European Commission

Review on potential for pumped hydro storage

Task 3 Final Report

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Release date 18 February 2019
Status Final
Version 6.0

This project has been funded and managed by:

EUROPEAN COMMISSION

Joint Research Centre
Directorate C — Energy, Transport and Climate
Unit C.3 — Energy Security, Distribution and Markets

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Executive Summary

This report provides a review on the potential for pumped hydro storage in Cyprus. The recent progress on pumped storage technology is investigated focusing on the technologies applicable for Cyprus. The current regulatory framework of the technology for Cyprus, along with regulatory, market and technical barriers has been analysed in detail. A review of recent studies on pumped storage integration for Cyprus has been conducted.

The overall applicability of pumped storage technology is investigated with the consideration of recent case studies available in the open literature. The recent studies included techno-economic studies, and integration of renewable energy sources to future pumped storage systems. Also the possible synergies for agricultural irrigation needs and power storage that could be coupled with a future pumped storage system are discussed.

Subsequently an economic analysis of future pumped storage systems in Cyprus is provided. The analysis includes the existing infrastructure that could be used in a future pumped storage system, along with the required investment for new equipment, and overall development and operation of future systems. A rough economic estimation, based on the most recent available values from literature data, is given.

Finally, a step-by-step proposal for future research and development actions in the field of pumped storage technology in Cyprus, including an analysis of the critical elements, is provided.

1 Introduction

1.1 Summary of the Objectives of this Task

Within this task a critical review of existing studies on pumped storage (PS) is provided. The following aspects are taken into account:

- The PS initiatives and mechanisms which have been undertaken in recent years, with emphasis on the last five years.
- The estimates that have been derived on the technical and economic potential of PS in Europe, as well as the factors which are preventing the full exploitation of such potential.
- The policies which have been put forward in order to foster PS initiatives.

The review on PS includes:

- An investigation of the potential in terms of techno-economic benefits, existing policies and incentives that could assist and hamper the application of such systems.
- The potential for coupling PS systems with renewable energy sources (RES), such as photovoltaic (PV) technology.
- A review of existing European PS business models, taking into account technical, market, environmental and social benefits, by examining PS experiences and mechanisms employed within European countries, with the aim of understanding what has favoured or hampered the development of PS in Europe.
- A review of studies for Cyprus, which include a consideration of all system capacities found as applicable for the Cyprus electricity infrastructure.

The task also investigates the possible synergies between agriculture irrigation needs and power storage by identifying the economic and technical potential, as well as the drivers, benefits, requirements and policies for evolving PS.

- Special consideration is given on issues related to available dam/reservoir infrastructure along with water volumetric capacity.
- It is investigated how the variation of water availability (in terms of percentage) throughout the year will affect the smooth operation of future PS installations between two existing reservoirs.
- It is examined whether water transport between the reservoirs would be beneficial for agriculture irrigation, in terms of cost and development of agricultural areas with lower water availability for both water transport and water extraction from available ground fills, by providing a cheaper solution for the operation of local ground water pumping units.

1.2 Hydroelectric Power Generation

A hydropower (HP) plant produces energy through the use of moving water [1]. Hydroelectric power plants (see Figure 1) convert the energy from the flowing water to mechanical and then electrical energy. The main components of these plants are turbines and generators, which are placed either inside or close to the reservoirs (dams). Pipelines (penstocks) transmit pressurized water from the reservoir to the power plant. Power transmission systems transport the generated electricity from the power plant to the consumption site [2].

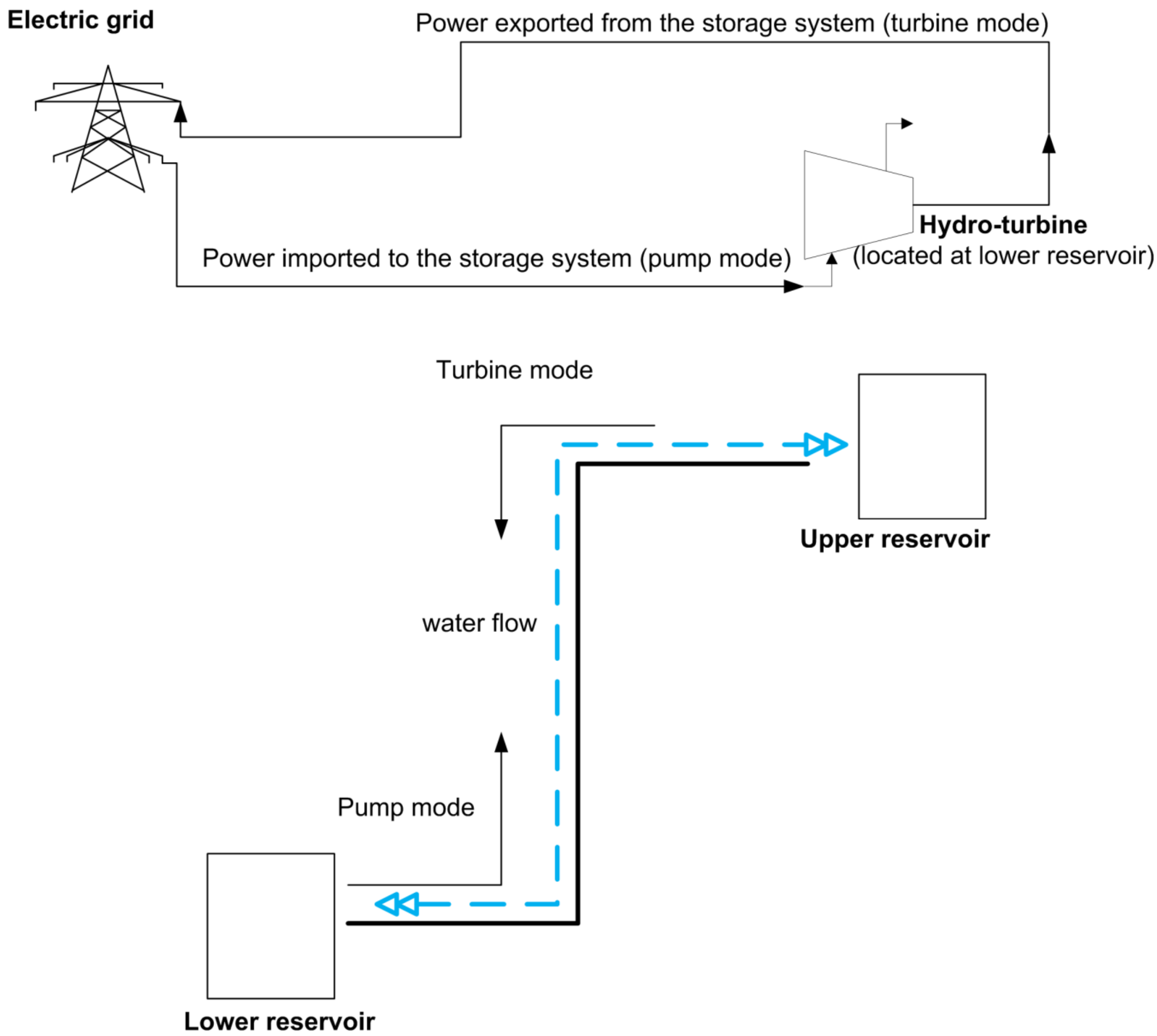

Figure 1. The components of a hydroelectric power plant.

The most important advantages of HP plants are [2]:

- Elimination of harmful emissions.
- Capability of rapid response to load changes.
- Relatively low operating costs.

HP plants are very responsive in terms of load management requirements, since through PS, electricity consumption occurs during low demand periods (i.e. low electricity price), while power generation takes place during peak demand, when the cost of electricity is high, and therefore more profitable [3].

The main disadvantages of HP plants are [2]:

- High initial capital cost.
- Potential site-specific and cumulative environmental impacts, including:
    - Altered flow regimes below storage reservoirs or within diverted stream reaches.
    - Water quality degradation.
    - Mortality of fish that pass through turbines.
    - Blockage of fish migration.
    - Flooding of terrestrial ecosystems by impoundments.

However, the above issues can be minimized, or eliminated, through proper design and operation of the plant. HP plants can also provide additional benefits, such as from recreation in reservoirs or in tail-waters below dams [2].

1.2.1 The Balancing Role of Hydropower

HP plants can act in a balancing role in power generation, provided that the energy sources are connected to the same grid as other renewable energy sources (RES) (wind power and photovoltaics (PV)). Wind and PV power generation is weather-dependant, which makes it difficult to match electric generation with load demand. HP can therefore provide a balance between input and output electricity on the grid. PS can also help maintain the desired frequency, since it can provide increased energy storage capability. The rapid start-up time (0.5–3 minutes) of HP is also an important advantage, which provides reliability and flexibility during operation, in terms of grid frequency and load-demand balancing. To use the HP technology in a balancing role, a storage reservoir is required within the plant, which can have a huge impact on the surrounding environment [4].

1.2.2 Large- vs. Small-Scale Hydropower

In terms of capacity, typical large-scale HP plants have a capacity above 10 MW. The total amount of installed HP capacity in EU is about 106 GW (excluding PS capacity). The large-scale HP installation covers 90% of this capacity. The leading countries, in terms of most installed small HP capacity in the EU are Italy, France, Spain, Germany, Austria and Sweden. In the EU there are more than 21,000 small HP installations that have an installed capacity at a total of 13,000 MW. In an average year, the small HP installations produce around 41,000 GWh. The small-scale HP installations are almost always run-of-the-river installations, which causes a smaller impact on the water environment than the larger installations with a water reservoir [4].

1.3 Pumped Storage: Basic Operational Characteristics

HP plants can be either conventional or PS. Under conventional HP plant technology fall all hydro plants except pumped hydro storage [5]. Conventional HP plants use the available water from a river, stream, canal system, or reservoir to generate electricity. In conventional multipurpose reservoirs and run-of-river systems, HP generation can be one of a number of functions, including: irrigation, flood control, navigation, downstream flow dilution for quality improvement, and municipal and industrial water supply. PS plants pump the water, usually through a reversible turbine that acts as a pump, from a lower supply source to an upper reservoir. The power capacity of a HP plant is primarily the function of the flow rate through the turbines and the hydraulic head. The hydraulic head is the elevation difference the water falls (drops) in passing through the plant or to the tail-water (which ever elevation difference is less). System design may concentrate on either of these flow and head variables or both, and on the HP plant installed designed capacity [2].

In order to establish a PS HP one needs both an upper and a lower reservoir reasonably close to each other, with a large head difference (i.e. located at different altitudes). To generate electricity, water is released and diverted from the upper reservoir and electricity is produced at turbines located at a lower elevation (see Figure 2).

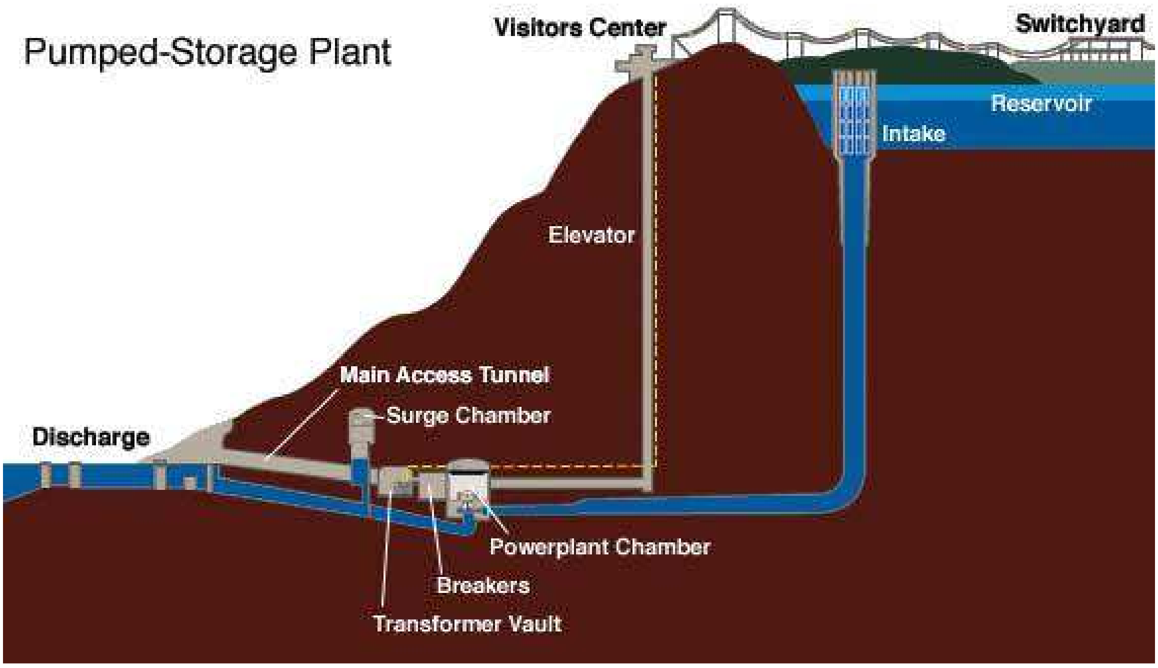

Figure 2. Schematic representation of a pumped storage hydropower plant [6].

Elevation difference is necessary to create a head. Therefore mountainous or hilly regions are usually the more favourable locations [4]. The amount of energy that can be stored is determined by the product of the regulation volume of the smaller of the two reservoirs, and the head difference between them [7]. A typical pumping station consists of a number of identical pumps working in parallel mode and raising water from a lower to an upper reservoir [8].

In summary, typical characteristics of PS technology are as follows:

- Lifetime: 40-80 years [5], [9], [10].
- Power capacity: up to 2000 MW [9].
- Operational efficiency: 70-85% [5], [9], [10]. Efficiency losses are due to the energy conversion: electrical-gravitational (and potential)-electrical [5].
- Storage time (i.e. the number of hours a plant can continue to generate electricity before running out of water): 4-10 hours [11].

Overall, PS is used for systems that need power to be supplied for a period between 4 to 10 hours, as it enables the system to participate effectively in voltage-frequency regulation, spinning reserve, non-spinning reserves markets, energy arbitrage and system capacity support. The value (in terms of both economics and reliability) of PS resources is derived from their ability to deliver power, when is mostly needed [9].

In the EU, electricity generation from PS HP plants is not considered as renewable, since pumping the water up consumes electricity produced by other power plants in the grid. Therefore PS plants become net energy consumers. In fact, more electricity is needed to pump water (from the lower to the upper reservoir) than the amount generated (when water is released from the upper reservoir into the lower one). However, this drawback is compensated for, by the flexibility these plants can provide [12].

1.4 Pumped Storage: Advantages and Disadvantages

A PS system consumes energy, but it is also an income producer. It can be brought online rapidly to operate in peak power production mode, when the cost of electricity is at its maximum value. On the other hand, pumping to replenish the upper reservoir takes place during off-peak hours (when electricity cost is low). Because of these characteristics, the system is cost effective, depending on price differentials in the wholesale market, even though it consumes more energy [2].

PS HP is well-suited for bulk power management applications, including on-peak/off-peak arbitrage and providing additional system capacity and balancing services. The advantages of PS HP include:

- It is a technically and commercially mature and reliable [13]. It is the largest and most widespread large-scale storage technology in power systems [9].
- It is an attractive option for islands, including management of supply and demand mismatching resulting from the integration of RES [14].
- It is classified as a real long-term response energy storage technology. It is also characterized by its fast response times and flexible start-stop [9], [15]. It possesses very quick ramp possibilities, with the ability to start-up and shut-down in only a few minutes, with a relatively large energy volume capacity. It has a fast load gradient (rate of change of nominal output in a given timeframe), as PS plants can ramp-up-and-down, by more than 40% of the nominal output per minute. PS with peak generation is able to cope with high generation-driven fluctuations and can provide active power within a short period of time [11].
- It has the ability to track load changes and adapt to drastic load changes [15].
- It has the ability to modulate frequency and maintain voltage stability [15].
- It is a highly efficient technology, with a round-trip efficiency of 70-85% [13].
- It has a high-speed adjustment capability, which ensures stable electricity supply [13].
- It can operate at a low cost, while capital costs are relatively lower than other storage technologies (per unit of generated electricity) [13]. Specifically, PS plants are five times less expensive than batteries, and four times less expensive than compressed air energy storage technologies [12]. Therefore PS can contribute in the stabilization of supply and electricity costs [13].
- It is offered with a very long lifetime [13].
- It does not involve consumption of valuable raw materials, like rare earths. Additionally it does not involve disposal problems, and can be combined with RES (e.g. natural inflows into storage reservoirs) [13].

The main disadvantages of PS are the following:

- The reservoirs have a negative impact on the environment [16].
- PS systems have a high capital cost, in comparison to conventional power generators [16].
- There is usually a difficulty in finding locations with sufficient water capacity for the installation of such systems, as there are few remaining undeveloped sites. Also, suitable sites are likely to face licensing problems due to environmental concerns, meaning that even if a plant receives permission, it could take years until all environmental studies are completed [16].

2 Best Practices and Recent Technological Developments

2.1 Characteristics of Pumped Storage Systems

2.1.1 Pumped Storage Power Plants vs. Conventional Power Plants

PS HP plants have an important role when optimizing the operation of the conventional power (thermal) generation fleet. As PS HP plants cover peak demand situations, while consuming electricity in periods of lower demand, they allow thermal power plants to stay connected and generate electricity, even at low-demand periods. Therefore PS HP plants can also contribute to the reduction of greenhouse gas emissions (GHG) from thermal power plants, since they do not need to deviate from the most efficient load. PS facilities work as a huge electricity storage resource, by charging or discharging power according to the demand of the system. PS HP plants use the water stored in the reservoirs repeatedly, without the need of natural inflow into the reservoirs. The role of PS HP plants is twofold: it provides a balance to the grid for demand-driven fluctuations, and a balance to generation-driven fluctuations. The latter is an increasingly important role due to the increase of variable RES in the electricity system [12]. The typical operating characteristics of PS systems, with a comparison to conventional power plants, are given in Table 1 [16].

Table 1. Typical operating characteristics of pumped storage systems and conventional power plants.

Operating characteristic	Nuclear power plants	Coal-fired Rankine cycle	Oil-fired Rankine cycle	Gas turbine	PS systems
Normal duty cycle	Base load	Base load	Base load-mid-merit	Peak load	Peak load-mid-merit
Unit start up-daily	No	No	Yes	Yes	Yes
Load following	No	Yes	Yes	Yes	Yes
Quick start (10 min)	No	No	No	Yes	Yes
Frequency regulation	No	Yes	Yes	No	Yes
Black start	No	No	No	Yes	Yes
Response time to sudden changes	High	Medium	Medium	High	High

2.1.2 Operational Modes: Peaking Mode vs. Storage Mode

In peaking mode, water is impounded and released when electricity generation is desired. In storage mode, water is extensively impounded and stored during high-flow periods to augment the water available during low-flow periods, allowing the flow releases and power production to be more constant. In many cases, a hybrid mode, combining the two aforementioned ones is applied [2].

2.2 Technology State-of-the-art for Pumped Storage Systems

2.2.1 Selection of Equipment and System Configuration

Pelton turbines have been identified as the preferred solution in most small systems, and by that configurations with separate pumps are necessary. The pumping stations are usually assumed to consist of a number of pumps with specific ratings that can be operated in parallel to control the total power in steps, although it has been shown that variable speed operation of at least one unit will be the most flexible solution [17].

2.2.2 Variable Speed Pumps

Recent developments in variable speed pumps used in PS systems can allow the increase of variable RES [18]. Novel PS systems can absorb volatile electricity surpluses and meet the requirements of new grid. With fixed-speed reversible units, variable speed pump-turbine or ternary pump-turbine units, PS technology can change from pumping to generating mode (and vice versa) in 25-30 seconds, making it the fastest, large-scale, electricity storage technology [19]. There has been a continuous development to increase the power rating and the maximum head of reversible pump-turbines. New PS systems are available at capacity above 400 MW, with more than 700 m of pumping head [19].

The main issue during the last 3-4 decades has been the introduction of power electronics equipment [17]. The main achievement in this respect has been the development of power electronically-controlled variable speed PS systems. There are many factors that have motivated the drive for variable speed operation of pump-turbines, both regarding the operation of the pump-turbine itself, and also from the power system point-of-view. The consideration of PS schemes for hybrid power systems in isolated electricity grids have until now been mainly focused on simple and robust solutions. The main purpose has been to improve the energy balance of the systems, when increasing the share of renewable energy. However, little attention has until now been focused on smaller-scale variable speed units for isolated grids [17].

2.2.3 Provision of Ancillary Services

It has been noted that a strong and diversified energy mix with a high share of RES needs the support of small- and large-scale PS in providing flexibility and ancillary service, because it is important to recognize the type of services, the storage capacity and capacity hurdles for the future [20]. Although PS provides crucial load-balancing and ancillary services to the grid and reduces the needs for transmission upgrades, PS facilities do not typically qualify as transmission infrastructure [15].

HP provides [19]:

- Balancing Ancillary services (FCR, FRR, RR).
- Electricity supply in remote areas, which are needed for balancing the grid.

Regarding system stability and security of supply, electricity system performance depends on stable frequency in the grid, which requires instantaneous adjustments to supply in order to match variations in demand. Therefore, a number of ancillary services are needed to manage the transmission system, in a way that secures system stability and supply. Due to the individual technical characteristics of generation technologies (RES and non-RES), generation options need economically-efficient flexibility. HP meets all these goals, since it is efficient, effective, predictable, controllable, mature, proven, reliable and renewable [19].

According to a recent Eurelectric position paper on the Water Framework Directive [21], a higher share of PV and wind power generation increases the need for ancillary services that contribute to maintaining secure and stable grids. This is because HP can provide back-up and reserve capacity, quick-start and black-start capability, regulation and frequency response, voltage support to control reactive power, and inertia. These ancillary services are increasingly important to the stability of the energy system and may also offer an alternate revenue stream for HP generators. These services are priced differently in various markets around the globe, although it is increasingly recognized that they are often not appropriately (or sufficiently) rewarded by energy markets [22]. PS allows critical load-balancing and ancillary services to the grid and decreases requirements for transmission upgrades, but usually it cannot qualify as transmission infrastructure [15].

According to the new Electricity Directive of 2019 (recast) [23] on the ownership of energy storage facilities by distribution system operators (Article 36), the following provisions have been included:

1. Distribution system operators shall not be allowed to own, develop, manage or operate energy storage facilities.
2. Member States may allow distribution system operators to own, develop, manage or operate energy storage facilities which are fully integrated network components and the regulatory authority has granted its approval or if all of the following conditions are fulfilled:
    a. Other parties, following an open, transparent and non-discriminatory tendering procedure, subject to review and approval by the regulatory authority have not been awarded with a right to own, develop, manage or operate such facilities or could not deliver those services at a reasonable cost and in a timely manner. Regulatory authorities may draw up guidelines or procurement clauses to help distribution system operators ensure a fair tendering procedure; and
    b. Such facilities are necessary for the distribution system operators to fulfil their obligations for the efficient, reliable and secure operation of the distribution system and they are not used to buy or sell electricity in the electricity markets, and
    c. The regulatory authority has assessed the necessity of such derogation and has carried out an assessment of the tendering procedure, including the conditions, and has granted its approval.
3. Regulatory authorities shall perform at regular intervals or at least every five years a public consultation for the existing energy storage facilities in order to assess the potential availability and interest of market parties to invest in such facilities. Where the public consultation, as assessed by the regulatory authority, indicates that third parties are able to own, develop, operate or manage such facilities in a cost-effective manner, regulatory authorities shall ensure that distribution system operators' activities in this regard are phased-out within 18 months. As part of the conditions for this procedure, regulatory authorities may allow the distribution system operators to receive reasonable compensation, in particular to recover the residual value of the investment they made into energy storage facilities.

Similarly for ownership of energy storage facilities by transmission system operators (Article 54), the following provisions have been included:

1. Transmission system operators shall not be allowed to own, develop, manage or operate energy storage facilities.
2. Member States may allow transmission system operators to own, develop, manage or operate energy storage facilities which are fully integrated network components and the regulatory authority has granted its approval or, if all of the following conditions are fulfilled:
    a. Other parties, following an open, transparent and non-discriminatory tendering procedure, subject to review and approval by the regulatory authority have not been awarded with a right to own, develop, control, manage or operate such facilities or could not deliver these services at a reasonable cost and in a timely manner. Regulatory authorities may draw up guidelines or procurement clauses to help transmission system

operators in ensuring a fair tendering procedure; and

b. Such facilities or non-frequency ancillary services are necessary for the transmission system operators to fulfil their obligations under this Directive for the efficient, reliable and secure operation of the transmission system and they are not used to buy or sell electricity in the electricity markets; and
c. The regulatory authority has assessed the necessity of such derogation, has carried out an ex-ante review of the applicability of a tendering procedure, including the conditions, and has granted its approval.

3. The decision to grant derogation shall be notified to the Agency and the Commission along with relevant information about the request and the reasons for granting the derogation.
4. The regulatory authorities shall perform at regular intervals or at least every five years a public consultation for the existing energy storage facilities in order to assess the potential interest of market parties to invest in such facilities. Where the public consultation, as assessed by the regulatory authority, indicates that third parties are able to own, develop, operate or manage such facilities in a cost-effective manner, regulatory authorities shall ensure that transmission system operators' activities in this regard are phased-out within 18 months. As part of the conditions for this procedure, regulatory authorities may allow the transmission system operators to receive reasonable compensation, in particular the residual value of the investment they made into energy storage facilities.

Targets for increasing RE are stimulating wind and solar power developments in many countries. Increased variable generation is seen to drive the demand for system reserve and increase the value of PS in ancillary services. PS projects may be remunerated in liberalized electricity markets through ancillary services payment, capacity payment, and electricity trading [24]. PS can provide ancillary services at high ramp rates, and they can also provide benefits from intraday energy price variation, by releasing energy at high demand periods, and buying energy at off-peak periods to pump water into the upper reservoir [25].

There are several different ancillary services or grid stabilizing services of HP, thus facilitating the integration of variable RES into the power system and providing a key tool for TSOs to maintain a stable and balanced grid [11], [12]:

- Back-up and reserve: HP plants have the ability to enter load into an electrical system from a source that is off-line. HP can provide this service without the consumption of additional fuel, leading to lower emissions.
- Quick-start capability: The quick-start capability of HP plants takes only a few minutes.
- Black start capability: HP plants have the capability to run at a zero-load. When loads increase, additional power can be delivered rapidly to the system in order to meet demand.
- Regulation and frequency response: HP contributes to maintaining the frequency within the given margins through continuous modulation of active power and to address moment-to-moment fluctuations in system power requirements. Its fast-response ability makes it especially valuable in covering steep load gradients (ramp rates), through its fast load-following.

3 Regulatory Framework in Cyprus

In this section the current status of the regulatory framework in Cyprus is presented, with an analysis on the regulatory, market, and technical barriers.

3.1 Regulatory Barriers

3.1.1 EU Policies: Water Framework and Renewable Energy Sources Directives

In the last decade two main policies have been formulated to regulate the future of HP in Europe: the Water Framework Directive (WFD) (2000/60/EC) [19] and the RES Directive (RED) (2009/28/EC) [26]. The latter Directive includes the following regulation: "In calculating the contribution of HP and wind power, the effects of climatic variation should be smoothed through the use of a normalization rule. Further, electricity produced in PS units from water that has previously been pumped uphill should not be considered to be electricity produced from RES." Also for the calculation of the share of energy from RES: "Gross final consumption of electricity from RES shall be calculated as the quantity of electricity produced in a Member State from RES, excluding the production of electricity in PS units from water that has previously been pumped uphill." The WFD brings about more stringent water quality measures while the RED sets higher targets for overall RE generation [3].

Hydroelectric power generation usually excludes PS plants that generate electricity during peak load periods by using water previously pumped into an elevated storage reservoir during off-peak periods when surplus generation is available, while energy losses in pumping are accounted for separately [1]. The European Parliament resolution of 21 May 2013 on current challenges and opportunities for RE in the European internal energy market (2012/2259(INI)) in terms of infrastructure requirements: "emphasizes that HP must play a central role in the planned development of RES, primarily to balance out the increasingly volatile generation of power by RES but also, through PS, as a method of storing electricity; stresses, therefore, that the existing development potential of hydroelectric power generation and PS in the EU must be fully exploited" [27].

3.1.2 Provisions of the Electricity Directive 2018/2001 [28], Regulation 2018/1999 [29] on Storage, and new Electricity Regulation of 2019 (recast)

In general, network and other regulated charges of storage units as both generation and demand is a significant barrier for its deployment. This is obvious in cases where generation faces much reduced network charges in respect to demand (this is the case in Cyprus).

Specifically the Electricity Directive 2018/2001 [22] includes the following provisions:

- "There is a need to support the integration of energy from RES into the transmission and distribution grid and the use of energy storage systems for integrated variable production of energy from renewable sources, in particular as regards the rules regulating dispatch and access to the grid.
- It is appropriate to allow for the development of decentralised RE technologies and storage under non-discriminatory conditions and without hampering the financing of infrastructure investments. The move towards decentralised energy production has many benefits, including the utilisation of local energy sources, increased local security of energy supply, shorter transport distances and reduced energy transmission losses. Such decentralisation also fosters

community development and cohesion by providing income sources and creating jobs locally."

Regulation 2018/1999 [29] indicates that Member States shall include in their integrated national energy and climate progress reports information on the implementation of the following objectives and measures:

- "National objectives related to other aspects of the internal energy market, such as increasing system flexibility, market integration and coupling, aiming to increase the tradeable capacity of existing interconnectors, smart grids, aggregation, demand response, storage, distributed generation, mechanisms for dispatching, re-dispatching and curtailment, and real-time price signals.
- National objectives and measures related to the non-discriminatory participation of RE, demand response and storage, including via aggregation, in all energy markets."

Also according to the new Electricity Regulation of 2019 (Paragraph 22) (recast) [30]:

- "To provide for a level playing field between all market participants, network tariffs should be applied in a way which does not discriminate between production connected at the distribution-level with regard to the production connected at the transmission level, either positively or negatively.
- They should not discriminate against energy storage, and should not create disincentives for participation in demand response or represent an obstacle to improvements in energy efficiency."

3.1.3 Licensing Procedures in Cyprus

Licensing of PS plants is currently inactive, since no updated information from the Cyprus Energy Regulatory Authority (CERA) has been provided since 2012. According to the CERA Annual report of 2012 [31], at that time, the European Commission had issued a Proposal for a Regulation on 19/10/2011 on guidelines for trans-European energy infrastructure in the context of implementation of its core energy policy objectives of competitiveness, sustainability and security of supply. The main objective of the proposal was to ensure coordination between Member States to optimize the development of energy infrastructure (gas, electricity, oil and carbon dioxide) across Europe. Specifically for a regulation concerning Cyprus, the objective was the full integration of the internal energy market, ensuring no Member State is isolated from the European network. In the context of attaining these targets, the proposal for a regulation provided for the submission to the European Commission of projects involving interconnection between Member States and third countries, referred to as «Projects of common interest». In the context of implementing the provisions of the above Proposal for Regulation, Cyprus had submitted a total of 4 projects (2 for gas and 2 for electricity) for evaluation as potential projects of common interest. The proposed projects for electricity were: (a) the EuroAsia Interconnector and (b) a PS Plant in Cyprus (200 million € for PS infrastructure at a capacity of 200 MW in the dams of Kannaviou/Arminou and 130 MW in Kourris). In the case of Cyprus, the project «EuroAsia Interconnector» was deemed eligible, while the project «Pumped Storage in Cyprus» was rejected, because it did not meet the regulation criteria [31].

According to the CERA Annual Report of 2012 [31], eligibility for a Proposed Project of Common Interest must meet the following general criteria:

1. The project is necessary for the implementation of the energy infrastructure priority corridors as set out in the Proposal for a Regulation.
2. The project displays economic, social and environmental viability.
3. The project involves at least two Member States, either by directly crossing the border of one or more Member States or by being located on the territory of

one Member State and having a significant cross-border impact.

In addition, a project falling under the electricity category shall contribute significantly to at least one of the following specific criteria [31]:

1. Market integration, competition and system flexibility.
2. Sustainability, inter alia through transmission of renewable generation to major consumption centres and storage sites.
3. Interoperability and secure system operation.

CERA planned to propose an updated regulatory framework for storage until the end of 2018. Specifically, the office of the Regulator has confirmed that in January 2019 the regulatory policy for storage in front of the meter for public consultation will be issued. Following that, the policy will be finalized and issued. In view of this, a policy on storage beyond the meter is expected around Spring 2019 [32]. However it has not been clarified, whether PS will be included in the updated regulatory framework, since it is considered technology-neutral.

Currently, in Cyprus, there is no regulatory framework to develop and integrate PS systems. Such a framework much be formed, including technical modalities and financial conditions for new PS power plants, based on large storage capacity [33]. Since most available studies have indicated that new PS projects would include the utilization of dams as reservoirs, this has to be done in cooperation with the Cyprus Water Development Department (WDD). However, it is noted that a specific regulation regarding PS is not currently available from the WDD.

3.1.4 Treatment of Pumped Storage as a Generation Asset

Since PS plants have not been established yet in Cyprus, some practices from other European members are briefly mentioned, to show possible regulatory barriers that could be faced in the future.

According to the new Electricity Directive (Article 54) of 2019 (recast) [23], TSO cannot own any storage facility, including PS systems.

A Eurelectric report from 2015, claims that existing regulations in several EU Member States treat PS both as a generation asset (it is hence required to pay a grid fee for transmission grid access) and a final consumer (requiring it to pay the grid access fee a second time) [11]. The authors suggest that double grid fees for PS power plants should be removed, to ensure a level playing field between storage technologies for the following reasons:

- PS does not constitute final electricity consumption and it should therefore not be treated as such when setting grid fees.
- Policymakers should refrain from introducing discriminatory taxes, fees or regulated costs on PS which distort the level playing field and result in a suboptimal use of, and underinvestment in, PS. Services offered by PS should be remunerated under well-functioning market conditions.
- Create a level playing field in Europe for power generation from domestic water resources, compared with other electricity production and storage technologies, with a special focus on the value of providing flexibility to the electricity system.
- Since HP and PS are scarce and constitute highly valuable resources, their potential has to be used to its optimum on a European scale.

In another Eurelectric report [20], its authors suggest that grid access costs for PS facilities should not prevent storage from playing its important role in providing flexibility to cope with balancing and intermittency of RES. The authors claim that national grid tariff mechanisms in Europe require a double grid access payment (once as producer, once as load). The authors suggest that charges imposed to end users (e.g. surcharges for RES-E, taxes, etc.) should not apply to PS facilities.

3.1.5 Environmental barriers for Pumped Storage in Cyprus

According to Poullikkas [16], the reservoirs have a negative impact on the environment, and also, suitable sites in Cyprus are likely to face licensing problems due to environmental concerns, meaning that even if a plant receives permission, it could take years until all environmental studies are completed.

The potential for the development of PS plants in Cyprus is likely to face significant barriers, in relation to environmental concerns and restrictions. Specifically, these may include *Natura 2000* protected areas, since almost the entire area within the Troodos region (an area covering more than 1/3 of the total area of the government-controlled areas of the Republic of Cyprus) falls within this category. This is unfortunate because the Troodos region seems ideal for pumped storage application, since it offers the desirable elevation (head) difference between nearby dams. The map in Figure 3 shows the locations of existing dams and *Natura 2000* protected areas in Cyprus (based on data from: [34], [35]). It has to be acknowledged that in future PS systems, the tubing network connecting the two dams (reservoirs) will have to avoid crossing the protected areas.

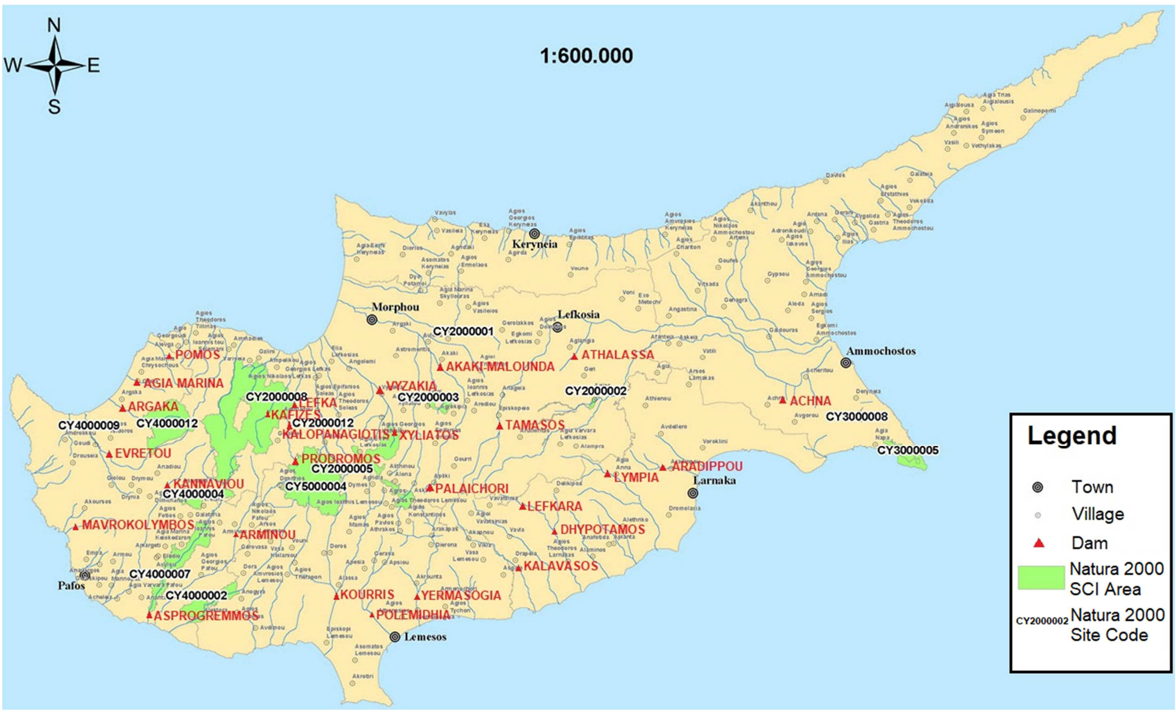

Figure 3. Locations of existing dams and *Natura 2000* protected areas in Cyprus (based on data from: [34], [35]). SCI: Site of Community Importance.

3.2 Market Barriers

3.2.1 Capital Cost

According to Poullikkas [16], PS systems have a high capital cost. This fact could discourage investors to establish PS plants, if this continues to represent a high risk in terms of investment. Capital cost could further increase, if new reservoirs will be needed, in addition to desalination plants to supplement water unavailability and water losses.

3.2.2 Levies and Fees for Network Use

Another significant market barrier for the development of PS technology in Cyprus are uncertainties arising from the development of levies and fees for network use, which represent an increasing burden for PS [11]. Also, grid fees could create a major disadvantage for PS plants, in comparison to other competing flexibility options [19].

3.3 Technical Barriers

3.3.1 Availability of Suitable Locations for Future Pumped Storage Plants

A major disadvantage of PS technology is that large amounts of land are needed for the reservoirs and there are few good sites near most large cities [36]. In this respect, given the small size of Cyprus, a difficulty is expected to be encountered in finding locations with sufficient water capacity [16]. Additionally very few undeveloped sites are currently available [16]. Further on, PS technology requires specific ground morphology for its application, i.e. an elevation difference between upper and lower reservoirs. This requirement significantly limits the available options in Cyprus. It is anticipated that some dams could be used as upper or lower reservoirs, but new reservoirs (new infrastructure) could be required as well.

3.3.2 Water Management Issues

Possible regulatory barriers that could discourage the implementation of PS in Cyprus include water management issues. Specifically the scarce availability of water in available dams (water availability is on average at 10-20% in the last five years in all major dams[1]) creates a major technical barrier for the development of PS plants.

[1] Estimated annual average value based on data from WDD [46].

4 Investigation of the applicability of Pumped Storage in Cyprus

4.1 Case Studies for Cyprus

In the case of Cyprus, where solar energy is available due to prolonged solar radiation, energy storage in the form of PS has been identified as a possible solution to the problem of supply vs. demand mismatch [16], [33]. Specifically, PV generated electricity could be converted to potential energy with a PS system connecting an upper and lower reservoir, and then reconverted to electricity when solar energy is unavailable (e.g. during evening hours or reduced sunshine hours).

At present, Cyprus has over 100 dams, 56 of which are included in the Register of the International Committee on Large Dams [33]. According to Poullikkas [37], the possibility of introducing PS systems into the Cyprus power system should be thoroughly studied in order to allow the future use of RES in the future. Due to the complexity of their design and licensing, PS systems could operate on a commercial basis not before 2022. The installed PS capacities, licensed PS capacities and capacities of PS projects in early planning stage in MW are shown in Figure 4 [12]. As shown, the total pump capacity and maximum time of full-load operation of the PS power plants in early planning stage for Cyprus is 190 MW for a maximum time of full-load operation at 11 hours.

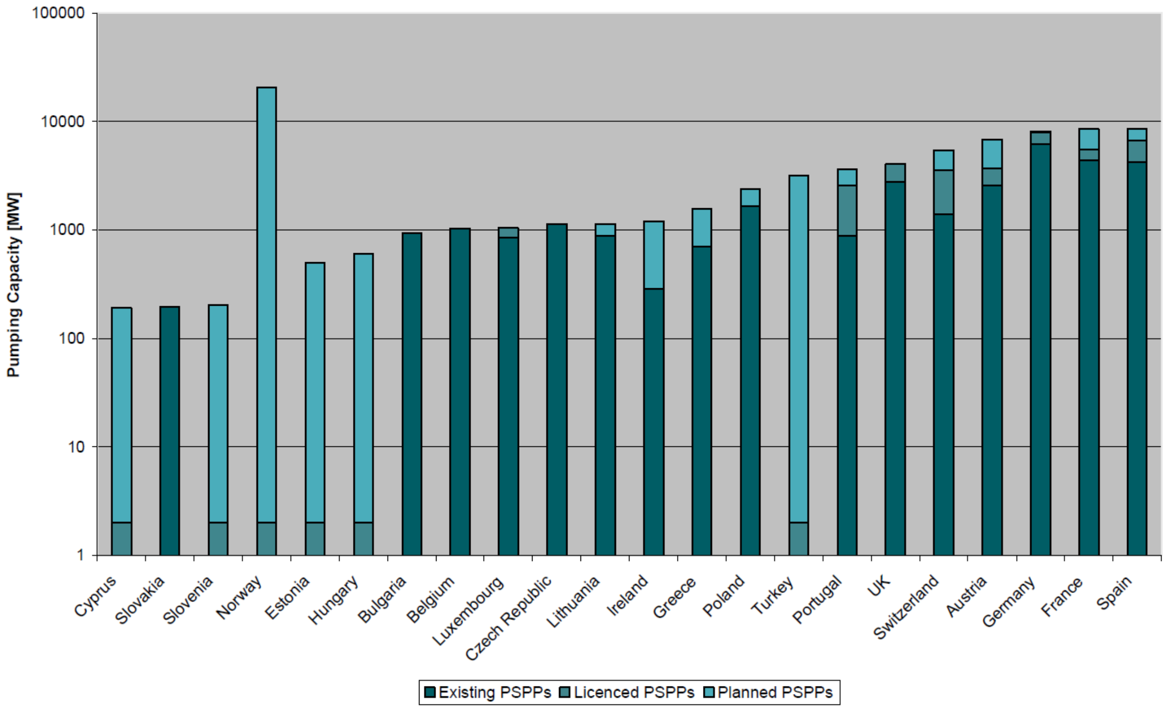

Figure 4. Installed PS capacities, licensed PS capacities and capacities of PS projects in early planning stage in MW [12].

Most available studies agree on the existence of a strong potential for the application of medium- and large-scale PS systems in Cyprus. However, future studies must focus on determining an optimal size for the PS system in a pattern that will ensure high use of the PS system and penetration of RES, but simultaneously avoiding: (a) curtailment of renewable electricity generation, (b) keeping the PS power plants idle.

In the next subsections (4.1.1-4.1.4), four recent studies ([16], [24], [33], [38]) on the potential of PS in Cyprus are presented. A comparison between the four aforementioned studies (summarized in Table 2) is not possible, because they have different starting points, assumptions and purposes.

Table 2. Summary of PS-related studies for Cyprus.

Study	Description-Objectives	Method	Findings
JRC, 2013 [38]	Evaluation of overall potential of PS in Europe (incl. Cyprus)	Two topologies: (a) two existing reservoirs, (b) one existing reservoir and one new reservoir	20 km scenario shows that the application of constraints in the case of Cyprus kept at least 30% of its potential
INSIGHT_E, 2015 [24]	Evaluation of various scenarios for storage in a small isolated power system	Three scenarios: (a) no storage, (b) enhanced storage, (c) domestic gas	PS is not deemed as cost-competitive, but if it were forced to be installed, it would be used extensively for the provision of Frequency Restoration Reserve (FRR)
Tsamaslis et al. 2017 [33]	Investigation of the possible application of PV-PS systems in Cyprus	Simulation of the effects of various scenarios with the inclusion of: (a) existing dams/reservoirs (lower) and new reservoirs (upper) The considered maximum capacity of the proposed system is defined by the total size of the upper reservoirs (i.e. 5.410 MCM)	A potential PV-PS system could adopt multiple strategies to utilize more wind energy and reduce RES curtailment The additional reservoir storage acquired will be used to reduce both balancing and oversupply related curtailments PV-PS systems could have significant benefits for the isolated Cyprus grid, where solar irradiation is high and grid stabilization is needed A comprehensive cost analysis must be included to provide a realistic picture of the actual potential of the system
Poullikkas, 2013 [16]	Technoeconomic study for the integration of PS in Cyprus	Calculation of the electricity unit cost of the generation system for various investigated scenarios The analysis included three candidate PS plants, with capacities ranging at 130-200 MW	Under certain parameters the use of PS systems could be beneficial for the large-scale integration of RES

4.1.1 Overall Potential of Pumped Storage in Cyprus

In a recent assessment of PS in Europe two topologies have been defined [38]:

- T1: two existing reservoirs with adequate elevation difference, which are close enough so that they can be linked by a new penstock and electrical equipment.
- T2: one existing reservoir, with a suitable nearby site for the building of a second reservoir.

The suggested scenarios include different maximum distances between the two reservoirs, and also a different minimum head for a similar maximum distance [38]:

- Distance: 1, 2, 3, 5, 10 and 20 km.
- Head: 50 m (instead of the standard minimum of 150 m head).

A comparison with the theoretical potential for the 20 km scenario shows that the application of constraints in the case of Cyprus kept at least 30% of its potential (see Figure 5) [38].

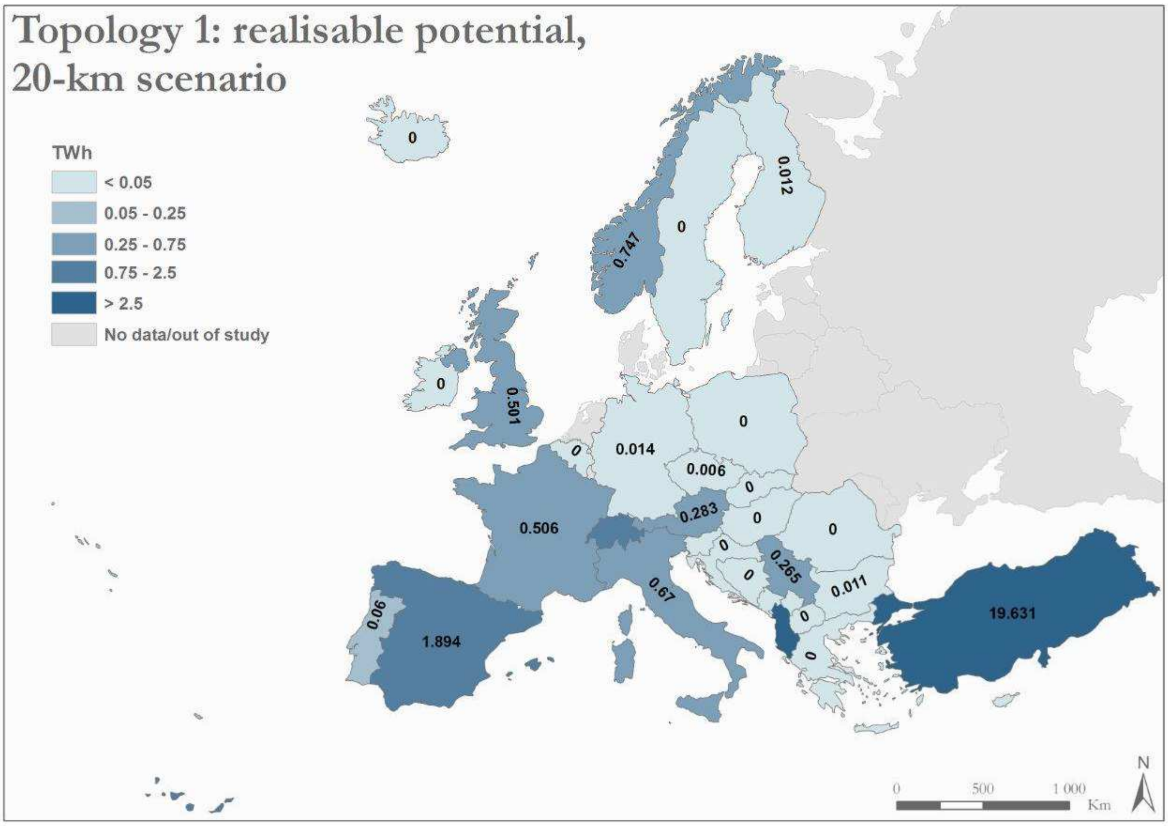

Figure 5. Maximum realizable potential under topology 1 (for Cyprus: <0.05 TWh) [38].

For Cyprus, the four defined potentials (i.e. T1 & T2 - theoretical and realizable) of PS capacity under the two topologies are the following:

- T1 theoretical:
  - 1 km: 0 GWh 5 km: 0 GWh 20 km: 31 GWh
- T1 realizable:
  - 1 km: 0 GWh 5 km: 0 GWh 20 km: 9 GWh
- T2 theoretical:
  - 1 km: 0 GWh 5 km: 33 GWh 20 km: 130 GWh
- T2 realizable:
  - 1 km: 0 GWh 5 km: 18 GWh 20 km: 86 GWh

The theoretical and realizable potential results for a 5-km scenario with two different heads, for Cyprus [38] have the following characteristics:

- T2 theoretical potential 5 km/50 m scenario
  - No. of sites: 24
  - Avg. head: 159 m
  - Avg. storage: 2 GWh
  - Total energy storage: 42 GWh
- T2 theoretical potential 5 km/150 m scenario
  - No. of sites: 14
  - Avg. head: 210 m
  - Avg. storage: 2 GWh
  - Total energy storage: 33 GWh
- T2 realizable potential 5 km/50 m scenario
  - No. of sites: 21

  - Avg. head: 158 m
  - Avg. storage: 1 GWh
  - Total energy storage: 27 GWh
- T2 realizable potential 5 km/150 m scenario
  - No. of sites: 12
  - Avg. head: 214 m
  - Avg. storage: 2 GWh
  - Total energy storage: 18 GWh

According to this study, the characteristics of the available reservoirs in Cyprus are the following [38]:

- Total no. of reservoirs: 52
- Total capacity: 286 MCM
- No. of selected reservoirs: 38[2]
- Capacity of selected reservoirs: 285 MCM

4.1.2 Storage in a Small Isolated Power System

In a recent study [24], an existing electricity supply model was taken and translated into an OSeMOSYS model, including code extensions that allow the incorporation of short-terms constraints into long-term energy system models. The following scenarios were assessed and compared:

- No Storage (NS) scenario.
- Enhanced Storage (ES) scenario. In this scenario, a 130 MW PS system was considered for installation in 2021. The storage options were allowed to contribute to the required operational reserve, while distributed storage options were also allowed to provide ancillary services. Natural gas was not considered as a fuel option.
- Domestic Gas (DG) scenario. This case investigated the financial competitiveness of storage options in the case where domestic natural gas reserves would become available for electricity generation by 2023.

The authors found that the inclusion of energy storage (see Figure 6) has a significant effect on RES penetration to power generation. In the NS scenario PV and wind capacities would reach 1,296 and 1,177 MW respectively by 2030, while in the ES scenario the respective values are 2,912 and 877 MW [24].

[2] The selected reservoirs are not specified in the aforementioned reference.

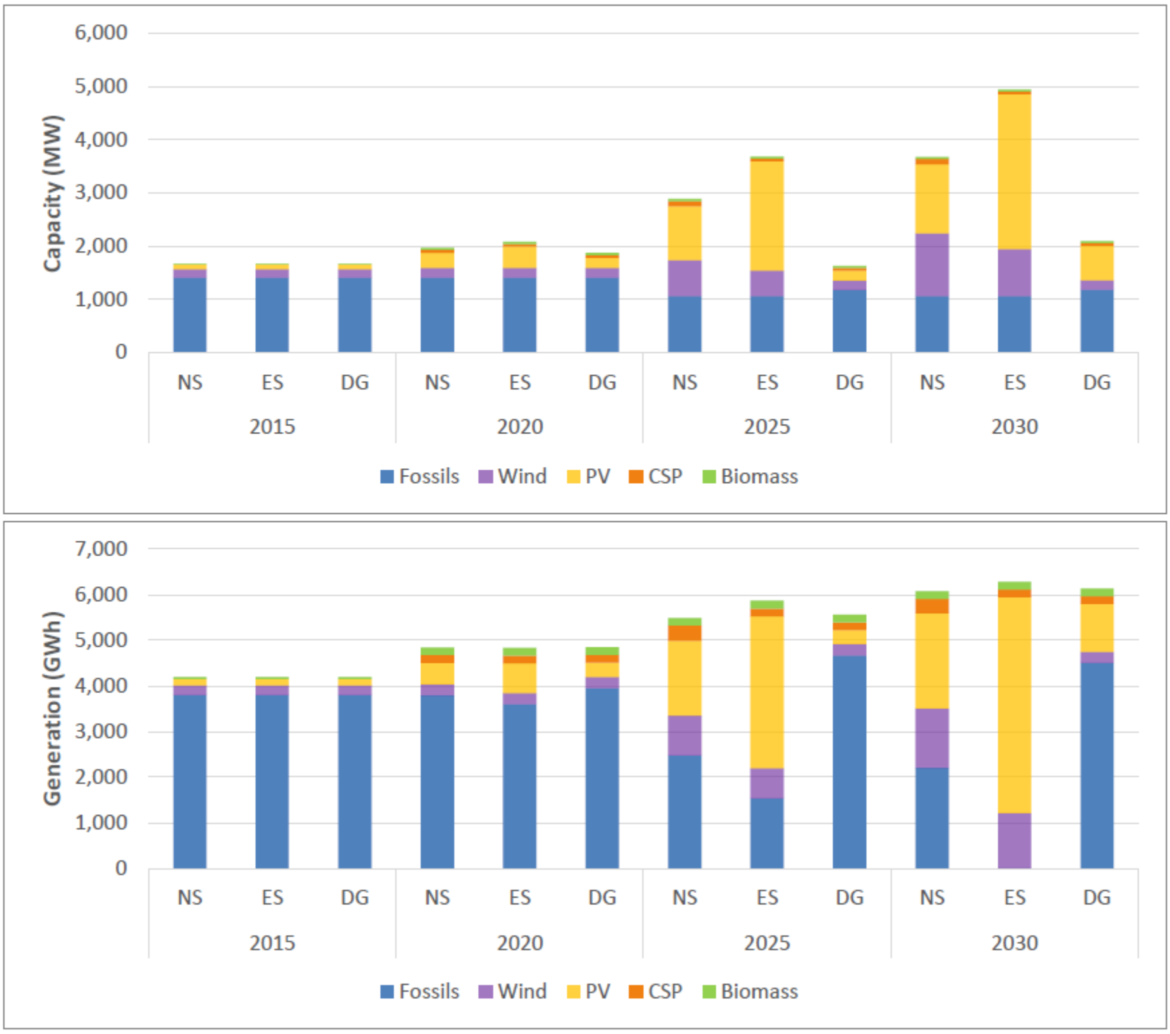

Figure 6. Evolution of capacity and generation mix in the three considered scenarios [24].

The authors state that although PS is not considered cost-competitive, if such systems were forced to be installed, it would be used extensively for the provision of Frequency Restoration Reserve (FRR). Operational reserve demand is considered, which corresponds to constant 60 MW, plus 50% of instantaneous wind generation, plus 10% of instantaneous PV generation [24]. The potential arrival of natural gas (DG Scenario) can have a major impact on the cost-competiveness of distributed PV and storage, as well as renewable generation as a whole. In the DG scenario, share of RE generation is limited to 27%. In regards to economic impact, in the ES scenario the introduction of storage coupled with subsequent capacity additions of renewable energy technologies lead to higher investment costs, but lower fuel and CO^2 costs, as compared to the NS scenario. Nonetheless, the cost savings achieved through substitution of oil with natural gas is much greater as can be seen in Figure 7. The average cost of electricity by 2030 is 30 €/MWh lower in the ES compared to the NS scenario, while in the DG scenario this is further reduced by about 20 €/MWh [24].

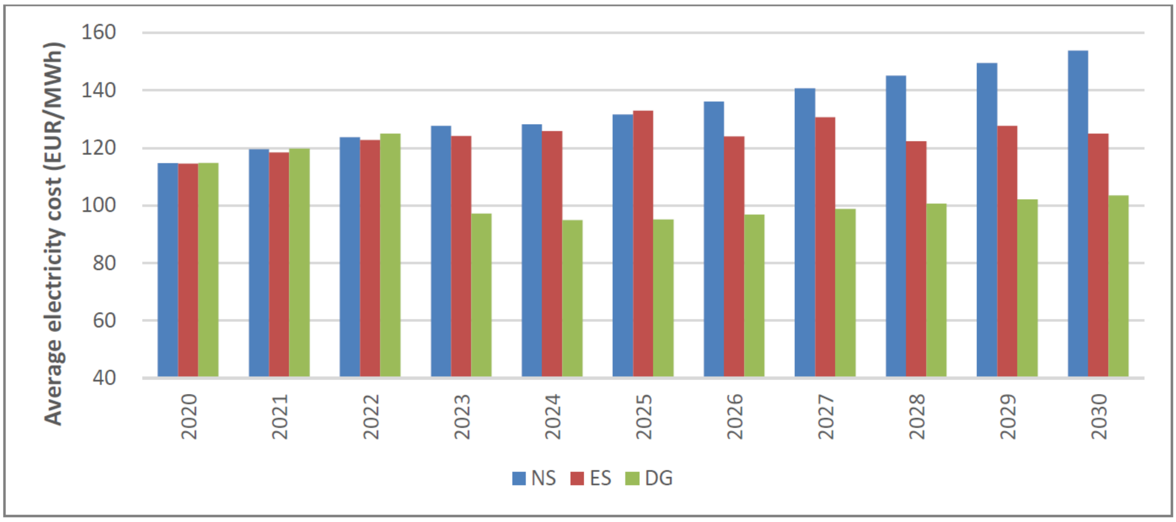

Figure 7. Average cost of electricity in the three considered scenarios [24].

The results of the study suggest that the introduction of energy storage could dramatically increase the share of variable RES in the electricity supply system of Cyprus. Even in the completely isolated system of Cyprus, RES in combination with storage options have the potential to improve the energy independence of Cyprus, as it will no longer rely on any fuel imports for electricity generation. It should be highlighted that cost-competitiveness of storage options, especially that of distributed PV generation coupled with Li-ion batteries, will be affected by the availability of natural gas. If natural gas becomes available, the deployment of distributed PV with storage will be suppressed dramatically. The authors concluded that the case of Cyprus is unique, because it lacks interconnections with other grid networks, and therefore demand for reserves has to be provided internally. However flexibility regarding intermittent RE generation is reduced, leading to a higher potential for curtailment [24].

4.1.3 Potential of Photovoltaic-Pumped Storage Systems in Cyprus

Recently (2017), a preliminary study was conducted to investigate the possible application of PV-PS systems in Cyprus [33]. The authors took into account all significant electrical grid and power stations operating parameters, to develop an algorithm able to simulate the effects of various scenarios applied in the Cyprus autonomous grid. The researchers assumed that the existing water reservoirs which meet capacity, grid, topographic (available height difference) and environmental criteria can be included as lower reservoirs, while new reservoirs will be needed for the role of upper reservoir [33]. The considered maximum capacity of the proposed system (see Table 3) is defined by the total size of the upper reservoirs (5.410 MCM).

Table 3. Capacities of the lower reservoirs (existing dams) and new upper reservoirs [33].

Existing water dams	Lower reservoirs	New upper reservoirs
Kourris	115,000	0.550
Dhypotamos	15,500	0.500
Lefkara	13,850	0,500
Arminou	4,300	0,300
Yermasogia	13,500	0,780
Kalavasos	17,100	0,450
Asprokremmos	52,375	0,450
Kannaviou	17,168	0,450
Mavrokolymbos	2,180	0,250
Evretou	24,000	0,450
Kalopanagiotis	0,363	0,180
Xyliatos	1,430	0,250
Klirou	2,000	0,300
Total Capacity	**278,766**	**5,410**

Two different scenarios of PV-PS systems were assumed [33]:

- Scenario A. 165 MW of PS capacity + 195 MW of PV based on 2 axis tracking.
- Scenario B. 85 MW of PS capacity + 85 MW of PV based on 2 axis tracking.

Figure 8 shows the real demand curve of the grid during a typical summer day (2 August 2013), along with the grid demand for scenarios A and B. The operation of the conventional power units is flattened out markedly, reducing the peaks and increasing the power during the low power demand periods [33]. Figure 9 shows results for a typical low demand day (10 April 2013), while Figure 10 during a typical winter day (1 December 2013). Figure 11 and Figure 12 show the all-year conventional power plant operation for scenarios A and B, respectively [33].

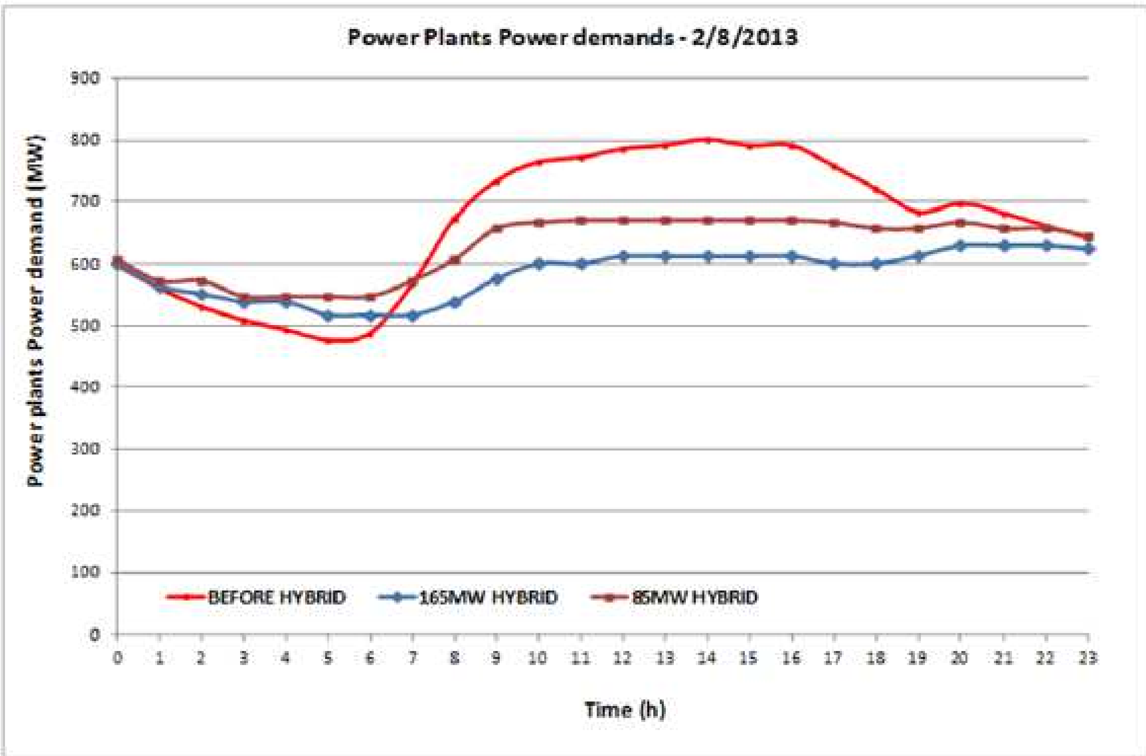

Figure 8. Existing (red) and achieved daily operation of the conventional units, during a typical summer day, after the implementation of scenarios A (blue) & B (brown) [33].

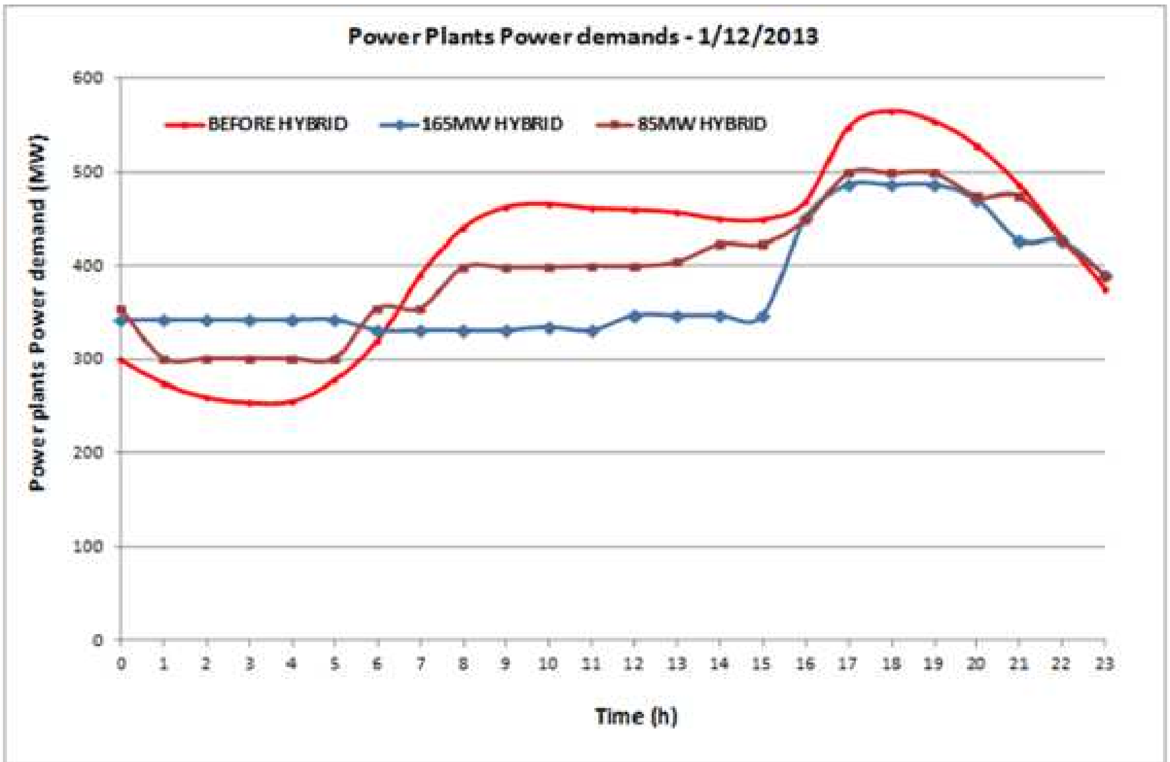

Figure 9. Existing (red) and achieved daily operation of the conventional power plants, during a typical winter day, after the implementation of scenarios A (blue) & B (brown) [33].

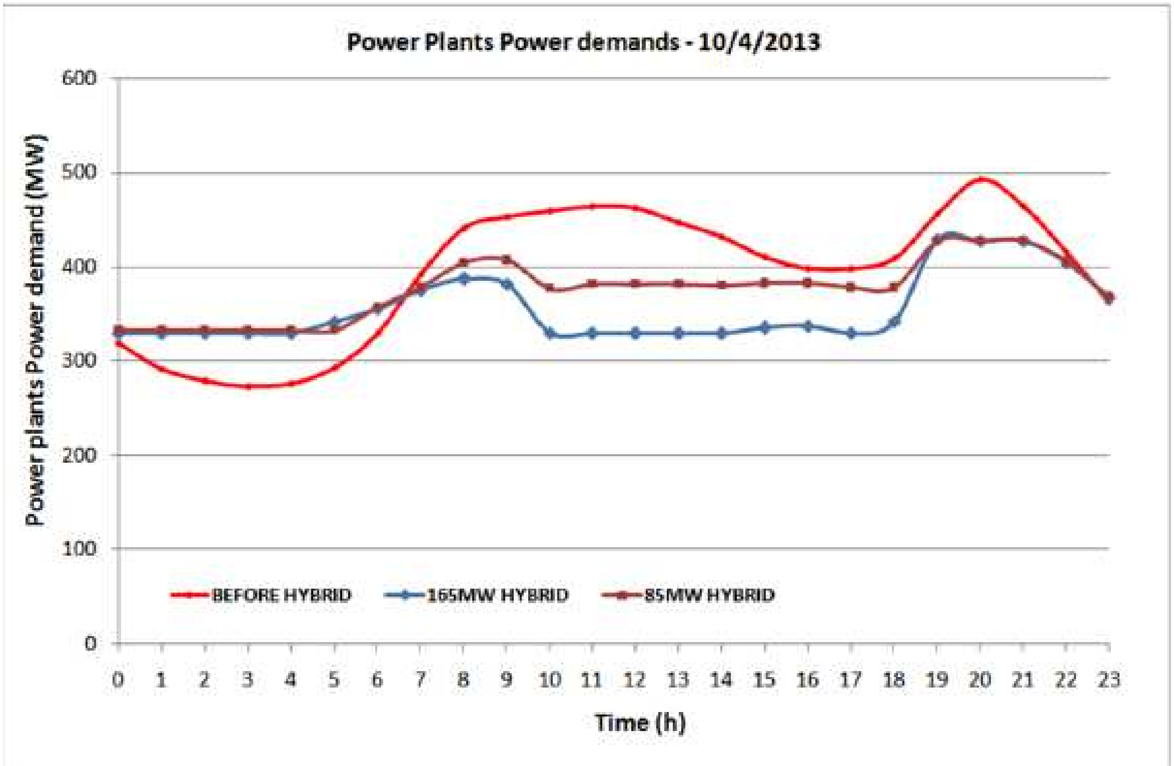

Figure 10. Existing (red) and achieved daily operation of the conventional power plants, during a low demand day, after implementation of scenarios A (blue) & B (brown) [33].

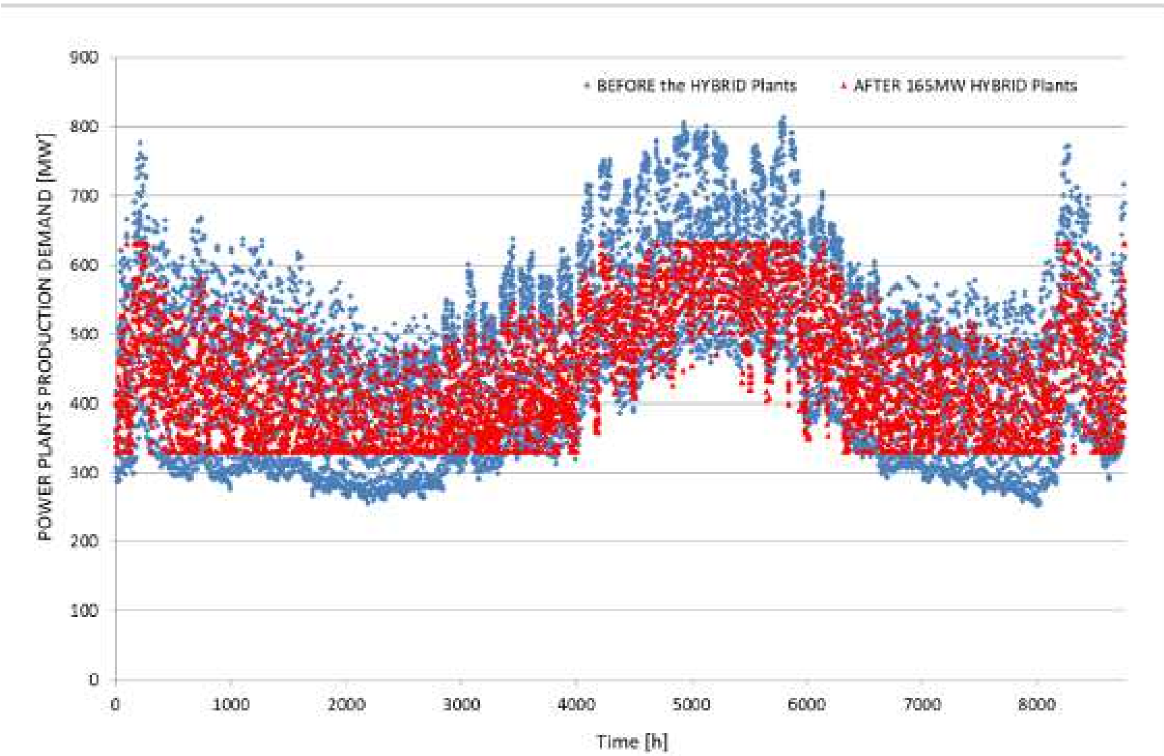

Figure 11. Existing (blue) and achieved (red) yearly operation of the conventional power plants after implementation of scenario A [33].

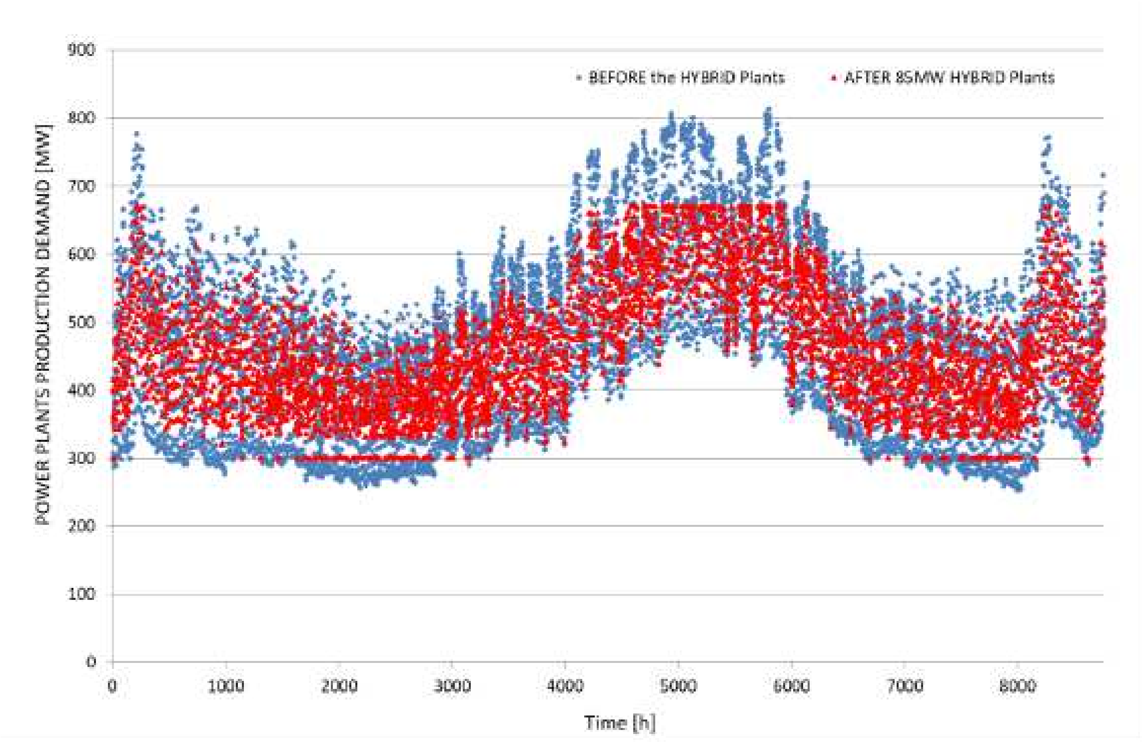

Figure 12. Existing (blue) and achieved (red) yearly operation of the conventional power plants after implementation of scenario B [33].

Table 4 shows that the proposed approach (scenarios A and B) could aid Cyprus to reach the targets for RES penetration [33].

Table 4. RES penetration before & after PV-PS system integration [33].

Scenario	RES Penetration (%)
Existing	7.0
B	13.0
A	17.1

The authors indicate that a PV-PS system could adopt multiple strategies to utilize more wind energy and reduce RES curtailment, including reducing minimum loads on must-run units, modifying units so that they can turn off daily (running units at lower load levels and incorporating demand response into reserves). The additional reservoir storage acquired will be used to reduce both balancing- and oversupply-related curtailments. The annual variation of power output of the existing power plants would be reduced from 560 MW to 300 and 370 MW for scenarios A and B, respectively. In conclusion, the authors emphasize that PV-PS systems could have significant benefits for the isolated Cyprus grid, where solar irradiation is high and grid stabilization is needed. However, a comprehensive cost analysis must be added in the future to provide a realistic picture of the actual potential of the system.

4.1.4 Technoeconomic Analysis of Pumped Storage in Cyprus

A technoeconomic study was conducted in 2013 to provide a comprehensive analysis on the integration of PS in Cyprus [16][3]. The study included the calculation of the unit

[3] Unfortunately more recent technoeconomic studies for Cyprus have not been conducted since then to provide more recent updated data.

cost of electricity under various scenarios. The simulation results suggest that under certain parameters the use of PS systems could be beneficial for the large-scale integration of RES. The analysis included three candidate PS plants (see Table 5), with capacities ranging from 130-200 MW, with the following assumptions [39]:

- The real prices correspond to 2010 values (base year).
- The assumed fuel cost projections correspond to the following prices for gasoil, LNG and HFO, respectively: 12.1, 7.2 and 7.2 €/MMBTU.
- The assessment period was 2010-2020.

Table 5. The three candidate PS plants.

PS technology	130 MW	200 MW	200 MW
Year of operation	2021	2021	2021
Nominal capacity (MWe)	130	200	200
Generation capacity (MWe)	132.2	203.2	203.2
Pumping capacity (MWe)	127.2	186.4	189.6
Overall efficiency (%)	77	77	77
Full load operation for electricity production (h)	8	8	8
Capital cost (€/kWe) (real price)	1185	760	754
O&M cost (€/kW-month)	0.915	0.646	0.613

The following dams (proposed power plant capacity) could be commissioned in the Cyprus power generation system after 2021: (a) Kourris (130 MWe), (b) Kannaviou (200 MWe), and (c) Arminou (200 MWe). The study assumed a fixed, overall plant efficiency at 77%, for continuous full-load turbine operation of 8 hours.

In order to investigate the technical and economic viability of PS systems in Cyprus, a number of scenarios were included in the study. Specifically, the following business-as-usual (BAU) and increased RES-E scenarios have been considered:

- **Scenario BAU**: RES-E energy share to reach 16% of total expected electricity demand in 2020, and then the RES-E capacity to remain constant up to the end of the assessment period.
- **Scenario BAU, PS 130 MW**: integration with BAU scenario with a PS plant of 130 MWe (Kourris) after 2021 and the remaining capacity to be satisfied by natural gas combined cycle (NGCC) (220 MWe capacity each).
- **Scenario BAU, PS 200 MW**: integration with BAU scenario with a PS plant of 200 MWe (Kannaviou) after 2021 and the remaining capacity to be satisfied by NGCC (220 MWe capacity each).
- **Scenario BAU, PS 330 MW**: integration with BAU scenario with two PS plants, one of 130 MWe (Kourris) and one of 200 MWe (Kannaviou) after 2021 and the remaining capacity to be satisfied by NGCC (220 MWe capacity each).
- **Scenario BAU, PS 530 MW**: integration with BAU scenario with three PS plants, one of 130 MWe (Kourris), one of 200 MWe (Kannaviou) and one of 200 MWe (Arminou) after 2021 and the remaining capacity to be satisfied by NGCC (220 MWe capacity each).
- **Scenario increased RES-E**: RES-E energy share to increase from 16% in 2020 to 50% in 2031 of total expected electricity demand. Expansion of the power generation system with RES-E technologies and the remaining capacity to be satisfied by NGCC (220 MWe capacity each).
- **Scenario increased RES-E, PHES 130 MW**: integration with the increased RES-E scenario with a PS plant of 130 MWe (Kourris) after 2021 and the remaining capacity to be satisfied by NGCC (220 MWe capacity each).
- **Scenario increased RES-E, PHES 200 MW**: integration with the increased RES-E scenario with a PS plant of 200 MWe (Kannaviou) after 2021 and the

remaining capacity to be satisfied by NGCC (220 MWe capacity each).

- **Scenario increased RES-E, PHES 330 MW**: integration with the increased RES-E scenario with two PS plants, one of 130 MWe (Kourris) and one of 200 MWe (Kannaviou) after 2021 and the remaining capacity to be satisfied by NGCC (220 MWe capacity each).
- **Scenario increased RES-E, PHES 530 MW**: integration with the increased RES-E scenario with three PS plants, one of 130 MWe (Kourris), one of 200 MWe (Kannaviou) and one of 200 MWe (Arminou) after 2021 and the remaining capacity to be satisfied by NGCC (220 MWe capacity each).

Figure 13 shows the power generation system natural gas (NG) consumption results for the following NG cases: (a) price base value, (b) 20% price decrease, and (c) 40% price decrease. Figure 14 shows the power generation system NG consumption results for the NG 20% price increase case. Figure 15 shows the Annual CO_2 emissions results for the following NG cases: (a) price base value, (b) 20% price decrease, and (c) 40% price decrease. Figure 16 shows the annual CO_2 emissions results for the NG 20% price increase case.

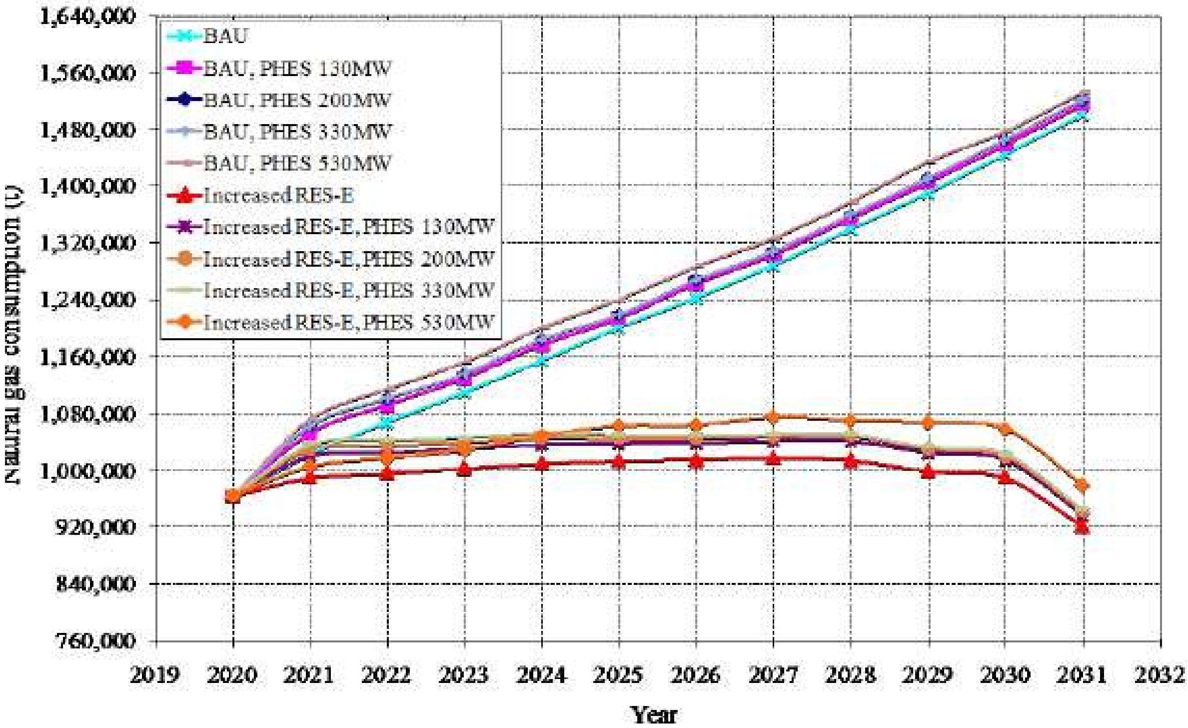

Figure 13. Power generation system natural gas consumption results for natural gas price base case, natural gas 20% price decrease case and natural gas 40% price decrease case [16].

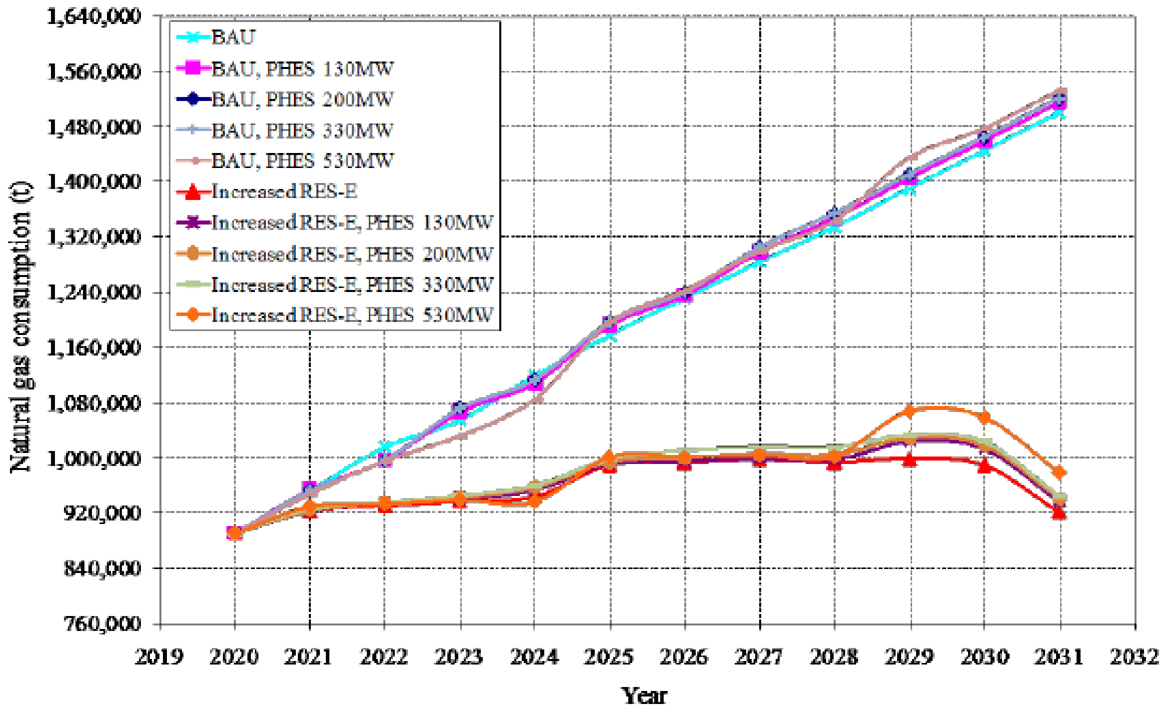

Figure 14. Power generation system natural gas consumption results for the natural gas 20% price increase case [16].

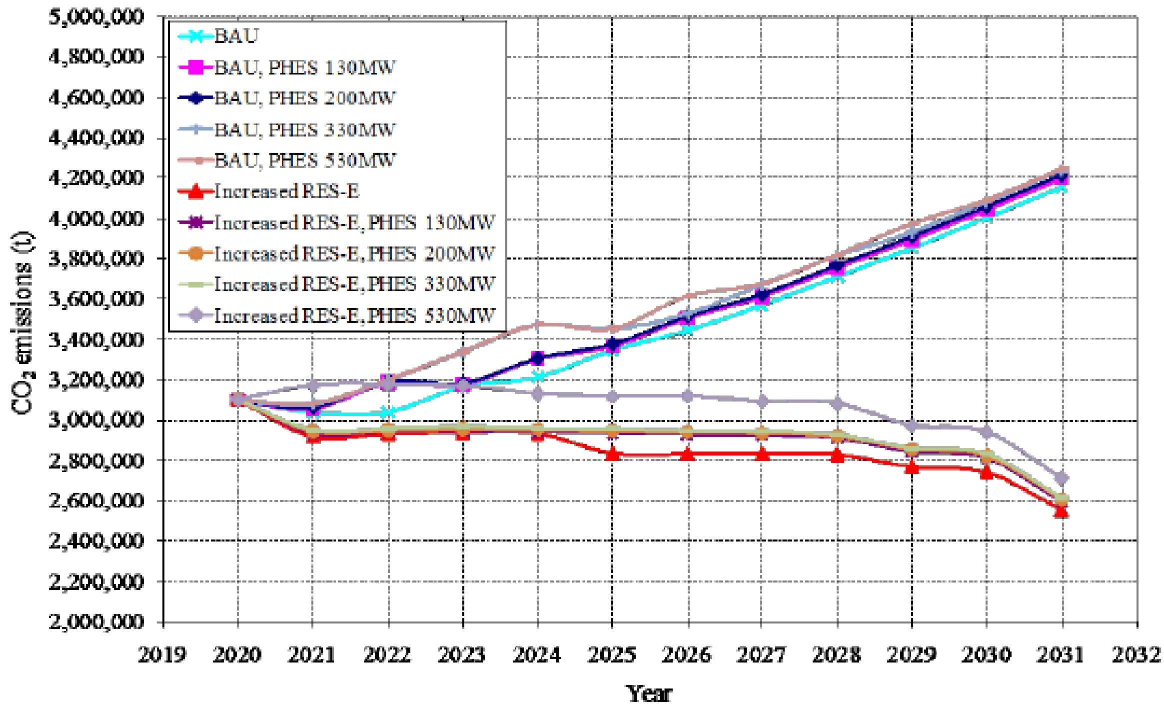

Figure 15. Annual CO_2 emissions results for natural gas price base case, natural gas 20% price decrease case and natural gas 40% price decrease case [16].

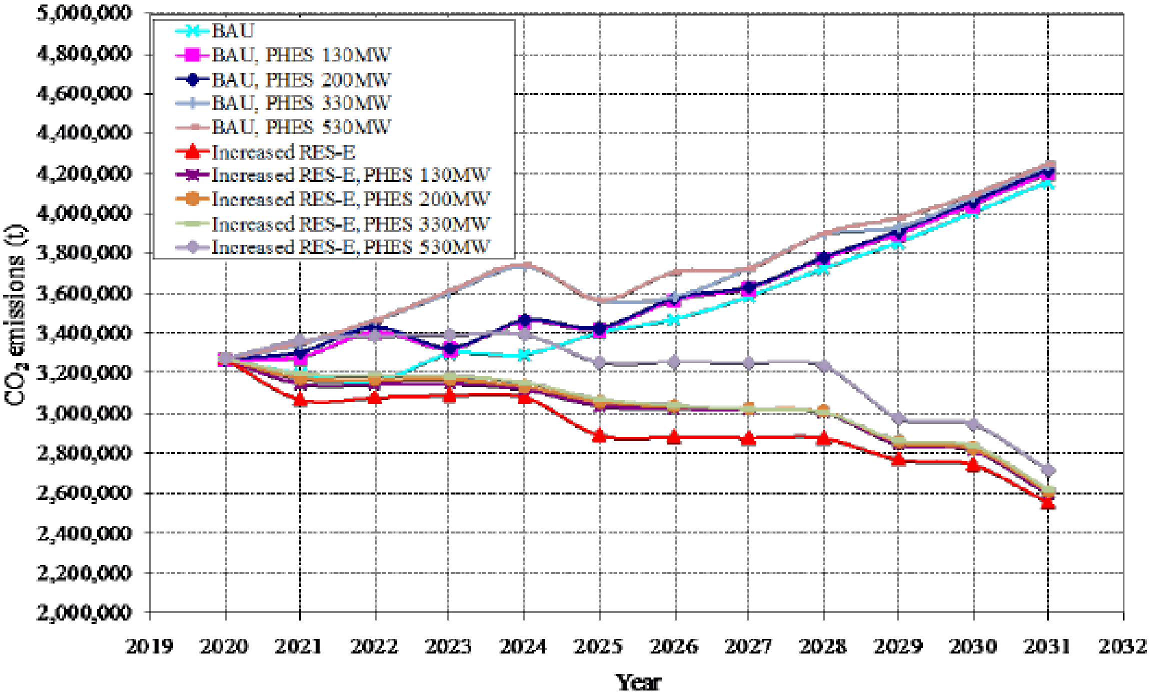

Figure 16. Annual CO_2 emissions results for the natural gas 20% price increase case [16].

Figure 17 shows the differential electricity unit cost increase from the BAU scenario for the base case NG price projections. Figure 18 shows the differential electricity unit cost increase from the BAU scenario for the NG 20% price decrease case. Figure 19 shows the differential electricity unit cost increase from the BAU scenario for the NG 40% price decrease case. Figure 20 shows the differential electricity unit cost increase from the BAU scenario for the NG 20% price increase case. Figure 21 shows the electricity unit cost overall results for all four different cases of NG projected price.

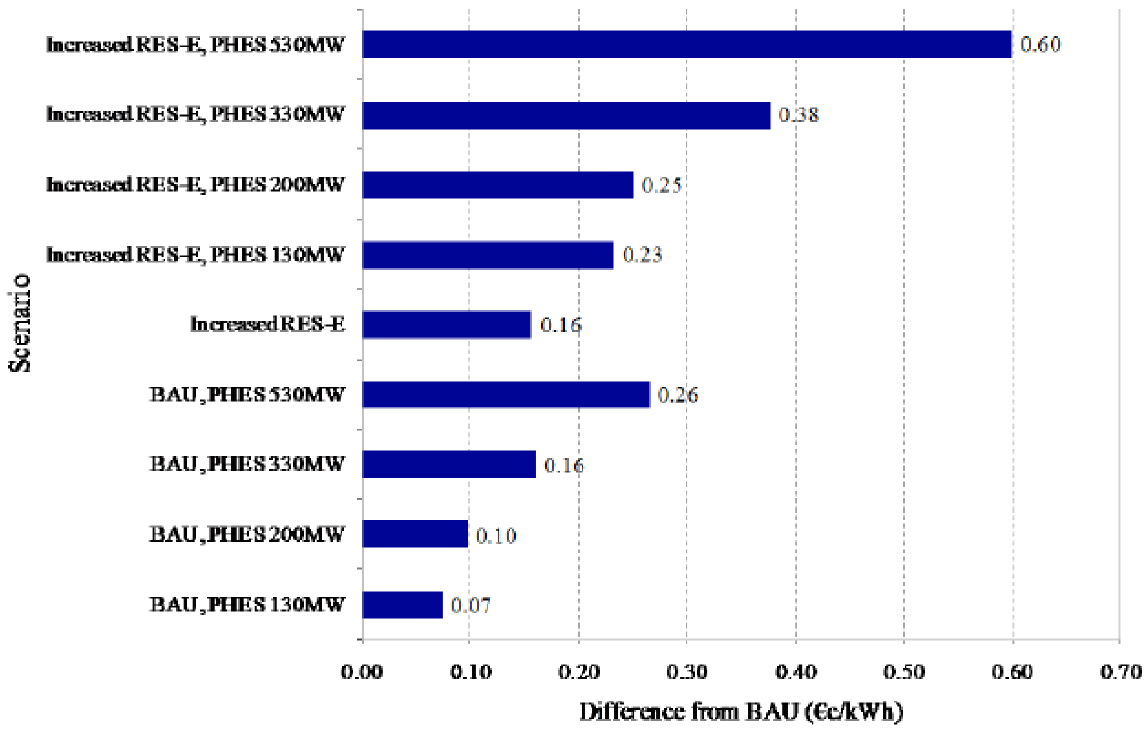

Figure 17. Differential electricity unit cost increase from the BAU scenario for the base case natural gas price projections [16].

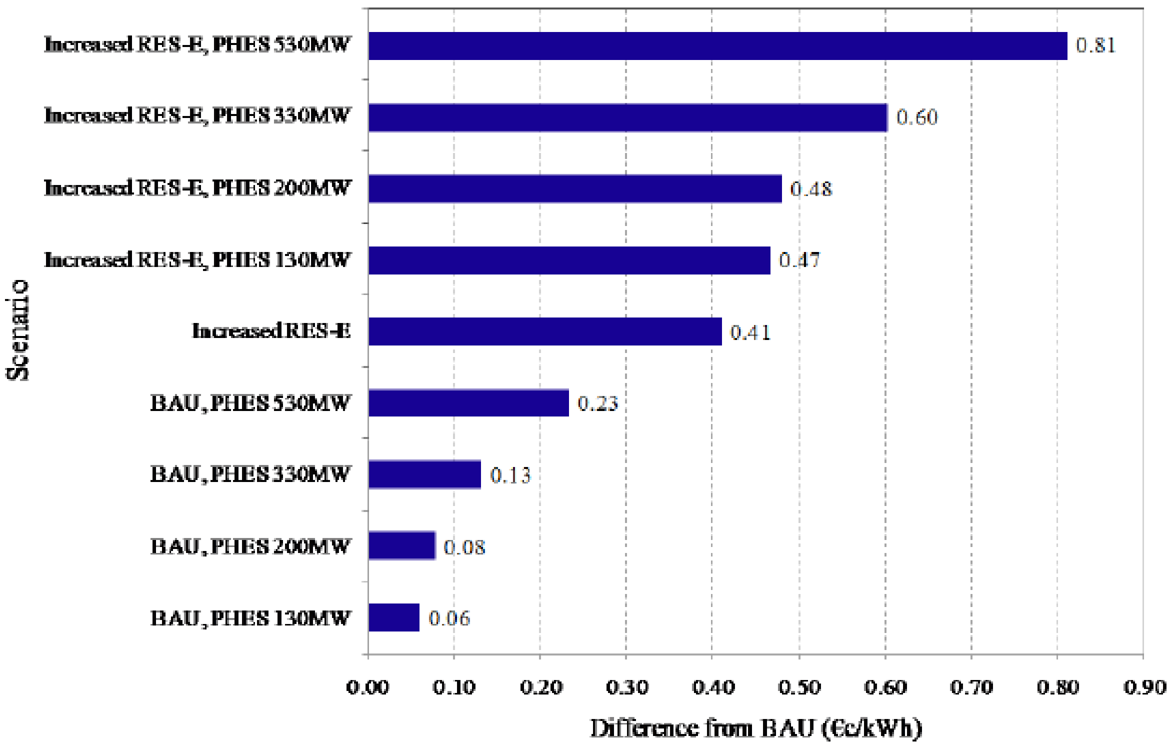

Figure 18. Differential electricity unit cost increase from the BAU scenario for the natural gas 20% price decrease case [16].

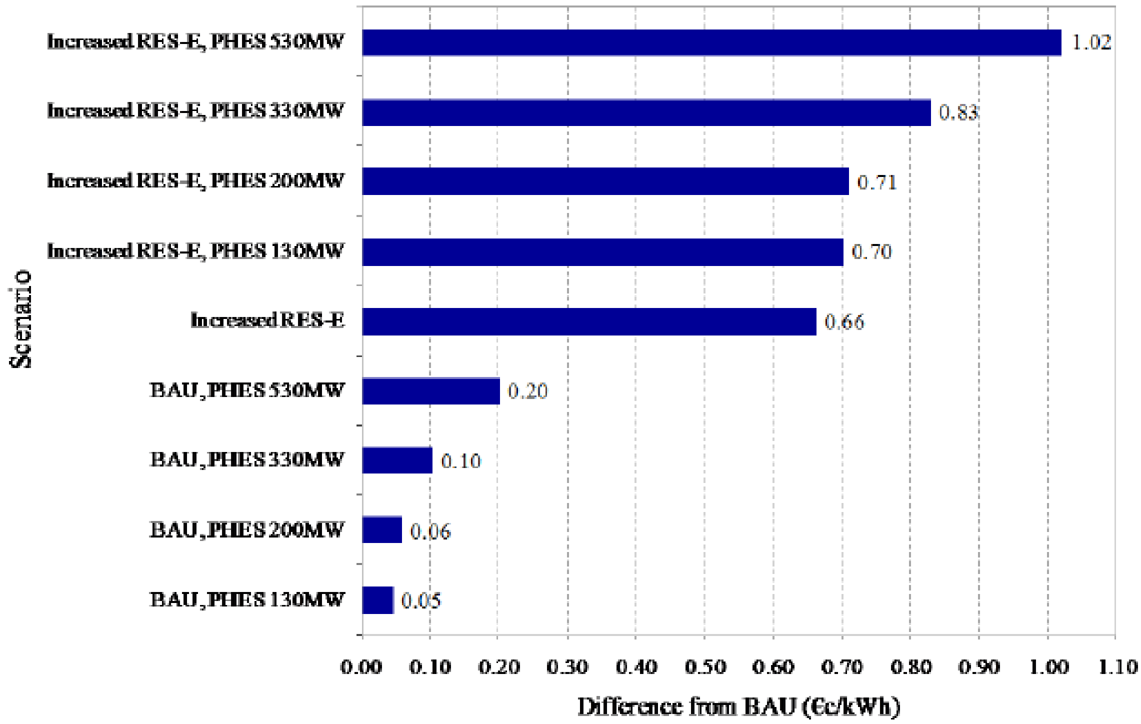

Figure 19. Differential electricity unit cost increase from the BAU scenario for the natural gas 40% price decrease case [16].

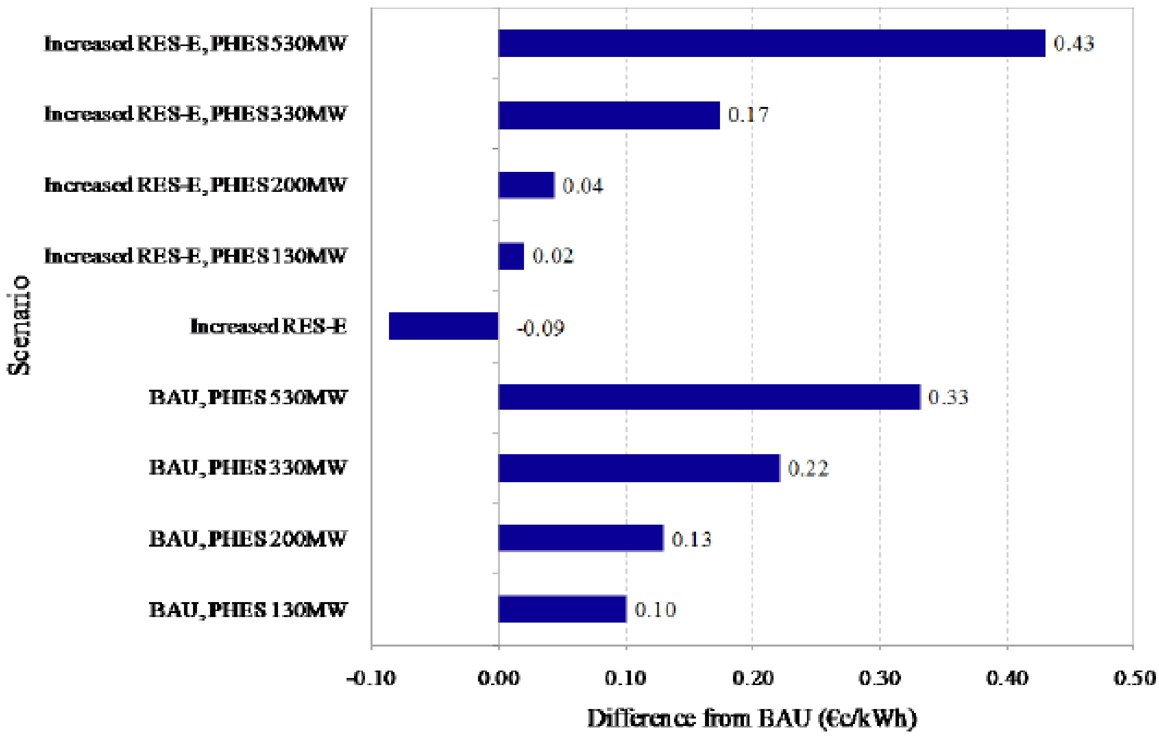

Figure 20. Differential electricity unit cost increase from the BAU scenario for the natural gas 20% price increase case [16].

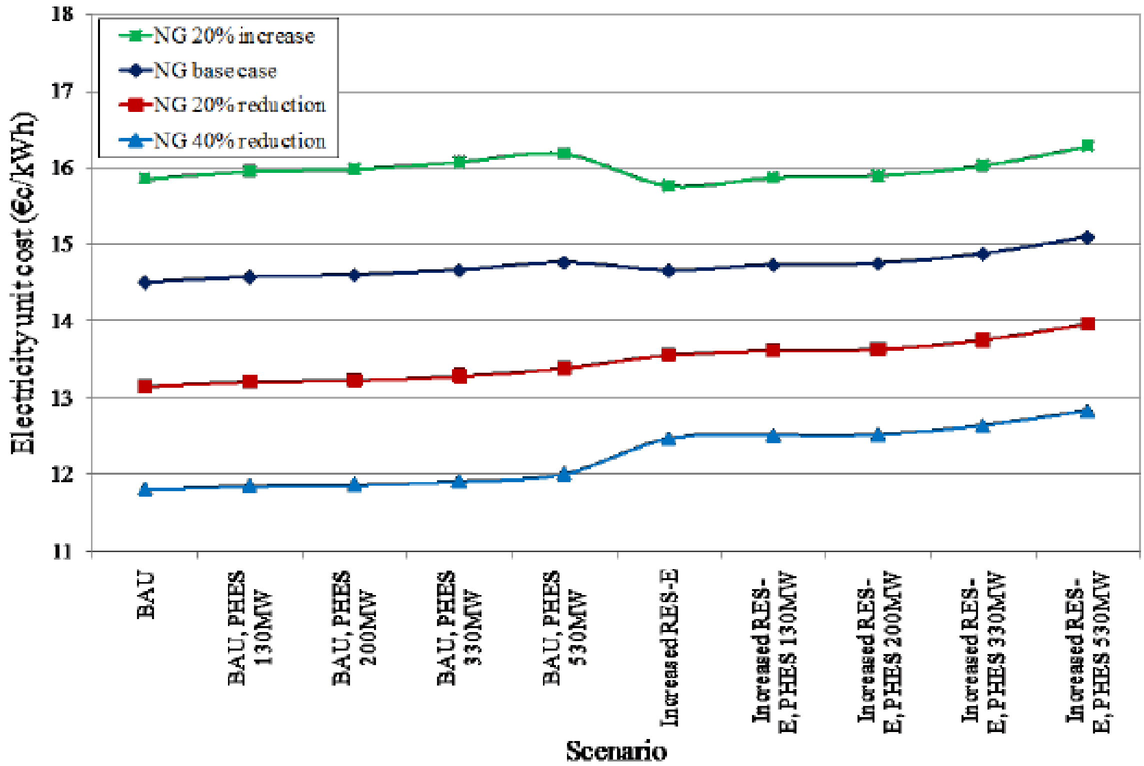

Figure 21. Electricity unit cost overall results for all four different cases of natural gas projected price [16].

The analysis in this study does not consider possible features of the PS system which are beneficial to system operation, flexibility, reduced start-ups, shutdowns of conventional units and capability to provide ancillary services [16]. The author also mentions that the small increase in CO_2 emissions and electricity unit cost could be justified if the above had been included.

In conclusion, the analysis in the study showed the following trends [16]:

- For the BAU scenarios with or without PS for all cases of the NG projected price, the electricity unit cost difference increased: (i) as the PS installed capacity increased, and (ii) as the NG projected price increased.
- For the increased RES-E scenarios with or without PS, the difference in electricity unit cost increased, as the PS capacity increased.
- As the NG projected price was reduced, the difference in the electricity unit cost compared to the BAU scenario increased. In this case a significant reduction of new NGCC plants occurs, causing a larger difference in the electricity unit cost for the lower NG projected price.
- For the NG 20% price increase case, the increased RES-E scenario without PS was found to have an electricity unit cost lower than that of the BAU scenario.

The study provides a starting point for the potential in terms of a theoretical maximum capacity of future PS systems in Cyprus. However the study has not included answers for a number of significant issues, such as:

1. Requirements for further infrastructure necessary to develop a complete and realistic PS system. Although it is not considered, one could assume that the selected dams will be used as lower reservoirs. In this case, the additional cost of building upper reservoirs must be specified and included in the costing. Also the cost of tubing (depending on the length between the reservoirs) must be specified.

2. It must be determined how the PS system will be powered. Assumingly through RES excess power from the network, or through purpose-build PV parks or wind turbines built near the area. In this case the additional cost must be included in the calculations.
3. Water availability vs. water required for the PS system is not specified. The selected dams are the two largest in Cyprus. However, on an annual basis, they only have an average water availability of 10-20%. Therefore it should be specified whether additional water must be imported, e.g. through desalination plants. In this case the additional cost of the desalination plants should be included in the economic calculations.

4.2 Agriculture Irrigation Needs and Power Storage: Possible Synergies

An additional advantage of a PS system is the possibility of using the water stored in the reservoirs for consumption or irrigation purposes, and for the protection against fires. Also, PS systems could potentially become an effective measure against climate change, either by increasing the stability of the electric grid, or by incorporating a desalination plant for clean-water production [8].

PS is a proven simple and cost effective energy storage method, provided suitable geographical characteristics and water availability are present [40]. It can be used to provide water for irrigation for agricultural purposes. It can also provide energy saves, since it can be used as an alternative to typical pumping units that are used to draw well water from 100-500 m deep aquifers up to ground level.

4.2.1 Resource Potential considering Precipitation Levels in the Future

Given the scarcity of water precipitation levels (currently and in the near future), PS systems could provide a solution if they are coupled to RES and desalination plants. RES (primarily PV units) provide the potential for a cheap powering option for the PS plants, while desalination plants can provide water for the reservoirs, as needed.

4.2.2 Water Loss in each Pump Cycle

The impact of water evaporation in the dams of Cyprus is estimated at an annual average value of 10-15%. This element is difficult to evaluate, and presents significant differences from one country to another [41]. Water loss in each pump cycle becomes critical only if the dam used as a reservoir will be used at its full capacity. Therefore water loss could be a critical factor for smaller reservoirs, because less water is available for cycling.

4.2.3 Water Management Constraints

The design of almost every PS system is highly dependent on the site characteristics. Apart from sufficient water availability, the topography and geology of the area must be favourable for the development of the PS system [15]. Additionally it must be noted that water is considered as a supply-dependent energy carrier [42].

More specific and comprehensive studies must be conducted for Cyprus, which are necessary to include critical water management constraints, such as an annual profile of energy inflows and outflow constrains. These values can only be estimated through studies on specific PS systems, with given power input and output capacities, and in relation to the characteristics of the reservoirs (e.g. water availability, height difference and distance between upper and lower reservoirs) in an hourly segment load profile for a whole year (i.e. 8760 time segments).

4.2.4 Seawater-based Systems

Katsaprakis et al. investigated the possibility of using seawater in PS systems in the Greek islands of Kasos and Crete [43]. The authors focused on certain issues that arise from using seawater and how these problems can be addressed. Although the obvious benefit of having water availability irrespective of weather conditions (i.e. rainfall), the use of seawater has some additional requirements. These include considerations for the sealing of the reservoir, special materials for the construction of the penstock, selection of hydrodynamic models, positioning of the pump station and the HP plant and seawater suction methods. Since seawater can be pumped directly from the sea, a lower reservoir is not needed, which partly compensates the higher costs arising from the use of corrosion-resistant materials for certain components.

However in the case of Cyprus, the existing water dams have been purposely built for fresh water storage, and therefore it is not expected that existing dams could be used to store salt water. Therefore new reservoirs (for the role of upper reservoirs) would be required to carry seawater. Again, a comprehensive technoeconomic study would need to be carried out to investigate the potential of seawater-based PS systems. The study will also need to investigate if certain locations in Cyprus have the necessary geological conditions for such PS system, with specific attention in dealing with salt water and the protection of marine life [44].

4.3 Economic Analysis

4.3.1 Existing Infrastructure

The existing infrastructure includes the existing dams, which will be used as lower and/or upper reservoirs.

4.3.2 Required Investments

Required investments in term of capital cost must include the following equipment:

1. **Hydro-turbine and pump units,** operating at turbine and pump modes, respectively. The most appropriate types for Cyprus are Pelton and Francis technologies.
2. **Tubing network**, to connect the lower and upper reservoirs.

Additionally, depending on the characteristics of a particular PS system, the following optional equipment could be required:

1. **New reservoirs**. In some cases the proximity of the existing dams may not be practical for the deployment of a PS system, requiring the construction of a new reservoir.
2. **Desalination plant**, to provide additional water to the PS system. It was recently reported that the cost of produced desalinated water in Cyprus is 0.75 €/m^3 (0.85 USD/m^3)[4] [45].

In addition to capital cost, the cost analysis must include operating and maintenance costs. It will also be necessary to estimate, within reasonable accuracy, the cost of the system. Lifetime may vary for the different components of the system, i.e. lifetime of hydro-turbine vs. lifetime of tubes, etc. Other factors could also include the possibility of increasing the capacity of an initial system (e.g. 1 MW to 2 MW, etc.).

[4] Comparatively, the cost of fresh water in Cyprus is 0.09-0.11 €/m^3 (0.10-0.12 USD/m^3) [45].

4.3.3 Calculations: Rough Cost Estimates

Cost data for the economic analysis have been collected from the literature, and are tabulated in Table 6. The following assumptions have been made [10]:

- Variable cost=0 €/MWh
- Lifetime=80 years
- Efficiency=0.75 (or 75%)
- Capital cost per energy storage N/A €/kWh

Table 6. Cost input data for the economic analysis of the PS system.

P_{ps}	Power output of PS system at design	130-530 MW [16]
C_{inv}	Investment[1,2]	2000 €/kW [10]
c_{om}	Fixed O&M cost	20 €/kW/year [10]

1 The installed facilities are not expanded in this model and are considered to be amortized [10].

2 This value includes only the base equipment (i.e. hydro-turbine and tubing network).

The total investment cost for a 200 MW PS system is calculated as follows:
$C_{ps}= C_{inv} * P_{ps}$ =2000 €/kW * 200E3 kW = 400 million €

The total annual cost for operation and maintenance for a 200 MW PS system is calculated as follows:
$C_{om}= c_{om} * P_{ps}$ =20 €/kW/year * 200E3 kW = 4 million €/year

The total investment cost and the total annual cost for operation and maintenance for the various capacities of PS systems suggested by [16] are tabulated in Table 7.

Table 7. Total investment cost and total annual cost for operation and maintenance for various capacities of PS systems.

P_{ps} (in MW)	C_{ps} (in million €)	C_{om} (in million €/year)
130	260	2.6
200	400	4.0
330	660	6.6
530	1060	10.6

5 Conclusions

In this report a critical review on pumped hydro storage has been conducted. The recent progress on pumped storage technology has been investigated focusing on the technologies applicable for Cyprus. The current regulatory framework of the technology for Cyprus, along with regulatory, market and technical barriers has been analysed in detail. A review of recent studies on pumped storage integration for Cyprus has been conducted. The recent studies included technoeconomic studies and integration of renewable energy sources to future pumped storage systems. Finally a rough economic estimation (based on the most recent available values from literature data) has been conducted.

5.1 Future Work

A preliminary step-by-step proposal for the development of pumped storage systems in Cyprus could include the following critical elements:

1. Conduct a technoeconomic feasibility study using available hourly data of the water availability in the dams (reservoirs), head (elevation) differences, load profile(s), etc. These will allow an initial rough estimation of PS system capacities.
2. The cost analysis must calculate the total system lifecycle cost with the inclusion of the following:
    a. Calculation of capital cost, using actual values of every component that will be used in the development of a particular PS system (incl. construction costs).
    b. Inclusion of maintenance and other occurring costs during system operation throughout its lifetime.
    c. Every component/subsystem lifetime must be specified.
3. Estimation of the possible economic benefits in comparison with conventional systems in terms of unit cost of electricity, fossil fuel savings, etc.
4. The expected decrease of carbon dioxide emissions from the adoption of PS systems must be quantified to investigate whether the PS system(s) can have a significant impact in emission reduction (in comparison to conventional technology).
5. Water availability for proposed systems, with a clear reference on the water scarcity in Cyprus. Methods to boost water availability must be considered in both economic and technical terms (e.g. water desalination).
6. Conduct simulation studies, which will include modelling and optimisation of various proposed PS system(s) in Cyprus. Such simulations will allow:
    a. Use of different topologies with inclusion of various areas in Cyprus where the system(s) could be developed, taking into account the available dams and environmental barriers (e.g. *Natura 2000* protected areas).
    b. Consideration of different capacities.
    c. Consideration of different turbine-pump technologies (e.g. Pelton, Francis, etc.).
    d. Consideration of different tubing network options, in terms of type, materials, etc.
    e. The optimisation strategy could follow a genetic algorithm approach with objective functions such as: minimisation of lifecycle cost, minimisation of carbon emissions, minimisation of fossil fuel consumption in power stations, maximisation of RES penetration in the grid, etc.
7. Development of a pilot system (e.g. 5 MW) to gain significant experiences and crucial data for possible future development of larger-scale PS plants (through scale-up estimations).
8. Revision of the feasibility study based on the data generated from the

simulation studies and the pilot system.

9. In case of positive results from the final feasibility study, the construction of the PS plants could be initiated, using a long-term development plan in the selected locations. This should include measures to scale-up further and optimize the development of future PS systems.

Also the following provisions must be taken into account in future studies:

1. To minimize capital cost and to have a realistic development of future PS systems, it will be desirable to use two existing dams for the roles of upper and lower reservoirs. This practice will eliminate the need for the construction of additional reservoirs. However, the two selected reservoirs must be close to each other, to minimize the length (and thereby the cost and losses) of the tubing network connecting the two reservoirs.
2. The total PS system (incl. upper and lower reservoirs, hydro-turbine, pumps, auxiliaries, and tubing network) must not coincide with *Natura 2000* protected areas or other restricted areas (e.g. populated or developed areas).
3. In addition to reservoir and system power capacity, all available dams (i.e. candidate upper and lower reservoirs) must be analysed in terms of actual water availability and elevation difference. This process will be crucial for the selection of appropriate hydro-turbines and pumps for the PS systems.

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Abbreviations

DSO	Distribution System Operator
HFO	Heavy Fuel Oil
HP	Hydropower
LNG	Liquefied Natural Gas
MCM	Million Cubic Metres
PS	Pumped Storage
PV	Photovoltaic
RE	Renewable Energy
RES	Renewable Energy Sources
T&D	Transmission and Distribution
TSO	Transmission System Operator
TSOC	Transmission System Operator - Cyprus