International Journal of Innovative Engineering Applications

Journal homepage: https://dergipark.org.tr/ijiea

AN EVALUATION OF PUMPED HYDROELECTRIC STORAGE SYSTEMS

Ayşenur Oymak[*1], *Mehmet Rıda Tür*[1]

[1]*Department of Electrical Electronics Engineering, Batman University 72100, Batman, Turkey*

Abstract

Review paper

In smart grids, storage systems are needed to increase the number of renewable energy sources connected to distribution systems and to ensure the continuity of energy. By supporting the system elements, energy storage can provide many services such as energy time shifting, interruption control, ensuring continuity in transmission and power quality improvements. In smart grid applications, difficulties are encountered in energy storage due to various problems such as charge/discharge, safety, size and cost. For this reason, energy storage systems should be developed for energy capacity, control and protection that can increase storage performance. Since there are interruptions and waves in renewable energy sources such as wind and solar, batteries are used for storage. In order to expand the use of clean energy and to ensure energy continuity, mechanical storage methods in large powerful systems have been emphasized. Storage studies have been carried out to increase efficiency, provide flexibility in electrical systems, reduce costs and improve storage time, and reduce power fluctuations. In this study, pumped hydroelectric storage plants, which is one of the storage methods, were examined. Advantages and disadvantages of pumped storage hydroelectric system are mentioned and hybrid pumped hydro storage is explained. Its economic contribution is also briefly mentioned. This storage method of pumped hydroelectric storage (PHES) has also been found to be hybrid systems that can be connected to variable speed turbines, groundwater, seawater and renewable energies to increase efficiency, reduce costs and save space. Among these systems, it has been observed that the system in which solar and wind are used as a hybrid is also advantageous in providing high profitability in the energy market. Thanks to its integration with the sun and wind, carbon emissions are reduced.

Keywords: *Energy storage, pumped hydroelectric storage, hybrid pumped hydro storage*.

1 Introduction

Transitions from systems based on carbon-intensive fossil fuels that harm the environment to lower-carbon energy or renewable energy sources are becoming the policies of countries [1]. Commonly used renewable energy sources are solar, wind, hydroelectric, geothermal, etc. can be sorted. There are hourly, daily, monthly and annual fluctuations in renewable and clean energy sources. For example, wind power is the speed of the wind; ocean energy to changes in tide level by waves and currents; solar energy to solar radiation intensity; in hydroelectric power plants, it also depends on the flow rate of the stream [2]. Therefore, energy storage systems are required to provide quality power and to efficiently hold solar and wind power in grids. Global electricity production of about 200,000 TWh per year will be needed when developing countries catch up with the energy consumption per capita in today's developed economies. Assuming electricity is generated by a combination of solar (60%), wind (30%) and other methods (10%), a total of 81 TW of solar energy and 17 TW of wind energy will be required. To eliminate fossil fuels by 2050, the distribution rates of solar and wind would need to increase by a factor of 20. Assuming that one day's energy storage is required with sufficient storage power capacity to be delivered over 24 hours, then approximately 500 TWh and 20 TW of storage energy and power will be necessary [3]. This shows the need for studies on storage. Intelligent energy storage systems are used to provide uninterrupted, flexible and quality power. The development of energy storage technologies is of great importance in solving power quality problems such as voltage drops and interruptions, both at the system and equipment level. However, energy storage; It also has benefits such as increasing system efficiency, enabling the integration of renewable energy sources, increasing grid stability and reliability [4, 5].

Energy storage systems, which have many methods, have a wide area today. Hydroelectric storage technology, which is more useful and has a larger storage area than energy storage systems, is a system with a large energy storage area [6]. It is preferred in high energy demands. Hydroelectric reservoirs can use limited sources of energy and storage energy produced from other renewable sources to increase the applicability of the electrical system. Looking at the studies done; Ali et al. in their study analyzed the techno-economic and socio-environmental benefits and barriers to pumped hydro applications. As a result of their research, they have seen that the interest in the closed circuit system has increased due to its water

* Corresponding author.

E-mail address: aysenur.oymak@batman.edu.tr (A. Oymak)

Received 18 February 2022; Received in revised form 14 May 2022; Accepted 31 August 2022

Doi: https://doi.org/10.46460/ijiea.1074300

supply, safety and low environmental impact [7]. Nehirr et al., in their studies, they examined hybrid renewable energy generation systems that ensure energy continuity. Assessment were made on unit sizing, control and energy management of hybrid systems [8]. Aktas et al., applied tests according to the load situation and power profile of the sun at the hybrid energy storage point by using a smart energy management algorithm for hybrid energy storage [9]. Faisal et al. studied and analyzed energy management, energy storage methods to increase continuous energy supply time [10]. Vasudevan et al., explained the use of pumped hydroelectric storage (PHES) in renewable energies in their study and focused on the classification and structure of the control system [11]. Mousavi et al., a real-time energy management strategy has been proposed for pumped hydro storage systems in farmhouses to manage excess renewable energy. It considers the state of the micro grid to efficiently adjust the pump power and turbine flow rate. It has been tested in fuzzy logic and artificial neural network to solve the prediction error problem. As a result, they observed that artificial neural networks reduce the electricity cost better [12].

Tian et al., in order to ensure the participation of these storages in the market, a risk method approach called downside risk constraints (DRC) was used in the study. Electricity market price uncertainties and uncertainty parameters are used together with stochastic programming. According to the results obtained, using the proposed downside risk constraints, pumped hydro storage (PHS) operators can experience zero risk conditions, reducing their profits by 33%, while the risk in profit is reduced by 100% against the risk-free strategy [13]. Gundu and Simon in their study, the linear integer program was preferred in order to plan the purchase of electrical energy at the minimum price according to the excess and low power of the houses in the case of energy storage. The performance of the new technique used has been validated in 12 bus distribution systems of 100 MVA. As a result, it is concluded that it is applicable for real-time smart grid environment [14]. Al-Masri et al., the effect of different photovoltaic models was investigated for the pumped hydro storage system. Two-diode (TD), single-diode (SD) and ideal single-diode (ISD) solar models were evaluated in terms of solar array size, reliability and ecological effects. As a result of the evaluations, they observed that the TD model was reliable with a reliability index of 98.558% [15].

The most important service of pumped hydro storage is its ability to function as storage, generate revenue by pumping water at cheap prices during off-peak periods and then sell it at higher rates during peak hours, and support intermittent renewable energy sources.

In this study, pumped hydroelectric storage (PHES), one of the smart energy storage systems, is emphasized. Here, PHES systems are explained and which of these systems is efficient has been evaluated. A brief analysis has also been made from an economic point of view.

2 Energy Storage Methods

Energy balance is very important in power systems, this balance brings with it the necessity of keeping the frequency 50 Hz. An energy storage system would enable smart grid concepts, one of the future-promoting technologies. Energy storage systems, which eliminate fluctuations associated with energy production, can facilitate the integration of renewable energy systems. The energy storage system can support system reliability and additionally offer some ancillary facilities such as load tracking. Moreover, energy storage systems can contribute to the stabilization of peak loads and in this way reduce generator failures. Energy storage is a necessary technology that uses stored electrical energy when there is peak load demand. The capacity factor of the base generation units can be increased in this way, it is also an effective factor for the use of stored energy at a low price [16]. Energy storage systems seem to be the key component in adapting to the diversity of new technologies, changing consumer habits and the changing mechanism of electricity generation and changing distribution system over the last decade. It can also provide various improvements in grid performance such as reliability, fast response and load matching capacity.

Energy storage has benefits such as increasing grid stability and security. Energy storage systems are an effective method for reducing fluctuations in power quality. The main technologies developed for energy storage are; electrical, mechanical, chemical and thermal storage technologies [17]. Energy storage processes are examined in three cases. The state of charge of electrical energy is in the form of storage and return of electrical energy to the system. In line with these stages, the total efficiency equation is given below.

$$\eta_{TOTAL} = \frac{E_{DEL}}{E_{GEN}} = \frac{E_{GEN}-E_{LOS}}{E_{GEN}} = \frac{E_{GEN}-E_{LOSC}-E_{LOSS}-E_{LOSD}}{E_{GEN}} \qquad (1)$$

$\eta_{TOTAL,}$ total energy storage efficiency; E_{DEL}, is the total electrical energy supplied to the system. E_{GEN} is the total generated energy. E_{LOS}, gives the total loss in storage; E_{LOSC}, is the total energy loss during charging; E_{LOSS}, is the total energy loss during storage ve E_{LOSD}, is the total loss at discharge [1].

The contribution of energy storage systems to smart grids is explicated as frequency control and meeting high power demands. Energy storage and conversion is ensured with batteries, compressed air, flywheels, thermal power, super capacitors, super conductors and fuel cells. Energy storage technologies can generally be examined under three headings: mechanical, electrochemical and electromagnetic storage.

Mechanical energy storage technologies include pumped water-based energy storage systems, compressed air energy storage systems and flywheels. Electrochemical energy storage technologies include battery and hydrogen-based energy storage systems. Electromagnetic energy storage technologies represent the group that includes super capacitors and super conducting magnetic energy storage systems. The energy storage system must be prepared for the form of application in from low power to large power and the type of generation that can be permanent, renewable. Among the energy storage systems, the methods that can be used in large-scale systems that have large capacity and can provide energy for a long time are pumped hydro storage and compressed air energy storage. The most efficient and economical method in large powerful systems is the pumped hydro storage system [18]. Figure 1 shows the discharge times of different energy storage systems at nominal power and their storage capacities in minutes, hours and days based on system power. As can be seen, pumped hydro energy storage systems from these systems provide storage at the level of MW and on a large scale. Since renewable energy sources cannot provide a continuous energy due to seasonal differences, long-term storage should be required. Table 1 shows a comparison of energy storage systems according to parameters. In figure 1, it is seen that the system that provides long-term storage among the energy storage systems is the pumped hydro storage systems [19].

Table 1. Comparison of energy storage methods according to different parameters.

Storage Tecnology	Power Capacity (MW)	Cycles number and time	Energy Density (Wh/L)	Efficiency %	Response time
Pumped water-based storage	100-1000	30-60 year	0.2-2	70-85	second-minute
Compressed air based storage	10-1000	20-40 year	2-6	40-75	second-minute
Hydrogen	0.01-1000	5-30 year	600 (200 bar)	25-45	second-minute
Li-ion Battery	0.01-100	1000-10000 day	200-400	85-98	10-20 ms
Flywheel	0.001-1	20000-100000 day	20-80	70-95	10-20 ms
Super capacitor	0.01-1	10000-100000 day	10-20	80-98	10-20 ms
Super conducting magnetic storage	0.1-10	20-30 year	0.2-5	90-97	100 ms

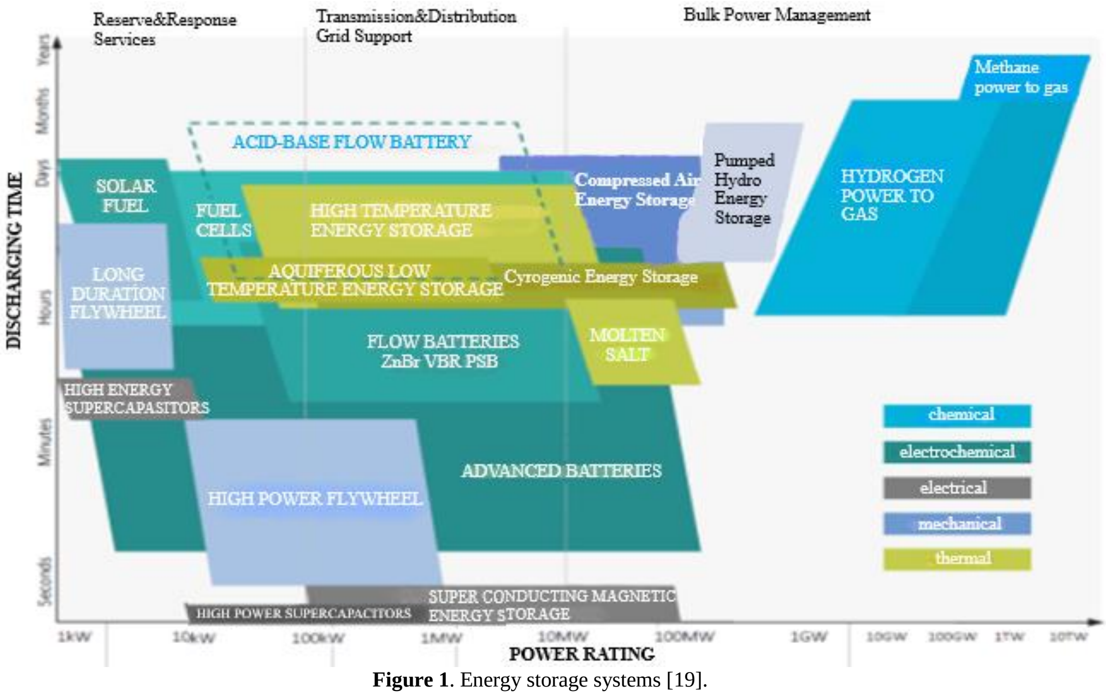

Figure 1. Energy storage systems [19].

3 Pumped Hydroelectrıc Storage System

Pumped storage hydroelectric power plants for the first time in the world emerged in the 1890s in the mountainous zones of Switzerland, Austria and Italy. In the early models, an independent pump wheel and turbine generator were used. Later, in line with the developments, the use of reversible pump turbines increased in pumped storage systems. [20].

Pumped hydroelectric storage power plant is a system that provides consumption when electricity demand is high, by storing electricity when electricity demand is low in facilities that are difficult to stop and costly, such as nuclear and thermal power plants. [21].

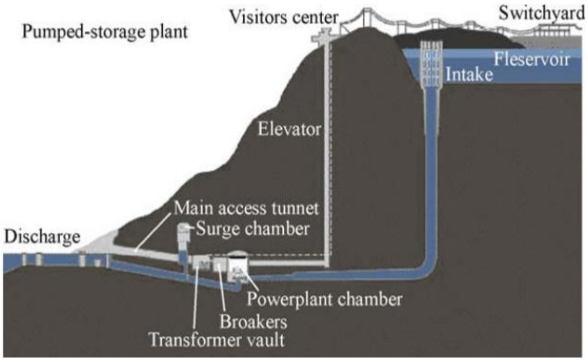

Figure 2. Pumped hydroelectric storage diagram [25].

In Figure 2, the circuit diagram of the pumped hydroelectric storage system is given. In pumped storage hydroelectric power plants, there are two reservoirs, the upper and lower reservoirs. River, natural lake, dam, sea or artificial pool are chosen as reservoirs. Pumped hydroelectric storage power plants provide storage as potential energy by pumping water from the lower reservoir to the upper reservoir [22]. When the energy demand is rise, electrical energy is produced by reducing the water accumulated in the upper reservoir to the lower reservoir [23]. When the energy demand is decrease, water is transported from the downer reservoir to the upper reservoir by pump. When the demand is low, when it needs to be operated at low capacities, the electrical energy to be obtained from discontinuous energy sources such as the sun and wind is stored using the electricity and the minimum load is pulled up. By producing electricity at times of high demand and expensive electricity, the maximum load is lowered and the ratio of minimum load to maximum load is increased. Thus, the amount of peak load is reduced, the base load value is increased, and the consumption in the peak load periods is shifted to the minimum consumption periods. In this way, the system load factor is increased and efficiency is increased [24]. It can be made a more useful system by integrating with renewable energy sources.

PHES is used for improving plant performance, regulating storage capacity, and power quality assurance. PHES has great power and energy, long service life, high efficiency and very small discharge losses [25]. PHES can adapt for the volatile situations of renewable resources by reacting quickly. A quantity of energy stored is rate to the height distinction between the two reservoirs and the volume of water stored. Thanks to small evaporations, the storage time of PHES can vary from hours to years. Considering evaporation losses, 71% to 85% of the electrical energy used to pump water into the upper reservoir can be recovered [26]. Pumped storage is classified three main categories:

Closed circuit: consists of two reservoirs, separated by a vertical distance, both of which are not connected to another body of water.

Most of the lands are far from the river when the terrain are examined for the installation of the pumped hydro storage system. Therefore, the non-river PHES system consists of a pair of artificial reservoirs placed several kilometers apart and connected by aqueducts, pipes and tunnels. Reservoirs can be custom built or existing reservoirs can be used [3, 27]. A combination of high head, low separation of reservoirs, and low dam wall volumes result in relatively low capital costs.

When the studies on pumped hydro storage are examined, the first studies started in 1982. Looking at the articles by years, the studies have intensified since 2016 and it has been examined that it has been focused on more in recent years. Looking at some studies on this subject;

Barboud et al., mentioned the historical development of PHES in electrical energy storage and compared many mechanisms with PHES within the framework of international market criteria, and an overview of energy storage was provided [28]. Deane et al., presented a review of a PHES facility, discussed technical and economic development, and stated that a reinforced PHES storage would offer a more flexible and efficient structure [29]. Punys et al., they examined the EU's operating PHES. In this article, power databases are observed to determine generation in mixed pump storage facilities in renewable and non-renewable energy sources [30]. Yildiz et al., examined a pumped hydroelectric storage power plant according to the day-ahead electricity market values in Turkey. An optimization algorithm has been developed with linear programming method in order to optimize day-ahead market offers of power plants. When the generation and revenue of the power plants controlled with the optimization method are examined, it is observed that the annual income went up by approximately 2.737% with the operation of the wind power plants alone and the productions were shifted to the hours when the demand power is high [31]. In the study of Makhdoomi and Askarzadeh, the crow CSA algorithm was developed in order to reduce the cost of a grid-connected hybrid system consisting of PV and pumped hydro storage and they observed that it decreases the cost [32].

3.1 Advantages and Disadvantages of Pumped Storage Systems

Pumped storage power plants can be used to make the energy produced in wind power plants, thermal power plants and hydroelectric power plants more reliable, especially today, where the use of renewable energy is increasing. As a result of the integration of PHES with wind energy, it can provide frequency control and uninterrupted supply. It also provides gigawatt-hour energy storage capacity. In high-power plants, it provides frequency regulation, harmonic damping and voltage control of a network by integrating with renewable energy plants. In order for the transmission system operators to regulate the electricity grid, it must be able to feed from backup energy in seconds, minutes and hours. Storage hydroelectric power plants provide high energy quickly, which can meet the load demand in a short time in the order of minutes [2, 24]. The disadvantages are the annual changes in the flow of the stream as an ecological effect. It is affected by environmental conditions such as deterioration of land structure, sediments that may occur in water, and water evaporation. The high cost of installation, the risk of erosion in the place to be established and the transportation problem between the reservoirs can be disadvantages [2, 24, 33].

3.2 Pumped Hydroelectric Storage Forms

The forms of pumped hydro storage are divided into four groups: variable speed pump turbines, underground pumped hydroelectric storage, seawater pumped hydro storage system, and Hybrid Pumped Hydro Storage (HPHES) systems for the use of photovoltaics and wind.

3.2.1 Variable Speed Pump Turbines

Variable speed pump storage is used as the first reserve to reduce the number of thermal power plants and to offer flexibility in frequency regulation. Its advantage is that it has the capability to control power in pumping mode. It supports the network to work in a reliable and continuous state. Since the generator is not connected to the grid, its rotation speed can be adjusted and optimized. Another major benefit of the variable speed pump turbine is which enhanced efficiency in turbine mode over fixed speed machines [2, 34]. The variable speed unit can prevent power disturbances from random spikes and contributes to maintaining grid stability.

3.2.2 Underground Pumped Hydroelectric Storage

Underground pumped hydroelectric systems are used as an alternative where pumped hydraulic systems cannot be installed. Figure 3 shows the schematic of the underground pumped hydroelectric storage system. These systems consist of two reservoirs, an underground reservoir and a surface reservoir. Underground reservoirs are places where abandoned mines are used. This storage system pumps water from underground to the upper reservoir, storing excess electricity in the form of potential energy. In periods when energy is needed, the water stored in the upper reservoir is transmitted to the underground reservoir and electricity is produced [35]. In underground pumped hydroelectric power plants, water transmission is provided by a pressurized well. As distinct from a pumped hydro storage systems, in underground pumped hydroelectric storage systems, water and air interact in water exchange in case of water transported to the upper reservoir and electricity generation from water in case of need. This pressure is created by the effect of air. The efficiency of underground pumped hydroelectric storage plants depends on the operating pressure in the underground water reservoir [36].

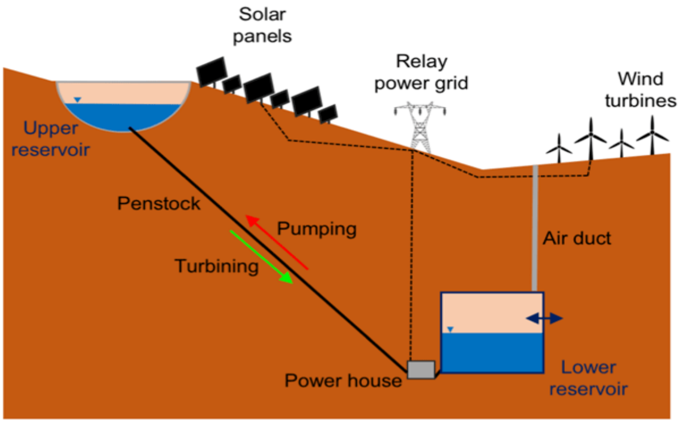

Figure 3. Underground pumped hydroelectric storage scheme [35].

3.2.3 Seawater Pumped Hydroelectric Storage System

In remote rural areas, isolated islands and offshore areas, a new type of storage called seawater pump hydro storage can be used. This storage system is a good alternative to pumping and using an artificial reservoir close to the sea. In addition, because it can provide a lower reservoir installation, construction and maintenance costs are reduced [37]. If it is well designed, it can be used in areas where it is difficult to utilize the conventional pumped storage system with long coastlines [2].

3.2.4 Hybrid Pump Hydro Storage (HPHES)

With a PHES system created by combining solar and wind, more energy storage provides a significant increase in flexibility, reliability and sustainability. Hybrid system is important in terms of electricity generation system and energy management [38]. The solar, wind and both wind and solar systems which used in hybrid pumped hydroelectric storage will be explained as in detail;

Firstly, the connection of hybrid wind and pumping system will be examined.

In order to increase wind energy capacity and reduce constraint, pumped hydroelectric storage, which provides generation with high energy density, is preferred. Changes in wind energy are supportive to close energy gaps and to provide electricity needs at long distances. The aim of the hybrid system is to increase the reliability of the system by using it with wind, to reduce the cost by using sea water as a reservoir for wind farms, and to increase the electricity production with wind energy. Studies mostly focus on system reliability and energy management [39]. Figure 4 shows the integrated working principle of the wind farm and pumped storage systems. In the hybrid system connected to the wind power plant, the supply of electricity produced and sold from wind energy is ensured by the pumped storage system. Excess electrical energy generated when wind speed increases is stored from the lower reservoir to the upper reservoir with the help of a pump. When wind speed decreases or electricity demand goes up, electricity is generated by running a hydraulic turbine and the grid can be fed. In this way, the unbalanced and fluctuating structure of the electrical energy can be stabilized [24]. In the literature, Zhang et al., investigated the principle of wind-pump storage integrated agricultural micro grid to meet both electricity and water load demand. Modeling has been done and it has been stated that it reduces operating costs [40]. For this system to work, there must be a balance in the total electrical power. In order to provide energy stability, it is necessary to establish a balance between supply and demand. If the supply is higher than the demand, the supply is reduced by the control unit. If demand is greater than supply, additional power is used. This additional power is provided by the wind. The control system that can provide the balance of power by considering customer satisfaction should be expressed as follows:

$$D_{PS}(t) = \frac{n_{pc}(t)Q_p(t)H_b\rho g}{\eta_{PS}} = P_{WF}(t) \tag{2}$$

$$[D_{LS}(t)]_{base} = P_{CPS}(t) \tag{3}$$

CPS; conventional power system

$$[D_{LS}(t)]_{peak} = P_{HP}(t) \tag{4}$$

In Eq. (2) is an equation used to match changes in energy demand for pumping with wind power. $Q_p(t)$ is the flow pumped by each of the pumps $n_{pc}(t)$, H_b is the pumping head, η_{PS} is the efficiency of power system, g is the gravitational acceleration and ρ is the water density. The time-dependent peak value of the load system depends on the hydraulic power. Positive feedback is provided in the control, that is, if the output is greater than the load, the load is increased to maintain a constant voltage and frequency. If the load is greater than the output, the load will decrease [41].

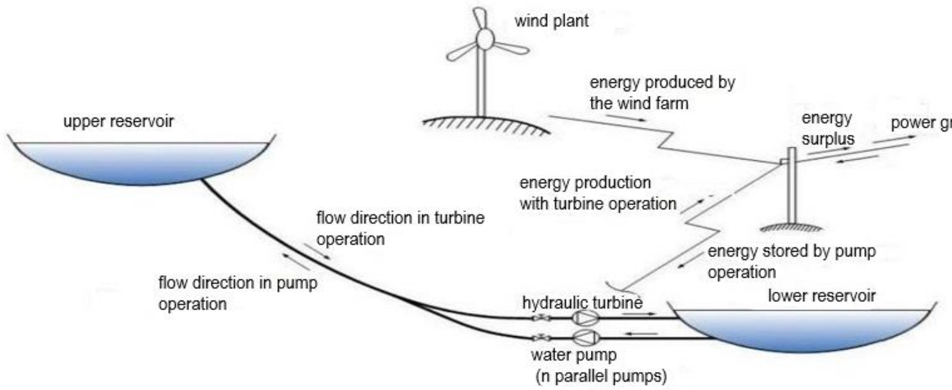

Figure 4. Scheme of pumped hydroelectric storage with wind-linked [24].

Secondly, the hybrid solar connection system is emphasized. Even if the sun is used during the day, there are a few interruptions compared to the wind. Pumped hydroelectric storage (PHES) uses mechanical storage to maximize solar energy use and prevent outages. This process is carried out in order to maximize the use of solar energy [39]. Solar-powered PHES systems are used as an energy storage subsystem, which plays an important role in replacing energy surplus, reducing interruptions in renewable energy sources, and balancing variable supply and demand. Mousavi et al., the effects of the solar connected pumped storage system on the micro grid were observed during sunny and cloudy times [42].

Bhoya et al., in their study, they performed energy analysis and optimization of a hybrid system consisting of a solar system integrated with pumped hydro storage to power a residence [43].

Figure 5 shows the Hybrid solar PV connected pumped hydroelectric storage system diagram. The working principle of the hybrid PHES can be briefly explained as follows. During periods when the balance between supply and demand is high, the pump uses the output from the sun to move water from the lower reservoir, sea, river or an artificial pond to the upper reservoir. By transformation the stored water to the lower reservoir, electricity can be generated via a turbine/generator unit to compensate for the imbalance during periods of high electricity demand and inadequate renewable energy generation. [44].

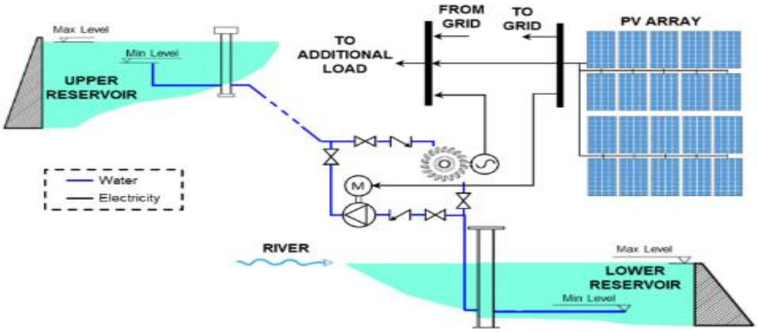

Figure 5. Hybrid solar PV connected pumped hydroelectric storage system diagram [44].

Thirdly, pumped hydroelectric storage system with both wind and solar connection is mentioned. It has been observed that there are deficiencies such as providing high energy storage, sizing system components, supply security and high investments in systems made using a single renewable energy source. In order to eliminate these deficiencies, the use of wind, solar and hydroelectricity together becomes a source that will make up for each other's deficiencies [39].

In the literature, in [45] proposes a hydro-based energy storage system and a clean, reliable and affordable hybrid energy conversion technology based on sunlight and wind. Prediction was made using genetic algorithm. As a result, it has been observed that there is a cost-effective, clean energy and climate change mitigation potential.

In systems where the sun and wind are used alone, the variables may have unpredictable situations. For this reason, systems where wind and sun are used together can better cope with frequency and voltage changes. The PHES subsystem consists of a dedicated pump/motor unit and a turbine/generator unit [39]. This is shown in figure 6.

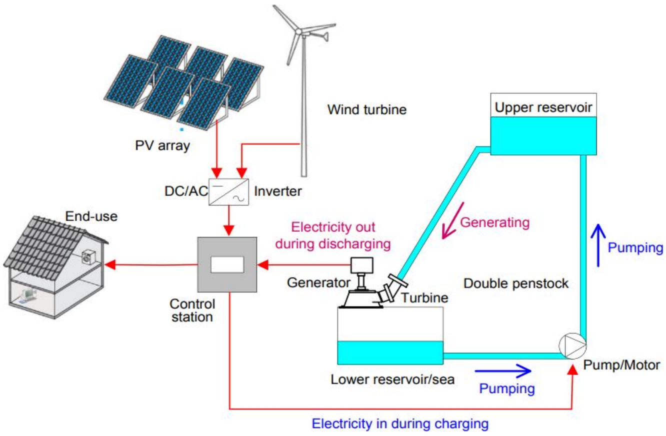

Figure 6. Hybrid solar-wind PHES scheme [46].

Pump/Motor unit: The flow rate of the water sucked from the lower chamber by the pumps is shown in Eq. (5). The power supply is provided by the hybrid renewable energy generator [46].

$$q_p(t) = \frac{\eta_p \cdot P_{h\to p}(t)}{\rho g h} = c_p \cdot P_{h\to p}(t) \tag{5}$$

Here $P_{h\to p}(t)$, represents the charging power from the pump to the hybrid generator, and h represents the height. Also, g is the acceleration of gravity, ρ is the water density, η_p pumping efficiency and c_p pumping coefficient. $q_p(t)$ is the volumetric flow of water supplied to the pump m^3/s.

Turbine/Generator unit: The turbine is a necessary element to ensure the conversion to energy. The transfer from the pump to the PHES system is also done through the turbine. A power component should be chosen depending on the height available and the flow rate [47].

In the event of a power outage, water is drawn from the upper reservoir to power the hydro turbines [15, 39]. The flow rate of the water taken by the turbine from the lower chamber to the upper chamber is shown in Eq. (6). Power from turbine/generator unit:

$$P_t(t) = \eta_t \rho g h \cdot q_t(t) = c_t \cdot q_t(t) \tag{6}$$

η_t is the total türbine/generator efficiency ve $q_t(t)$ is the volumetric flow rate of water taken into the turbine m^3/s.

The power produced by the turbine is limited between its minimum load power and its rated power [47].

Upper Reservoir: The amount of water stored in the upper reservoir must be able to satisfy the electricity demand in an island region to be fed if there is no electricity supply for several consecutive days. In order to meet the electricity demand, turbine water input power is obtained when the efficiency of turbine power and turbine power are calculated and proportioned. The water is transferred from the upper reservoir at h height to the lower reservoir. The gravitational potential energy stored in the upper reservoir is expressed as [46, 48]:

$$E_C = n_{day} \cdot E_{load} = \frac{\eta_t \cdot \rho \cdot V \cdot g \cdot h}{3.6\times 10^6} \tag{7}$$

In Eq. (7) E_C, is the energy storage capacity of a water tank (kWh); n_{load}, is the number of independent days in the loaded state; E_{load}, is the daily load energy is which consumed; V, is the volume or storage capacity of the water tank.

The total amount of water that can be stored in the UR at any time t is expressed as:

$$Q_{UR}(t) = Q_{UR}(t-1)(1-\alpha) + q_p(t) - q_t(t) \tag{8}$$

Where α designates the leakage and evaporation loss and q_p means the flow rate of the pump (m3/s).

The time to fully charge the reservoir is the ratio of the volume to the pump's flow rate.

PHES can generate profits when water is pumped into the upper reservoir during the low pricing period and then electricity is generated through the turbine to load or sell back to the grid during the peak pricing period. However, due to pump losses, PHES can buy more electricity from the grid. [49].

3.3 Economic Aspects of Pumped Storage Hydroelectric Power Plants

Because of the fast development of the global economy, the need for electricity is increasing. Therefore, hybrid renewable energy systems have a significant place in the electricity market. For example, let's consider a PV system with energy storage. When the electricity price is fall, it is stored with the storage system. This stored electricity is then sold when the electricity price is rise. Pumped hydroelectric storage is preferred as the energy storage system. Thus, maximum profit will be achieved. [50].

In the energy market, pumped hydroelectric storage is operated by independent system operators. In pumped hydroelectric storage generation and pumping mode, decision is made based on the facility's commitment status, ancillary service programs and energy status before submitting a bid to the day ahead market [51].

The budget of PHES projects depends on plant components and hydroelectric plant costs. Since the cost functions and components of the PHES system are similar to hydroelectric power plants, the implementation costs can be estimated by taking the hydroelectric power plant values as a reference. In the pumping phase, energy market regulations including different tariff situations, transmission and distribution utilization rates are utilized both in energy purchase and energy sales [2]. The maximum profit obtained according to the purchase and sale offers made in the electricity market shows that these power plants are economically good. Profit is the difference between revenue and cost [52, 53].

$$profit = \sum_t (revenue^t - cost^t) \quad (9)$$

$$revenue^t = p(t) * G(t) \quad (10)$$

p(t); t is the electricity reference price at time, G(t); represents the amount of electricity offered. If the result is negative, electricity is purchased. If it is positive, it means electricity is being sold.

$$cost^t = C_{conv}(t) + Y_{conv}(t) * S_{conv} \quad (11)$$

$C_{conv}(t)$; production cost of the plant, $Y_{conv}(t)$; binary value, S_{conv}; expressed as the initial cost of the unit. İf the unit was turned on at time t is 1, otherwise 0.
$C_{conv}(t)$ expression is calculated as follows.

$$C_{conv} = (a * P_{conv}(t)^2 + b * P_{conv}(t) + c) * X_{conv}(t) \quad (12)$$

a, b, c; t are the electricity cost coefficients in time. $P_{conv}(t)$; the amount of power produced by the unit in t time and $X_{conv}(t)$; binary value. If t also produces electricity, it is expressed as 1, if it does not produce, it is expressed as 0.
$X_{conv}(t)$ ve $Y_{conv}(t)$ binary coefficient takes value 0 or 1.

$$P_{conv}^{min} * X_{conv}(t) \leq P_{conv}(t) \leq P_{conv}^{max} * X_{conv}(t) \quad (13)$$

The power which generated by the unit should not exceed the minimum and maximum power generation value.

$$-ramp \leq P_{conv}(t) - P_{conv}(t-1) \leq ramp \quad (14)$$

The change in the amount of production should not exceed the ramp rate.

$$X_{conv}(t) - X_{conv}(t-1) \leq Y_{conv}(t) \quad (15)$$

In order to know whether the unit is turned on or not, the above expression of binary values is used.

$$P_{turbine}(t) \leq P_{turbine}^{max} \quad (16)$$

The turbine output power should not exceed the maximum turbine output power.

$$P_{p\imath mp}(t) \leq P_{pump}^{max} \quad (17)$$

In the same way, the pump output power should not exceed the maximum output power of the pump.

$$0 \leq V_t \leq V_{max} \quad (18)$$

V_t ; Volume of PHES in upper reservoir at time t, V_{max}; PHES is the maximum volume of the upper reservoir. Day-to-day and end-of-day storage volume should equal half of the upper reservoir maximum volume.

$$storage(t) = storage(t-1) + P_{pump}(t) + P_{turbine}(t) \quad (19)$$

$storage(t)$; it represents the energy stored at the end of each hour. Stored should not exceed the maximum storage capacity.

$$P_w(t) + P_s(t) + P_{conv}(t) + P_{turbine}(t) = G(t) + \frac{P_{pump}(t)}{\tau} \quad (20)$$

The energy balancing equation is that the sum of the energies produced must equal the sum of the commercially available electricity and the electricity used to pump the water in the lower reservoir of the pumped storage hydroelectric power plant [52].

The daily income of a pumped hydroelectric storage system with hybrid connection to solar power plants is calculated as follows:

$$R = \sum_{t=1}^{24} (P_{PV} + P_t) \times SP_t - 1.5 \sum_{t=t1}^{t2} P_t \times SP_t \quad (21)$$

R: income, P_{PV}; PV power generation, P_t ; is the charge-discharge power of the PHES at time t and SP_t is the instant payment price at t time t1 is the time PHES started buying power and t2 is the time it finished buying power. The purpose of the user is to maximize the economic benefit by adjusting the charge and discharge power. If we find the maximum of the expression given in Equation 20, the time when the utility reaches the maximum surface is found. [50].

4 Conclusıon

Hydroelectric power plant with pumped storage, which is one of the mechanical systems more suitable for use in large power systems in energy storage, has been examined.

Energy storage methods have been investigated in detail by many researchers and it has been observed that pumped hydro storage is a system that provides hours and weeks of storage in high-power systems, both environmentally and cost-effectively.

PHES has been found to be hybrid systems that can be connected to variable speed turbine, groundwater, seawater and renewable energies to increase efficiency, reduce cost and save space. Among these systems, it has been observed that the system in which solar and wind are used as a hybrid is also advantageous in providing high profitability in the energy market.

Considering the location definitions for PHES applicability, it may be beneficial to use rivers and shores as reservoirs. Because the use of rivers and shores in low reservoirs can be efficient in terms of construction and cost. Also, using large rivers as lower reservoirs increases efficiency by providing a large increase in the amount of water, while also being used for hydroelectric power plant. This research shows that energy storage is not only a technical necessity, but also contributes to cost advantages and climate. It is a critical and urgent issue to implement local adaptation actions in order to reduce the risks arising from climate change. In order to leave a livable environment to future generations, it is foreseen that this system, which provides completely renewable environment-friendly storage in large powers, should be focused on and implemented. It will be able to contribute to Turkey in terms of cost, frequency regulation and water requirement. The intermittent nature of renewable resources requires the use of longer storage. With this storage, both the continuity of the energy will be ensured and the supply-demand balance will be ensured. The fall height, hydraulic slope, grid connection and geological structure of Turkey's hydroelectric reservoirs are suitable for the installation of these pumped hydro storage plants.

Declaration

This article is not available in a working group that requires ethical committee approval.

References

[1] Barbour, E., Wilson, I. G., Radcliffe, J., Ding, Y., & Li, Y. (2016). A review of pumped hydro energy storage development in significant international electricity markets. *Renewable and sustainable energy reviews,* 61, 421-432..

[2] Vilanova, M. R. N., Flores, A. T., & Balestieri, J. A. P. (2020). Pumped hydro storage plants: a review. *Journal of the Brazilian Society of Mechanical Sciences and Engineering,* 42(8), 1-14..

[3] Blakers, A., Stocks, M., Lu, B., & Cheng, C. (2021). A review of pumped hydro energy storage. *Progress in Energy,* 3(2), 022003..

[4] Kocaman, B. (2013). Akıllı şebekeler ve mikro şebekelerde enerji depolama teknolojileri. *Bitlis Eren Üniversitesi Fen Bilimleri Dergisi,* 2(1), 119-127..

[5] McIlwaine, N., Foley, A. M., Morrow, D. J., Al Kez, D., Zhang, C., Lu, X., & Best, R. J. (2021). A state-of-the-art techno-economic review of distributed and embedded energy storage for energy systems. *Energy,* 229, 120461.

[6] Punys, P., Baublys, R., Kasiulis, E., Vaisvila, A., Pelikan, B., & Steller, J. (2013). Assessment of renewable electricity generation by pumped storage power plants in EU Member States. *Renewable and Sustainable Energy Reviews,* 26, 190-200.

[7] Ali, S., Stewart, R. A., & Sahin, O. (2021). Drivers and barriers to the deployment of pumped hydro energy storage applications: Systematic literature review. *Cleaner Engineering and Technology, 5,* 100281..

[8] Nehrir, M. H., Wang, C., Strunz, K., Aki, H., Ramakumar, R., Bing, J., ... & Salameh, Z. (2011). A review of hybrid renewable/alternative energy systems for electric power generation: Configurations, control, and applications. *IEEE transactions on sustainable energy*, 2(4), 392-403.

[9] Aktas, A., Erhan, K., Özdemir, S., & Özdemir, E. (2018). Dynamic energy management for photovoltaic power system including hybrid energy storage in smart grid applications. *Energy*, 162, 72-82.

[10] Faisal, M., Hannan, M. A., Ker, P. J., Hussain, A., Mansor, M. B., & Blaabjerg, F. (2018). Review of energy storage system technologies in microgrid applications: Issues and challenges. *Ieee Access,* 6, 35143-35164.

[11] Babu, T. S., Vasudevan, K. R., Ramachandaramurthy, V. K., Sani, S. B., Chemud, S., & Lajim, R. M. (2020). A comprehensive review of hybrid energy storage systems: Converter topologies, control strategies and future prospects. *IEEE Access, 8,* 148702-148721.

[12] Mousavi, N., Kothapalli, G., Habibi, D., Lachowicz, S. W., & Moghaddam, V. (2020). A real-time energy management strategy for pumped hydro storage systems in farmhouses. *Journal of Energy Storage,* 32, 101928.

[13] Tian, M. W., Yan, S. R., Tian, X. X., Nojavan, S., & Jermsittiparsert, K. (2020). Risk and profit-based bidding and offering strategies for pumped hydro storage in the energy market. *Journal of Cleaner Production,* 256, 120715.

[14] Gundu, V., & Simon, S. P. (2020). A novel energy routing technique with hybrid energy storage for residential electricity cost minimization in a smart distribution network. *Energy sources, part A: Recovery, utilization, and environmental effects,* 1-18.

[15] Al-Masri, H. M., Magableh, S. K., Abuelrub, A., Saadeh, O., & Ehsani, M. (2020). Impact of different photovoltaic models on the design of a combined solar array and pumped hydro storage system. *Applied Sciences,* 10(10), 3650.

[16] Bagheri-Sanjareh, M., Nazari, M. H., & Hosseinian, S. H. (2021). Energy management of islanded microgrid by coordinated application of thermal and electrical energy storage systems. *International Journal of Energy Research,* 45(4), 5369-5385.

[17] Kutucu, N., Terzi, Ü. K., & Ayirga, H. Y. (2017, April). Technical and economic analysis of energy storage systems in smart grids. In *2017 5th International Istanbul Smart Grid and Cities Congress and Fair (ICSG)* (pp. 166-170). IEEE.

[18] Rehman, S., Al-Hadhrami, L. M., & Alam, M. M. (2015). Pumped hydro energy storage system: A *technological review. Renewable and Sustainable Energy Reviews,* 44, 586-598.

[19] Pärnamäe, R., Gurreri, L., Post, J., van Egmond, W. J., Culcasi, A., Saakes, M., ... & Tedesco, M. (2020). The acid–base flow battery: Sustainable energy storage via reversible water dissociation with bipolar membranes. *Membranes,* 10(12), 409.

[20] Yang, C. J. (2016). Pumped hydroelectric storage. *In Storing Energy* (pp. 25-38). Elsevier.

[21] Gürsakal, H., & Uyumaz, A. (2021). Pompaj Depolamalı Hidroelektrik Santrallerin Optimizasyonunda Karlılık Analizi Ve Çalışma Süresi Tayini. *Mühendislik Bilimleri ve Tasarım Dergisi*, 9(2), 436-452.

[22] Guittet, M., Capezzali, M., Gaudard, L., Romerio, F., Vuille, F., & Avellan, F. (2016). Study of the drivers and asset management of pumped-storage power plants historical and geographical perspective. *Energy*, 111, 560-579.

[23] Chauhan, A., & Saini, R. P. (2014). A review on Integrated Renewable Energy System based power generation for stand-alone applications: Configurations, storage options, sizing methodologies and control. *Renewable and Sustainable Energy Reviews*, *38*, 99-120.

[24] Ünver, Ü., Bilgin, H., & Güven, A. (2015). Pompaj depolamalı hidroelektrik sistemler. *Mühendis ve Makina,* 56 (663), 57-64.

[25] Zhao, H., Wu, Q., Hu, S., Xu, H., & Rasmussen, C. N. (2015). Review of energy storage system for wind power integration support. *Applied energy,* 137, 545-553.

[26] Chen, H., Cong, T. N., Yang, W., Tan, C., Li, Y., & Ding, Y. (2009). Progress in electrical energy storage system: A critical review. *Progress in natural science,* 19(3), 291-312.

[27] Stocks, M., Stocks, R., Lu, B., Cheng, C., & Blakers, A. (2021). Global atlas of closed-loop pumped hydro energy storage. *Joule*, 5(1), 270-284.

[28] Barbour, E., Wilson, I. G., Radcliffe, J., Ding, Y., & Li, Y. (2016). A review of pumped hydro energy storage development in significant international electricity markets. *Renewable and sustainable energy reviews,* 61, 421-432.

[29] Deane, J. P., Gallachóir, B. Ó., & McKeogh, E. J. (2010). Techno-economic review of existing and new pumped hydro energy storage plant. *Renewable and Sustainable Energy Reviews,* 14(4), 1293-1302.

[30] Punys, P., Baublys, R., Kasiulis, E., Vaisvila, A., Pelikan, B., & Steller, J. (2013). Assessment of renewable electricity generation by pumped storage power plants in EU Member States. *Renewable and Sustainable Energy Reviews,* 26, 190-200.

[31] Yıldız, C., & Şekkeli, M. (2016). Türkiye gün öncesi elektrik piyasasında rüzgar enerjisi ve pompaj depolamalı hidroelektrik santral için optimum teklif oluşturulması. *Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi,* 22(5), 361-366.

[32] Makhdoomi, S., & Askarzadeh, A. (2020). Daily performance optimization of a grid-connected hybrid system composed of photovoltaic and pumped hydro storage (PV/PHS). *Renewable Energy,* 159, 272-285.

[33] Kabalcı, E., Bayındır R., & Tür, M.R. (2021). Mikroşebekeler ve dağıtık üretim sistemleri. *Ankara: Nobel Akademik Yayıncılık*

[34] Valavi, M., & Nysveen, A. (2018). Variable-speed operation of hydropower plants: A look at the past, present, and future. *IEEE Industry Applications Magazine,* 24(5), 18-27.

[35] Pujades, E., Orban, P., Archambeau, P., Erpicum, S., & Dassargues, A. (2018). Numerical study of the Martelange mine to be used as underground reservoir for constructing an Underground Pumped Storage Hydropower plant. *Advances in Geosciences*, 45, 51-56.

[36] Menéndez, J., Fernández-Oro, J. M., Galdo, M., & Loredo, J. (2020). Efficiency analysis of underground pumped storage hydropower plants. *Journal of Energy Storage,* 28, 101234.

[37] Wu, Y., Zhang, T., Chen, K., & Yi, L. (2020). A risk assessment framework of seawater pumped hydro storage project in China under three typical public-private partnership management modes. *Journal of energy storage, 32*, 101753.

[38] Simão, M., & Ramos, H. M. (2020). Hybrid pumped hydro storage energy solutions towards wind and PV integration: Improvement on flexibility, reliability and energy costs. *Water*, 12(9), 2457.

[39] Javed, M. S., Ma, T., Jurasz, J., & Amin, M. Y. (2020). Solar and wind power generation systems with pumped hydro storage: Review and future perspectives. *Renewable Energy,* 148, 176-192.

[40] Zhang, M. Y., Chen, J. J., Yang, Z. J., Peng, K., Zhao, Y. L., & Zhang, X. H. (2021). Stochastic day-ahead scheduling of irrigation system integrated agricultural microgrid with pumped storage and uncertain wind power. *Energy,* 237, 121638.

[41] Bueno, C., & Carta, J. A. (2006). Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands. *Renewable and sustainable energy reviews, 10(4)*, 312-340.

[42] Mousavi, N., Kothapalli, G., Habibi, D., Lachowicz, S. W., & Moghaddam, V. (2020). A real-time energy management strategy for pumped hydro storage systems in farmhouses. *Journal of Energy Storage,* 32, 101928.

[43] Bhayo, B. A., Al-Kayiem, H. H., Gilani, S. I., & Ismail, F. B. (2020). Power management optimization of hybrid solar photovoltaic-battery integrated with pumped-hydro-storage system for standalone electricity generation. *Energy Conversion and Management,* 215, 112942.

[44] El-Jamal, G., Ghandour, M., Ibrahim, H., & Assi, A. (2014, November). Technical feasibility study of solar-pumped hydro storage in Lebanon. In *International Conference on Renewable Energies for Developing Countries 2014* (pp. 23-28). IEEE.

[45] Nyeche, E. N., & Diemuodeke, E. O. (2020). Modelling and optimisation of a hybrid PV-wind turbine-pumped hydro storage energy system for mini-grid application in coastline communities. *Journal of cleaner production,* 250, 119578.

[46] Ma, T., Yang, H., Lu, L., & Peng, J. (2014). Technical feasibility study on a standalone hybrid solar-wind system with pumped hydro storage for a remote island in Hong Kong. *Renewable energy,* 69, 7-15.

[47] Petrollese, M., Seche, P., & Cocco, D. (2019). Analysis and optimization of solar-pumped hydro storage systems integrated in water supply networks. *Energy*, 189, 116176.

[48] Morabito, A., & Hendrick, P. (2019). Pump as turbine applied to micro energy storage and smart water grids: A case study. *Applied energy,* 241, 567-579.

[49] Kusakana, K. (2019). Optimal electricity cost minimization of a grid-interactive Pumped Hydro Storage using ground water in a dynamic electricity pricing environment. *Energy Reports,* 5, 159-169.

[50] Liu, K., Hu, W., Xu, X., Huang, Q., Zhang, Z., & Chen, Z. (2019). Optimized Operation of Photovoltaic and Pumped Hydro Storage Hybrid Energy System in the Electricity Market. *In 2019 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia),* (pp. 4306-4311).

[51] Aburub, H., Basnet, S., & Jewell, W. T. (2019). On the use of adjustable-speed pumped hydro storage operation in the US electricity market. *Journal of Energy Storage*, 23, 495-503.

[52] Akkaş, Ö. P., Arıkan, Y., & Çam, E. (2018). Elektrik Piyasasında Sanal Güç Santrali İşletiminin Optimizasyonu için Modelleme Önerisi. *International Journal of Engineering Research and Development*, 10 (3), 12-19.

[53] Anilkumar, T. T., Simon, S. P., & Padhy, N. P. (2017). Residential electricity cost minimization model through open well-pico turbine pumped storage system. *Applied energy,* 195, 23-35..