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Power Storage with Pumped-Hydro Storage Systems in the Island of Crete, Greece. A PESTEL Analysis

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

ABSTRACT: The deployment of pumped-hydro storage (PHS) systems in the island of Crete, Greece allows the higher integration of the abundant renewable energies of the island into the electric grid increasing its stability and quality. Pumped-hydro storage is broadly used worldwide for energy storage having many advantages compared with other energy storage technologies. The clean energy transition in Crete 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 Political, Economic, Social, Technological, Environmental and Legal (PESTEL) analysis regarding the development of PHS systems in Crete has been conducted. The external factors affecting their deployment have been analyzed. It has been indicated that the Greek and EU policies regarding the promotion of renewable energies and the mitigation of climate change affect their deployment in Crete. Additionally, the acceptance of PHS systems from local communities, the increase of local employment and the public concern about water availability as well as the maturity and reliability of PHS technology, the good morphological characteristics in Crete affect the deployment of PHS systems in the island. Finally, the impacts of PHS systems on natural ecosystems, landscapes, natural habitats, water resources and climate change affect the deployment of PHS systems in Crete. 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, electricity, mechanical energy, PESTEL analysis, pumped-hydro storage, renewable energies

1. INTRODUCTION

Coping with the global challenge of climate change requires 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. Several power storage technologies have been developed while few of them are currently used worldwide [1], [2], [3]. Pumped-hydro storage is a mature, reliable and well-known power storage technology with extensive global applications [4], [5], [6], [7], [8]. Use of PHS systems in remote and isolated islands facilitates the integration of solar and wind energy into their power systems [9], [10], [11], [8]. 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 assist in the higher integration of solar and wind energy into its power grid improving its quality characteristics. PESTEL analysis is a valuable strategic management tool that helps organizations to understand the external factors affecting their plans assisting them in making rational decisions [12], [13], [14].

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

The text is structured as follows: After the literature review the power system in Crete is described and the PHS technology is analyzed. Next, the development of PHS systems in Crete is discussed followed by the presentation of PESTEL methodology. After that, a PESTEL analysis of deploying 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 PESTEL analysis of power storage systems in Crete. It fills a gap regarding the PESTEL 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 the grid operator in Crete.

2. LITERATURE SURVEY

The energy storage systems have been classified [1]. The authors categorized them according to the physical form of energy stored including mechanical, electrical, electrochemical, chemical and thermal energy. They used various characteristics of the power storage systems for their assessment such as: energy density, storage capacity, efficiency, charge and discharge power and response time. The current advances in energy storage technologies have been explored [2]. The authors stated the basic principles in energy storage technologies and their economic characteristics. They mentioned the applications of power storage in energy systems focusing on typical case studies in

China. The energy storage systems and technologies have been reviewed [3]. The authors compared each form of energy storage system based on its characteristics such as: capacity, lifetime, cost, et cetera. They mentioned that for large energy storage systems, PHS and compressed energy storage systems are good options while for smaller storage systems li-ion and lead-acid batteries are more suitable. The technology of PHS systems has been studied [4]. The authors stated that the technology is well-established and commercially accepted while it has been used since 1890s. They mentioned that PHS systems is the best option for small autonomous island's grids while their efficiency varies in the range of 70-80% and their typical size in the range of 1,000-1,500 MW. The risks, obstacles and challenges in the electrical energy transition in Europe have been explored [5]. The authors stated that the clean energy transition in Europe is taking place without the development of the required energy storage systems increasing the grid instability and the danger of blackout. They mentioned that the European power system rejects green power because of low demand, lack of interconnection lines and very low power storage capacity. The energy storage systems in non-interconnected European islands have been reviewed [6]. The authors stated that the clean energy transition in non-interconnected power systems requires the use of power storage systems. They assessed several power storage technologies comparing their characteristics. They also mentioned two power storage systems in the non-interconnected islands of Ikaria, Greece and Terceira, Portugal. The drivers and barriers related to the deployment of PHS systems have been examined [7]. The authors stated that the most important drivers were the grid resilience, the generation of revenues and the rural development. They also mentioned that the most important barriers were the lack of good infrastructure near potential sites and the initial high capital requirements. The feasibility of developing electrical energy storage systems in Terceira island, Portugal has been investigated [8]. The authors stated that according to the regional plan in Azores islands, by 2018, 60% of the electricity would be generated be renewable energies. They compared two power storage technologies including PHS systems and battery storage for deployment in Terceira island combined with various renewable energy sources. They concluded that the best option for power storage in the island was a PHS system. A SWOT analysis for the deployment of PHS systems in Crete has been conducted [9]. The author stated that the main strengths of deploying PHS systems in the island are: the maturity and the reliability of the technology, the good geomorphological characteristics in the island, the high domestic value of these systems, the improvements in grid characteristics, their long life-span and their high storage capacity. The benefits of PHS systems in four archipelago including Azores, Madeira, Canary islands and Cape Verde have been analyzed [10]. The authors stated that each island has unique characteristics influencing the potential of deploying PHS systems. They mentioned that PHS technology can play a significant role in their clean energy transition. The coverage of energy demand by increasing the use of renewable energies in El Hierro island, Spain has been investigated [11]. The authors stated that the existing power system in El Hierro island comprises a wind farm, a PHS system and diesel generators while the participation of renewable energies in the energy mix is around 50%. They mentioned that the installation of solar-PV systems and electric batteries can significantly increase the share of renewable energies in covering the energy demand in the island. The use of Political, Economic, Social and Technological (PEST) method in strategic analysis has been studied [12]. The author investigated the deficiencies in PEST analysis proposing improvements related with the construction of a systemic PEST analysis diagram. A PESTEL methodology analysis of the photovoltaic market in Poland has been implemented [13]. The authors identified several opportunities and benefits to photovoltaic development. They stated that the environmental benefits, the economic advantages, the social acceptance and the enhanced energy security are the main opportunities for developing solar-PVs in Poland. They also mentioned that there are various barriers including the old grid infrastructure, the high investment cost and the political uncertainties. A PESTLE analysis for the development of renewable energies in Malawi has been conducted [14]. The author stated that 89% of energy consumption in Malawi is supplied by biomass sources while only 8% of the population has access to electricity. They mentioned that several renewable energies can be used for power generation in the country. Several barriers though hinder their development including unreliable financing mechanisms, shortage of trained human resources, lack of coordination among local institutions and unclear energy regulations. The marine energy environment combining traditional bibliometric and PESTEL analysis has been reviewed [15]. The authors stated that the deployment of marine energy has several opportunities and challenges. They mentioned that the research in this field is focused on tidal power and on the ways to improve its efficiency. The PESTEL framework in energy policy research has been explored [16]. The author investigated the transfer and adaptation of the PESTEL framework from the field of strategic management to other fields like the policy research and the energy sector. A PESTEL and SWOT analysis regarding the renewable energy development in Togo has been conducted [17]. The authors stated several policies which could enhance the renewable energies' deployment in Togo including: financial support for renewable energies' investments, the training of personnel in renewable energies' technologies, the local participation in the design and operation of renewable energies' projects, the introduction of a tariff scheme, the liberation of the energy sector and the governmental support of private energy investments. The role of energy storage systems for a secure energy supply has been examined [18]. The authors stated that power storage systems are fundamental for ensuring the energy supply and the voltage power quality to customers. They mentioned two issues which should be addressed such as safety measures particularly for batteries and the concept of circular economy which should be considered in power storage systems. The PHS systems have been critically reviewed [19]. The authors stated that power storage assist the integration of intermittent renewable energy sources into the grid increasing its stability. Assessing various power storage technologies, they mentioned the hydrogen storage achieved the highest score followed by lithium-ion batteries. The large-scale stationary electricity storage plants in Europe have been examined [20]. The authors stated that currently PHS plants represent over 99% of the power storage capacity worldwide while battery storage has increasing applications. They mentioned that in the EU-28 there are 160 PHS plants with a full cycle storage capacity at 602 GWh while by adding Norway and Switzerland there are 188 PHS plants with total storage capacity at 1,313 GWh. The opportunities of electricity storage in the Greek non-interconnected isnads have been explored [21]. The author stated that non-interconnected islands are, for many reasons, an ideal testbed for deploying power storage systems. He mentioned that two technologies have achieved licenses for many projects including PHS and battery storage systems with capacities in the range of 100 KW to 10 MW. He also stated that there are two power storage systems in Ikaria island combining wind energy and PHS and in Tilos island combining wind energy, photovoltaic energy and battery storage. The PHS systems in Portugal have been studied [22]. The authors stated that these storage systems is the most efficient option allowing the integration of renewable energies in the power system improving also the stability and efficiency of the grid. They mentioned two PHS systems in Portugal, one in Alqueva using fresh water and one in Cape Verde islands using sea water. The energy transition in Sifnos island, Greece has been investigated [23]. The authors stated that the properly planned clean energy transition in islands can contribute in their economic and social development. They mentioned that the clean energy transition in Sifnos island has been undertaken by the local energy community and the major project consists of a hybrid wind farm and a PHS system while any excess electricity will be used for potable water and hydrogen production. The hybrid solar, wind and PHS systems in Poland have been analyzed [24]. The authors stated that the hybrid systems can cover almost 40% of the non-industrial consumer energy demand without increasing the energy cost by more than 25%. The role of PHS systems in net-zero economies has been examined [25]. The author stated that PHS systems allow the storage of low-carbon electricity for later use. She mentioned that these storage systems have many advantages such as maturity and reliability, long lifetime, high domestic value, high storage capacity et cetera. The feasibility of developing hybrid wind-PV-PHS systems in Greece has been explored [26]. The authors stated that the gradual development of PHS systems in parallel with wind parks and solar-PV systems is required in the country. They mentioned that the complex morphology of Greece favors the deployment of PHS systems as a low-cost power storage solution. The PHS systems have been reviewed [27]. The authors stated that PHS systems offer significant benefits in terms of energy storage and management particularly for integrating renewable energies into the grid. However, they mentioned, these systems have various environmental and socioeconomic implications that must be considered and addressed. The role of PHS systems in supporting the transition to a zero-carbon economy has been studied [28]. The authors stated that long-duration energy storage is required to support deep decarbonization. They mentioned that off-river PHS systems offer virtually unlimited, mature, low-cost, low-impact and long-duration power storage in most countries. The underground PHS system in Madeira island, Portugal has been studied [29]. The authors stated that the underground PHS system is the first global PHS system operating since 2007. They mentioned that its maximum power is 24 MW, the water volume in the reservoirs is 40,000 M^3 while the height difference between the two reservoirs is 450 meters. The hydropower plants and the PHS systems in EU have been examined [30]. The authors stated that currently EU hosts 46 GW of PHS systems corresponding at one quarter of the global installed capacity while China hosts 50.9 GW of PHS systems. A low head, high flow seawater PHS system in Dundrum, Northern Ireland has been studied [31]. The power of the PHS system was 100 MW while its energy storage capacity was 320 MWh. The authors have conducted a preliminary cost analysis of the PHS system stating that it is not profitable without governmental financial support. The seawater pumped-hydro storage plant concept has been investigated [32]. The authors stated that seawater pumped-hydro storage harnesses the coastal mountainous topography and the abundant seawater while it requires the construction of only one reservoir. It also avoids the problems related to freshwater scarcity which is used in conventional PHS systems. The feasibility of developing a seawater PHS plant in Sri Lanka has been studied [33]. The authors stated that the construction of this a plant is feasible while its power has been estimated at 49 MW, the volume of the upper reservoir at 868,750 M^3 and its altitude at 80-90 M. They mentioned that the evaporation of seawater could be a problem while the test of the soil at the reservoir's site is necessary. The possibility of using floating solar photovoltaics in the hybrid energy systems in the islands of El Hierro, Spain and Crete, Greece has been investigated [34]. The author stated that the installation of floating solar-PVs on the surface of the water reservoir in the existing PHS system in El Hierro island with 30% coverage ratio would produce annually solar electricity corresponding at 4.59% of the total annual consumption in the island. He also mentioned that the installation of floating solar-PVs on the surface of water reservoir in the planned PHS system in Amari, Crete, Greece with 30% coverage ratio would produce annually solar electricity corresponding at 2.52% of the total annual consumption in the island in 2018.

3. THE POWER SYSTEM IN CRETE

The power system in Crete plays a crucial role in supporting the island’s economy, population, and infrastructure. Due to its geographical isolation, the development and operation of the power system has historically faced significant technical, economic, and environmental challenges. For many years, Crete’s electricity supply relied mainly on local thermal power plants fueled by oil and diesel. These conventional power stations provided reliable electricity but resulted in high operational costs, dependence on imported fuels, and considerable greenhouse gas emissions. Additionally, older power plants raised environmental concerns and faced increasing regulatory pressure under European Union climate and energy policies. In recent decades, Crete has made significant progress in integrating renewable energy sources into its power system. The island has abundant wind and solar potential, which has led to the installation of numerous wind farms and solar photovoltaic systems. Renewable energies now contribute at a substantial share of electricity generation, helping reduce emissions and fuel imports. However, the intermittent nature of wind and solar energy presents challenges for maintaining grid stability and results in its limited flexibility. A major recent development in Crete’s power system has been the construction of electrical interconnections with mainland Greece. Subsea high-voltage cables now link Crete to the national grid, allowing electricity to be imported and exported as needed. These interconnections improve energy security, reduce reliance on local fossil-fuel plants, and facilitate the higher penetration of renewable energies into the grid. Despite these improvements, challenges remain. Electricity demand in Crete fluctuates significantly, especially during the summer tourist season, placing strain on the power system. Technologies such as energy storage systems, smart grids, and demand-side management are increasingly important for addressing these challenges. Therefore, the power system in Crete is undergoing a transition from a fossil-fuel-dependent and isolated system toward a cleaner, more interconnected, and sustainable energy model.

4. THE PUMPED-HYDRO STORAGE TECHNOLOGY

Pumped-hydro storage technology is one of the most widely used and reliable methods for large-scale energy storage in the world. It plays a crucial role in modern electricity systems by balancing supply and demand, improving grid stability, and supporting the integration of renewable energy sources. Despite being developed over a century ago, PHS technology remains highly relevant as countries transition toward cleaner and more sustainable energy systems. PHS works on a simple principle: storing energy in the form of gravitational potential energy. A PHS system consists of two water reservoirs located at different elevations. During periods of low electricity demand or when excess electricity is available—often from intermittent renewable energy sources such as wind or solar power—electricity is used to pump water from the lower reservoir to the upper one. When electricity demand is high, the stored water is released back down to the lower reservoir through turbines, generating electricity in a similar way to conventional hydropower plants. One of the main advantages of PHS technology is its ability to store large amounts of energy over long periods. Unlike batteries, which may be limited by capacity, lifespan, or material availability, PHS systems can store gigawatt-hours of energy and operate for several decades with relatively low degradation. Another significant benefit of PHS systems is their high efficiency and reliability. Modern PHS plants typically achieve round-trip efficiencies of 70 % to 85 %, meaning that most of the energy used for pumping can be recovered during electricity generation. In addition, the technology is mature and reliable, with proven operational performance. Pumped-hydro storage also plays a key role in supporting renewable energy integration. Renewable energy sources like wind and solar energy are inherently intermittent, as their output depends on weather conditions and time of day. PHS systems help address this challenge by storing excess renewable energies when production is high and releasing it when production is low. However, PHS technology also faces several challenges. One of the main limitations is its dependence on suitable geographical conditions. PHS requires significant elevation differences and access to water, which restricts the number of viable sites. Environmental concerns can also arise, including ecosystem disruption, land use impacts, and changes to local water systems. Therefore, PHS technology is a cornerstone of large-scale energy storage and a critical component of future low-carbon energy systems. Its ability to store vast amounts of energy, provide grid stability, and support renewable energy integration makes it indispensable despite its geographical and environmental constraints. As energy demand grows and renewable energy deployment increases, PHS systems will continue to play a vital role in ensuring a secure, efficient, and sustainable electricity supply.

5. THE IMPORTANCE OF DEVELOPING PUMPED-HYDRO STORAGE SYSTEMS IN CRETE

Crete, the largest island in Greece, faces significant energy challenges due to its geographical isolation and growing electricity demand, particularly during the tourist season. Historically, the island has relied heavily on fossil-fuel-based power generation, resulting in high energy costs, environmental pollution, and dependence on imported fuels. In this context, PHS systems represent a highly important solution for enhancing energy security, sustainability, and grid stability in Crete. Crete possesses excellent renewable energy potential, especially in wind and solar power. While these resources provide an opportunity to reduce carbon emissions and transition to clean energy, their intermittent nature poses challenges for maintaining a stable electricity supply. PHS systems help address this issue by storing excess renewable electricity during periods of high production and releasing it when demand exceeds generation. Another key advantage of PHS in Crete is improved energy reliability. Electricity demand on the island fluctuates significantly between seasons, with sharp increases during summer months due to tourism and air conditioning use. PHS systems can respond rapidly to peak demand, reducing the risk of blackout and the need to operate costly and polluting backup power plants. This contributes to a more resilient and efficient electricity system. From an environmental perspective, PHS systems support Crete's transition toward a low-carbon energy system. By enabling higher penetration of renewable energies and reducing reliance on oil-fired power plants, PHS systems help lower GHG emissions and local air pollution. In addition, PHS systems can provide long-term economic benefits. Although initial investment costs are relatively high, PHS systems have long operational lifetimes and low operating expenses. Over time, they can reduce electricity generation costs and contribute to energy independence. Therefore, PHS systems are of great importance for Crete's energy future. They enhance renewable energy integration, improve grid stability and quality, reduce environmental impacts, and support a secure and sustainable electricity system for the island.

6. THE PESTEL METHODOLOGY

The PESTEL method is a strategic analysis tool used by organizations to understand the external factors that can influence their performance and decision-making. The acronym PESTEL stands for Political, Economic, Social, Technological, Environmental, and Legal factors. By examining these six dimensions, organizations and institutions can better anticipate opportunities, identify threats, and adapt their strategies to a constantly changing environment. The political factor refers to the influence of government policies, political stability, taxation, trade regulations, and public spending. Political decisions can have a major impact on how organizations operate, especially those involved in international markets. The economic factor focuses on the overall economic environment in which organizations operate. This includes inflation rates, interest rates, economic growth, exchange rates, and unemployment levels. The social factor examines demographic and cultural aspects of society, such as population growth, age distribution, education levels, lifestyles, and consumer attitudes. Social trends influence preferences and demand for products and services. The technological factor relates to innovations and technological developments that can affect or transform organizations. Advances in digital technology, automation, artificial intelligence, and communication systems can improve efficiency but also disrupt traditional business models. The environmental factor has become increasingly important in recent years. It includes ecological concerns such as climate change, pollution, sustainability, and resource management. Governments and consumers are placing greater pressure on organizations to adopt environmentally responsible practices. Organizations that address environmental issues proactively can enhance their reputation and comply with environmental regulations more effectively. Finally, the legal factors refer to laws and regulations that affect operation, including labor laws, health and safety standards, consumer protection and data protection regulations. Compliance with legal requirements is essential to avoid penalties and maintain trust. Therefore, the PESTEL method is a valuable framework for analyzing the external environment of an organization. By systematically evaluating political, economic, social, technological, environmental, and legal factors, organizations can make better strategic decisions and improve their long-term sustainability.

7. PESTEL ANALYSIS OF DEPLOYING PUMPED-HYDRO STORAGE SYSTEMS IN CRETE

A PESTEL analysis regarding the deployment of PHS systems in Crete has been conducted and presented below.

7.1 Political factors

The development of PHS systems in Crete is strongly influenced by political factors at local, national, and European level. These factors shape the regulatory environment, investment climate, and strategic priorities that determine whether such large-scale energy projects can be successfully implemented. At the national level, Greek energy policy plays a decisive role. Greece's commitment to reduce greenhouse gas emissions and increase the share of renewable energies, in line with European Union climate targets, creates a favorable political framework for the development of energy storage technologies such as PHS systems. National energy and climate plans promote the integration of renewable energies and recognize energy storage as a key enabler for grid stability, especially in island systems like Crete. European Union policies also significantly influence PHS development. In addition, EU funding mechanisms and recovery programs can provide financial support for infrastructure projects, reducing investment risks. However, compliance with EU environmental and competition regulations can increase administrative complexity and project approval times. Political decision-making at the regional and local level is equally important. Political opposition from local communities or environmental groups can delay or prevent projects, particularly if concerns arise regarding landscape alteration or water resource management. Transparent governance and stakeholder engagement are therefore critical political factors. Another key political issue is the regulation of electricity markets and storage ownership. Uncertainty in regulatory frameworks or changes in government priorities can discourage long-term investments. Therefore, the development of PHS systems in Crete is closely tied to political stability, supportive energy policies, effective regulation, and coordination between national and regional authorities. Strong political commitment is essential to unlock the full potential of PHS systems for Crete's sustainable energy future.

Table 1. Political factors affecting the deployment of PHS systems in Crete

1	The Greek policy regarding the integration of renewable energies in the local grid
2	The EU policy regarding the promotion of energy storage systems and their financial support
3	Political opposition from local communities due to environmental issues
4	Clear regulations regarding the role and the integration of PHS systems in the electric grid

Source: own estimations

7.2 Economic factors

The development of PHS systems in Crete is significantly influenced by a range of economic factors that affect project feasibility, investment decisions, and long-term viability. As a large-scale infrastructure technology, PHS systems require substantial upfront capital, making economic conditions a critical determinant of development. One of the most important economic factors is the high initial investment cost**.** PHS projects involve major civil works, including reservoirs, tunnels, pumping stations, and transmission infrastructure. In Crete, these costs can be further increased due to challenging terrain, island logistics, and limited local construction resources. As a result, access to financing and favorable economic conditions are essential for project development. The cost of electricity generation on the island also plays a key role. Historically, Crete has relied on oil-fired power plants with high fuel and operating costs. PHS systems can help reduce these costs by enabling greater use of low-cost renewable energies. However, the economic attractiveness of PHS systems depend on electricity price differentials between low-demand and peak-demand periods. Adequate market signals are necessary to ensure that PHS systems can generate sufficient revenue. Another important factor is the availability of financial incentives and funding mechanisms**.** Support schemes such as subsidies, feed-in tariffs, capacity payments, or EU co-financing can significantly improve project economics. Without such mechanisms, private investors may be reluctant to commit capital due to long payback periods and revenue uncertainty. The interconnection of Crete with mainland Greece also influences economic viability. While interconnections reduce electricity costs and improve supply security, they can affect the market value of storage by altering price volatility and reducing the need for local flexibility. This creates uncertainty regarding future revenue streams for PHS projects. Finally, long-term economic benefits, such as reduced fuel imports, lower system operating costs, and increased energy security, strengthen the attractiveness for PHS systems. Therefore, the development of PHS systems in Crete depends on balancing high upfront costs with long-term economic savings, stable regulatory frameworks, and supportive financial conditions.

Table 2. Economic factors affecting the deployment of PHS systems in Crete

1	The high initial investment cost of PHS systems
2	The availability of financial incentives for deploying PHS systems
3	The cost of electricity generation
4	The interconnection of the Cretan grid with the mainland and its consequences on the power system in the island
5	The increased grid stability and the energy security in Crete

Source: own estimations

7.3 Social factors

Social factors play an important role in shaping the development of PHS systems in Crete, as these projects directly interact with local communities, land use, and public perceptions. Public acceptance is one of the most influential social determinants. Employment and local economic benefits are another key social factor. PHS systems can create jobs during construction and operation phases, contributing to regional development. Local households usually benefit from lower electricity prices. Water use is another socially sensitive issue. Crete experiences periodic water scarcity, particularly during dry seasons. Even though PHS systems typically reuse water in a closed loop, public concerns about water availability and competition with agricultural or domestic needs can affect social acceptance. Finally, social awareness of climate change and renewable energy is increasing. Many residents recognize the need for cleaner energy solutions and reduced dependence on fossil fuels. This growing environmental consciousness can positively influence public attitudes toward pumped-hydro storage, provided that projects are transparently planned and socially inclusive. Therefore, the development of pumped-hydro storage systems in Crete depends heavily on public acceptance, perceived local benefits, public concern about climate change and water-related concerns. Addressing these social factors through engagement and transparency is crucial for successful project implementation.

Table 3. Social factors affecting the deployment of PHS systems in Crete

1	Acceptance of PHS systems from local communities
2	Increase in local employment and lower electricity prices in households located nearby the PHS plant affect positively the local communities
3	Public concern about water availability may affect negatively the local communities
4	Public concern about deployment of renewable energies in Crete and climate change mitigation may positively affect the deployment of PHS systems

Source: own estimations

7.4 Technological factors

Technological factors play a critical role in the development of PHS systems in Crete, influencing both feasibility and performance. PHS technology is mature and reliable based on well-established engineering principles, including hydrodynamics, turbine efficiency, and reservoir design. The availability of advanced construction and civil engineering technologies is also a crucial factor. Crete's mountainous terrain presents both opportunities and challenges: high elevation differences are favorable for energy storage, but constructing reservoirs, tunnels, and pipelines requires specialized techniques and equipment. Integration with the electricity grid is another important technological consideration. PHS systems must operate in coordination with Crete's grid, which includes both local generation and interconnections to mainland Greece. Additionally, emerging technologies such as underground or seawater-based PHS can expand the range of viable sites in Crete, addressing geographical and environmental constraints. Therefore, technological factors are central to the development of pumped-hydro storage in Crete. Modern engineering solutions, efficient turbines, advanced construction methods, grid integration capabilities, and innovative PHS designs all contribute to making these systems technically feasible, reliable, and effective in supporting the island's transition toward renewable energies and energy independence.

Table 4. Technological factors affecting the deployment of PHS systems in Crete

1	PHS technology is mature and reliable based on well-established engineering principles and techniques
2	The good morphological characteristics in Crete favor the construction of water reservoirs in different heights
3	Good integration with the local electricity grid affects the deployment of PHS systems in Crete
4	Emerging technologies such as underground or seawater-based PHS systems favor their deployment in Crete

Source: own estimations

7.5 Environmental factors

Environmental factors are a critical consideration in the development of PHS systems in Crete. As large-scale infrastructure projects, PHS systems can significantly impact natural ecosystems, water resources, and landscapes, which makes environmental assessment and management essential for their successful implementation. One of the main environmental considerations is the protection of natural habitats and biodiversity. Crete is home to unique flora and fauna, many of which are endemic, and its mountainous regions contain fragile ecosystems. The construction of reservoirs, tunnels, and access roads may disrupt habitats, alter land use and affect local wildlife. Water management is another important factor. PHS systems require significant volumes of water, although it is generally used in a closed-loop system. In Crete, where water scarcity is a problem today, especially during dry summer months, projects must ensure that storage operations do not conflict with agricultural, domestic, or ecological water needs. Finally, PHS systems can positively impact the environment by enabling higher integration of renewable energies and reducing reliance on fossil-fuel power plants. This contributes to lower greenhouse gas emissions, improved air quality, and the island's overall sustainability goals. Therefore, environmental factors—including ecosystem protection, water management, landscape preservation, and sustainability considerations—play a major role in the planning and development of PHS systems in Crete.

Table 5. Environmental factors affecting the deployment of PHS systems in Crete

1	The impacts of PHS systems on natural ecosystems and landscapes
2	The disruption of natural habitats during the construction works
3	The impacts of PHS systems on limited water resources in Crete

4	The positive impacts of PHS systems on climate change mitigation increasing the integration of renewable energies and reducing the use of fossil fuels

Source: own estimations

7.6 Legal factors

Legal factors are a key consideration in the development of PHS systems in Crete, as compliance with national, regional, and European Union regulations is essential for project approval, construction, and operation. These factors influence permitting processes, project timelines, and investor confidence. PHS projects must comply with laws related to energy production, environmental protection, water management, and land use. Clear legal frameworks regarding ownership, operation, and revenue structures are critical to encourage private investment in PHS systems. Compliance with the EU Water Framework Directive, Habitats Directive, and environmental impact assessment requirements is mandatory for PHS projects, especially because Crete contains protected ecosystems and sensitive landscapes. Local and regional planning laws further influence PHS development. Projects must align with land-use plans, zoning restrictions, and protected area guidelines. Additionally, safety and operational regulations, including those related to dam construction, reservoir management, and turbine operation, must be strictly followed to prevent accidents and ensure public safety. Therefore, the legal environment significantly affects the development of PHS systems in Crete. Navigating these legal requirements effectively is essential to ensure project feasibility, minimize delays, and foster investor confidence, ultimately enabling the successful deployment of PHS systems on the island.

Table 6. Legal factors affecting the deployment of PHS systems in Crete

1	The legal framework regarding ownership, operation, and revenue structures regarding PHS systems affect their deployment in Crete
2	Regulations related with the EU Water Framework Directive, Habitats Directive, and environmental impact assessment affect the deployment of PHS in Crete
3	Local and regional planning laws such as land-use plans, zoning restrictions, and protected area guidelines affect the deployment of PHS in Crete
4	The existing safety and operational regulations affect the deployment of PHS in Crete

Source: own estimations

8. DISCUSSION

Pumped-hydro storage is a well-known, mature and reliable power storage technology broadly used worldwide allowing the integration of intermittent energy sources, such as solar and wind energy, into the power grid improving its stability and the quality characteristics. 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 electric grids. Several studies related with the deployment of PHS systems in remote and isolated islands have been also conducted. Crete has abundant solar and wind energy resources which can generate significant amounts of "green electricity" with the support of electricity storage systems. Unfortunately, power storage systems including batteries or PHS have not been deployed so far in Crete. Several aspects of developing PHS systems in the island of Crete have been explored using PESTEL analysis focusing of the external factors affecting the deployment of these systems. PESTEL analysis is a strategic tool that helps organizations to make rational decisions examining the external factors that affect their operation and the implementation of their projects. The analysis of political, economic, social, technological, environmental, and legal factors affecting the deployment of PHS systems in Crete has been conducted. The analysis indicates the external factors influencing positively or negatively the developing of PHS systems in Crete facilitating the integration of solar and wind electricity into the power grid. Our analysis although simple has several limitations including its qualitative and static nature and the subjective bias that might exist. Future research should combine the results of SWOT and PESTEL analysis on this issue giving deeper insight on the factors affecting the deployment of PHS systems in Crete.

9. CONCLUSIONS

A PESTEL analysis regarding the deployment of PHS 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 Greek and the EU policies regarding the promotion of renewable energies and power storage systems affect the deployment of PHS systems in Crete,

d) The high investment cost of PHS systems, the financial subsidies for their construction and the cost of electricity affect the deployment of PHS systems in Crete,
e) The acceptance of PHS systems from local communities, the increase in local employment and the public concern about water availability affect the deployment of PHS systems in Crete,
f) The maturity and reliability of PHS technology, the good morphological characteristics in the island, the good integration with the local grid and the technological innovations affect the deployment of PHS systems in Crete,
g) The impacts of PHS systems on natural ecosystems, landscapes, natural habitats, water resources and on climate change mitigation affect the deployment of PHS systems in Crete, and
h) The legal framework regarding energy storage and PHS systems, land-use plans, protected area guidelines, environmental impact assessment as well as safety and operational regulations affect the deployment of PHS systems in Crete.

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 PESTEL analysis indicates that several political, economic, social, technological, environmental and legal factors affect positively or negatively the deployment of PHS systems in the island of Crete.

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