. One of the most established methods of power storage is mechanical energy storage, particularly pumped-hydro storage. Another mechanical storage method is compressed air energy storage. In this system, surplus electricity is used to compress air and store it in underground caverns or tanks. Electrochemical storage, primarily through batteries, is one of the most rapidly developing energy storage methods. Electric batteries store energy by converting electrical energy into chemical energy and releasing it when required. Lithium-ion batteries are the most commonly used due to their high energy density, fast response time, and decreasing costs. Other battery types, such as lead-acid, sodium-sulfur, and flow batteries, also play important roles in specific applications. Despite their advantages, batteries face challenges including limited lifespan, resource constraints, recycling issues, and safety concerns. Thermal energy storage is another important method, particularly in combination with renewable energy systems. This approach stores energy in the form of heat or cold for later use. For example, molten salt is commonly

used in concentrated solar power plants to store heat during sunny periods and release it to generate electricity when sunlight is unavailable. Thermal storage systems are relatively cost-effective and durable, but they are often location-specific and less suitable for long-distance energy transport. Power storage in capacitors and supercapacitors is another method of electrical energy storage. Capacitors store energy in an electric field between two conductive plates separated by an insulating material. They can charge and discharge very quickly, making them useful for short-term energy storage and power conditioning. Supercapacitors, also known as ultracapacitors, store much larger amounts of energy than conventional capacitors by using high-surface-area electrodes and electrochemical processes. Chemical energy storage, especially hydrogen, is gaining increasing attention as a long-term and large-scale solution for power storage. Hydrogen is produced using electricity through a process called electrolysis, which splits water into hydrogen and oxygen. When renewable electricity is used for this process, the resulting hydrogen is considered "green hydrogen." The hydrogen can then be stored in tanks, pipelines, or underground facilities and later converted back into electricity using fuel cells or combustion turbines. Therefore, power storage is a critical component of modern energy systems, particularly as the world transitions toward renewable energy. Mechanical, electrochemical, electrical, thermal, and chemical storage methods each have unique advantages and limitations. While technological and economic challenges remain, continued research and investment are likely to make advanced storage methods essential elements of a sustainable and resilient energy future. The main power storage systems are presented in Table 1, while the characteristics of several power storage systems in Table 2.

Table 1. Main power storage methods

Mechanical storage	Chemical storage	Electrical storage	Thermal storage	Electrochemical storage
Pumped-hydro systems	Hydrogen energy	Capacitors and supercapacitors	Sensible heat	Lithium-ion batteries
Flywheels			Latent heat	Lead-acid batteries
Compressed air				Other types of batteries

Source: several authors

Table 2. Characteristics of several power storage systems

	Lead-acid battery	Li-ion battery	Flywheel storage	Hydrogen - fuel cell	Pumped-Hydro storage	Thermal energy storage	Compressed air storage
Specific energy (Wh/kg)	25-50	75-200	5-150	30-45	0.5-1.5	150-250	-
Specific power (W/kg)	75-300	500-2,000	180-1,800	500	0.01-0.12	10-30	3-24 (kWh/M ³)
Efficiency (%)	75-85	85-97	85-95	33-42	70-87	75-90	40-70
Average capital cost (\$/kW)	2,140	2,512	867	3,243	1,413	70-3,000	300-1,250
Average capital cost (\$/kWh)	437	546	4,791	540	58	11-73	2-250
Life span (years)	5-15	5-20	15-25	20-40	40-80	20-40	20-40
Storage capacity	Wh to MWh	10MW - 1,000 MW	kWh-MWh	MWh to TWh	100 MWh – 10 GWh	MWh to GWh	500-2,500 MWh
Response time	< 1 sec	10-100 ms	5-20 ms	min	10-30 ms	min to hours	5-15 min

Source: several authors

5. Pumped-Hydro Power Storage: A Key Energy Storage Technology

Pumped-hydro power storage is the most widely used power storage technology while PHS systems have a share higher than 90% in the global power storage systems. It plays a crucial role in balancing electricity supply and demand, particularly as renewable energy sources such as wind and solar energy become more prevalent. By storing excess electrical energy in the form of gravitational potential energy, PHS helps ensure grid stability, reliability, and efficiency. The basic operating principle of pumped-hydro power storage is relatively simple. The system consists of two water reservoirs located at different elevations. During periods of low electricity demand or excess power generation, electricity is used to pump water from the lower reservoir to the upper reservoir. This process stores energy. When electricity demand rises, the stored water is released from the upper reservoir back to the lower one, flowing through turbines that generate electricity. This reversible process allows PHS systems to act both as energy consumers and

energy producers. One of the main advantages of pumped-hydro power storage is its high efficiency and reliability. Modern systems typically achieve round-trip efficiencies of around 70 to 85 %, meaning that most of the energy used for pumping can be recovered during electricity generation. Additionally, pumped-hydro plants have long operational lifespans, often exceeding 50 years, making them a cost-effective long-term investment. They can also respond quickly to changes in electricity demand, providing essential services such as frequency regulation and grid stabilization. PHS is particularly valuable in integrating renewable energies, such as solar and wind energy, into power systems. In recent years, technological advancements have expanded the potential of pumped-hydro storage. These developments could make pumped-hydro storage more adaptable and environmentally sustainable. Therefore, pumped-hydro power storage remains a cornerstone of global energy storage infrastructure. Its proven efficiency, large-scale capacity, and ability to support renewable energy integration make it an essential technology for modern power systems.

6. The pumped-hydro power storage system in Amari, Crete

The planned PHS system in Amari, Crete represents one of Europe's most ambitious and strategically significant renewable energy investments. The first PHS system in Crete will be located in the mountainous region of Amari on the island of Crete integrating wind power generation with pumped-storage hydroelectricity, creating a flexible and reliable form of clean energy production and storage that can support the island's grid while reducing dependence on fossil fuels. This project, led by TERNA Energy, is designed to harness the region's abundant wind energy resources through a wind farm of approximately 26–27 turbines with around 89 MW of installed capacity and pair them with a pumped-hydro storage system at the existing Potamoi Dam reservoir in Rethymno prefecture. The hybrid plant also strengthens the reliability of the power network, particularly during peak demand periods or when intermittent wind energy production alone would be insufficient. By storing wind electricity and releasing it when needed, the pumped-storage mechanism enhances grid stability and complements Crete's broader transition to renewable energies.

7. The SWOT Method: An Overview and Its Importance in Strategic Planning

The SWOT method is a widely used strategic planning tool that helps individuals, organizations, and businesses evaluate their current position and make informed decisions. By analyzing several elements, decision-makers can gain a structured understanding of internal and external factors that influence success. Due to its simplicity, flexibility, and effectiveness, the SWOT method is commonly applied in business management and project planning. Strengths and weaknesses are internal factors, meaning they originate within the organization. Strengths refer to positive attributes that provide a competitive advantage. Identifying strengths allows organizations to understand what they do well and how they can leverage these advantages to achieve their goals. Weaknesses, on the other hand, are internal limitations or areas that need improvement. These may include lack of resources, outdated technology, poor management, limited market presence, or skill gaps among employees. Recognizing weaknesses is essential

because it enables organizations to address problems before they escalate. Although identifying weaknesses can be challenging, it encourages self-awareness and promotes long-term growth. Opportunities and threats are external factors, meaning they arise from the environment outside the organization. Opportunities represent favorable conditions that can be exploited for growth or improvement. By identifying opportunities, organizations can plan strategically and stay ahead of competitors. Threats are external challenges or risks that could negatively impact performance. These may include strong competition, economic downturns, changing regulations, technological disruptions, or shifts in customer behavior. Identifying threats helps organizations prepare for uncertainty and develop strategies to minimize risks. One of the main advantages of the SWOT method is its simplicity and versatility. It does not require complex data or advanced analytical tools, making it accessible to organizations of all sizes. Additionally, it encourages structured thinking and teamwork, as stakeholders can collaborate to identify and discuss relevant factors. However, the SWOT method also has some limitations. It can be subjective, as the analysis depends on the perspectives of those conducting it. Furthermore, SWOT analysis does not provide direct solutions but it only highlights factors that must be addressed. Therefore, the SWOT method is a valuable strategic tool that helps organizations understand their internal capabilities and external environment. By analyzing strengths, weaknesses, opportunities, and threats, decision-makers can develop more informed, rational and effective strategies. Despite its limitations, when used thoughtfully and systematically, the SWOT method remains an essential component of strategic planning and decision-making.

8. SWOT analysis of developing Pumped-Hydro Power Storage in Crete

The strengths, weaknesses, opportunities and threats of storing power with pumped-hydro systems in Crete are analyzed below.

8.1 Strengths — Pumped-Hydro Power Storage in Crete

Crete has abundant renewable energy resources, especially wind and solar energy, which offer great potential for cleaner energy production. One of the greatest strengths of incorporating pumped-hydro energy storage into the island's energy system lies in its ability to balance intermittent renewable energy generation and improve grid stability. Without sufficient storage, variable outputs from solar and wind power can result in energy curtailment, where excess power is wasted because the grid cannot absorb it safely. Although grid interconnection with mainland Greece is almost finished and expected to enhance reliability significantly, storage remains essential for full exploitation of local renewable energies both before and after interconnection. PHS's ability to supply large-scale capacity over extended periods makes it suited to complement these grid upgrades. Another strength of PHS systems is the long operational lifespan and mature technology it provides. PHS is also a proven technology worldwide, forming the largest share of global grid energy storage capacity, and Crete stands to leverage this mature solution for long-term energy resilience. Moreover, the island's topography and existing water infrastructure support PHS development. Therefore, PHS systems can significantly enhance local energy security and decrease reliance on imported fossil fuels, which have historically dominated

electricity production on the island. Overall, the strengths of integrating PHS systems into Crete’s energy mix include improved reliability, renewable energy integration, mature technology, and alignment with local conditions, all of which help position the island for a more resilient and sustainable energy future. The strengths of installing PHS systems in Crete are presented in Table 3.

Table 3. Strengths of installing Pumped-Hydro Power Storage in Crete

1	Increases the reliability of the island’s energy system while it can offer services to the local grid such as frequency regulation, reserve capacity and peak shaving
2	Facilitates the integration of intermittent renewable energies in the local energy system.
3	The technology of PHS is mature, reliable and well-known worldwide
4	The geomorphological characteristics of Crete favor the construction of these systems
5	The long operational lifespan allows their operation for decades with appropriate maintenance
6	It has high domestic value and important employment impacts across local, regional and national economy.
7	It has low capital cost (\$/kWh) compared to electric batteries and hydrogen
8	It has significantly higher storage capacity compared to electric batteries.

Source: own estimations

8.2 Weaknesses — Pumped-Hydro Power Storage in Crete

Despite the clear benefits, there are inherent weaknesses in deploying PHS systems on Crete that must be acknowledged. The most significant challenge is the high capital cost and long lead times associated with construction and development of new PHS facilities. Additionally, while Crete’s topography offers some opportunities, not all suitable sites are readily available. In a Mediterranean climate with seasonal rainfall variability, reliable water supply becomes a constraint. Ensuring that reservoirs can be filled consistently enough for storage operations adds a layer of complexity not faced by electric batteries or other mechanical storage technologies. Another weakness relates to the environmental impacts of traditional PHS projects. Though more environmentally friendly than fossil fuel generation, PHS can alter local ecosystems, affect groundwater and river dynamics, and influence habitats if not carefully managed. There may also be public resistance from communities concerned about landscape changes, biodiversity loss, or disruption of agricultural lands. Integration challenges also exist at the technical level. Adequate control systems, forecasting tools, and operational protocols must be in place to fully benefit from PHS systems. Therefore, while PHS holds strong promise for Crete, weaknesses include high investment costs, geographic and water limitations, environmental concerns, integration complexities and competition from other power storage options, each requiring thoughtful mitigation and planning. The weaknesses of installing PHS systems in Crete are presented in Table 4.

Table 4. Weaknesses of installing Pumped-Hydro Power Storage in Crete

1	High investment cost
2	Long time for planning and construction
3	Several promising locations in Crete have limited water resources
4	PHS systems may have local environmental impacts including flooding, dam, pipework, power station and electricity transmission lines and may face protests from local communities
5	Integration challenges, such as voltage fluctuations or unexpected power flows, exist at the technical level.

Source: own estimations

8.3 Opportunities — Pumped-Hydro Power Storage in Crete

Crete's transition toward a clean energy future creates a wide array of opportunities for PHS systems to play an influential role. The island's abundant renewable energy potential, especially in wind and solar energy, means that integrating PHS can unlock much higher penetration of clean sources than currently achievable. Intermittent renewable generation often leads to energy curtailment — where power must be reduced or wasted because the grid cannot absorb it — but storage systems like PHS can capture this surplus and return it to the grid when needed, reducing wasted energy and improving system efficiency and revenues. The ongoing interconnection with mainland Greece adds new dimensions to this opportunity. Although the linkage alone enhances stability, PHS systems in Crete could support not only local demand but also participate in broader grid services once fully integrated. This includes offering frequency regulation, reserve capacity, and peak shaving services across a larger interconnected network. European Union funding mechanisms and climate targets present another significant opportunity. Technological advancements also open doors for hybrid systems where PHS works in concert with other technologies such as battery storage or even "green hydrogen" production. PHS systems in Crete can be combined with the installation of floating photovoltaics on the surface of both reservoirs. In this case, PHS systems can be transformed in hybrid energy systems, simultaneously generating solar electricity and storing electricity. Renewable energy-driven power storage reduces carbon footprints and enhances resilience against fuel price volatility, which is particularly beneficial for islands dependent on imported fuels. In essence, Crete's renewable potential, EU funding frameworks, interconnection opportunities, technological synergies, and economic benefits present rich opportunities for PHS to contribute meaningfully to the island's clean energy future. The opportunities of installing PHS systems in Crete are presented in Table 5.

Table 5. Opportunities of developing Pumped-Hydro Power Storage in Crete

1	Pumped-hydro storage can capture the surplus solar and wind electricity, which is currently wasted when it is not needed by the grid
2	Development of PHS in Crete can be financed by the EU-funded mechanisms
3	It helps the clean energy transition of Crete towards net-zero emissions according to global climate goals
4	PHS systems in Crete can be integrated with other power storage systems such as electric batteries and hydrogen-forming hybrid energy storage systems
5	Deployment of PHS in Crete can be combined with the installation of floating photovoltaics on the surface of water reservoirs, generating green electricity
6	After the interconnection of the electric grids, deployment of PHS in Crete could support both the local and the integrated grid.

Source: own estimations

8.4 Threats — Pumped-Hydro Power Storage in Crete

While there are many promising opportunities, several threats could hinder or complicate the development and operational success of PHS systems in Crete. A primary concern is regulatory and bureaucratic barriers. Large infrastructure projects across Europe often face prolonged permitting processes, stringent environmental assessments, and complex stakeholder negotiations. Environmental and social resistance represents another major threat. Opposition from local communities can slow progress or force costly redesigns to mitigate perceived or real impacts. Economic volatility also poses risks. Large-scale energy projects are vulnerable to fluctuations in material costs, labor markets, and financing conditions. Technological disruption is another threat. Rapid advancements in alternative storage technologies could make traditional PHS systems less competitive over time. Climate change itself introduces additional risks. Although renewable energy and power storage are tools to combat climate change, shifts in rainfall patterns, drought conditions, or prolonged dry periods could limit the availability of water resources needed for PHS systems. Finally, the global energy landscape remains uncertain, especially in the context of geopolitical tensions and supply chain disruptions. Taken together, regulatory hurdles, environmental and community resistance, economic uncertainty, competitive technological advancements, climate variability, and geopolitical instability represent substantial threats to the deployment of PHS systems in Crete. Proactive planning and flexible policy frameworks will be crucial to navigate these challenges. The threats of installing PHS systems in Crete are presented in Table 6.

Table 6. Threats of installing Pumped-Hydro Power Storage in Crete

1	Regulatory and bureaucratic barriers can delay the approval and implementation of PHS projects
2	Development of PHS projects may face opposition from local communities due to landscape changes and habitat disruption which may delay or postpone their implementation
3	Competition from improved alternative power storage technologies, such as battery storage, compressed air storage and hydrogen, poses a potential threat for pumped-hydro storage
4	Development of large energy storage projects face economic uncertainty due to changes in the prices of raw materials, labor and machinery as well as the geopolitical instability
5	Climate change reduces the precipitation in Crete which may affect reservoir refill rates and storage reliability.

Source: own estimations

9. Discussion

PHS is a well-known, mature and reliable power storage technology broadly used worldwide which allows the integration of intermittent energy sources, such as solar and wind energy, into the power grid. Several remote and isolated islands such as El Hierro, Spain and Madeira, Portugal have already installed PHS systems supporting the integration of renewable energies in their grids. Crete has abundant solar and wind energy resources which can produce significant amounts of “green electricity” with the support of electricity storage systems. Several aspects of developing pumped-hydro power storage systems in the island of Crete have been explored using SWOT analysis. Their strengths, weaknesses, opportunities and threats have been identified. Our analysis indicates that Crete has the prerequisites for developing PHS systems, facilitating the integration of solar and wind energy into the power grid. Several existing barriers hindering the promotion of PHS systems in Crete should be removed. Our analysis although simple has several limitations including its qualitative and static nature and the subjective bias that might exist. Future research should be focused in conducting a PESTEL analysis complementing our current findings and giving deeper insight on the deployment of PHS systems in Crete.

10. Conclusions

A SWOT analysis regarding the deployment of pumped-hydro storage systems in the island of Crete, Greece has been conducted. The main findings of the study can be summarized as follows:

- a) Further integration of intermittent energy sources, like solar and wind energy, in the electric grid of Crete requires the development of power storage systems.
- b) PHS systems consist of a mature, reliable and well-known technology for power storage with broad applications worldwide,
- c) The main strengths of deploying PHS systems in Crete include the maturity and reliability of the technology, the favorable morphology in the island for their construction, their long operation life span, their high domestic value and their high storage capacity.

- d) The main weaknesses of deploying PHS systems in Crete include the high investment cost, the long planning and construction time, the undesired environmental impacts that may occur and the probability of facing constraints in water supply due to climate change.
- e) The main opportunities of deploying PHS systems in Crete include the possibility of support by EU funds, the capturing of solar and wind electricity that is currently wasted, the possibility of installing floating photovoltaic panels on the surface of reservoirs and the possibility of integrating them with other power storage systems.
- f) The main threats of deploying PHS systems in Crete include the regulatory and bureaucratic barriers, the opposition from local communities that may occur, the competition from improved alternative power storage technologies like electric batteries and the economic uncertainty due to geopolitical instability.

Our study indicates that the clean energy transition in Crete requires the integration of the abundant local renewable energy resources in the power system. The construction of power storage systems in the island, such as PHS systems, is necessary for further development of wind farms and solar photovoltaic systems. The conducted SWOT analysis indicates that the deployment of PHS systems in the island has many advantages and should be supported with various policy measures.

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