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PV connected pumped-hydro storage system

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Abstract
Storage systems are needed to increase the number of renewable energy sources that can be integrated into distribution systems in smart grids and to ensure the continuity of energy. Energy storage can support system operators and provide many services such as energy time shifting, capacity backup, outage management, transmission congestion relief and power quality improvements. Batteries and storage are used due to interruptions and waves in renewable energy sources such as wind and solar. In order to expand the use of clean energy and to ensure energy continuity, mechanical storage methods are emphasized in large power systems. Storage studies have been carried out to increase efficiency, reduce costs and improve storage time. In this study, pumped storage and compressed air storage systems, which are mechanical storage methods, are briefly mentioned. Then, the PV integrated pumped storage system model is emphasized. PHS has been said that the system in which solar are used as a hybrid is advantageous in providing high profitability in the energy market. Thanks to its integration with the sun carbon emissions are reduced. The system will also be useful in meeting irrigation and water needs.

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 is 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 overtake the energy consumption per capita in today's developed economies. Assuming electricity is generated by a conjunction 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 remove 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. Energy storage is a necessary technology that uses stored electrical energy when there is peak load demand. Intelligent energy storage systems are used to provide continuous, 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, 38].

The conversion and storage of energy is done with batteries, compressed air, flywheels, thermal power, ultra/super capacitors, superconductors, and fuel cells [6]. Mechanical energy storage technologies include pumped water-based energy storage systems, compressed air energy storage systems and flywheels. Mechanical energy storage is generally preferred in large power plants. The most preferred mechanical energy storage methods are compressed air storage and pumped hydro storage. Pumped hydro and compressed air storage system is a new energy storage system that can be combined with electricity generation from renewable energy sources such as wind and solar.

Energy storage systems, which have many methods, have a wide area today. Pumped hydro 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 [7]. 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;

Dong et al. [8] conducted to evaluate the performance of pumped hydro and compressed air storage system in terms of energy associated with power generation from photovoltaic (PV) system. The proposed system can both store energy and generate electricity. Marefati et al. [9] In their work, performance study of a new energy storage system, namely Pumped-Hydro and Compressed Air storage system, combined with organic Rankine cycle (ORC) and Linear Fresnel solar reflector (LFR). As a result, it has been shown that the energy needed by the pump for isothermal operation and the energy level in the container are 3.24 and 2.43 MJ/m3, respectively. It has been stated that the isentropic process requires less solar collector area than the isothermal process. Mousavi et al. [10] 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 microgrid 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. Al-Masri et al. [11] The effect of different photovoltaic models was investigated for a combined solar array and 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%. Bhayo et al. [12] studied, the analysis and optimization of a stand-alone hybrid renewable energy system to power a residential unit of 3,032 kWh/day was made and examined in 4 cases. it has been shown that as a result there will be less dependence on battery storage. Punys et al. [13], examined power databases to determine production in mixed pumped storage facilities from renewable and non-renewable energy sources. Yildiz et al. [14] examined a pumped hydroelectric storage power plant according to 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 the power plants. When the generation and revenues of the power plants controlled with the optimization method are examined, it is observed that the annual income has enhanced by approximately 2.737% with the operation of the wind power plants alone and productions have shifted to the hours when the demand power is high. In the study by Makhdoomi and Askarzadeh [15], the crow CSA algorithm was developed and observed to reduce the cost of a grid-connected hybrid system consisting of PV and pumped hydro storage.

In this study, pumped hydro storage and air pressure storage, which are mechanical storage methods, are mentioned in order to better understand the subject. Then, pumped hydro storage connected to solar energy, which is our main topic, is explained in detail and the stages of creating a mathematical model are expressed. As a result, implementation of local adaptation actions to reduce the risks from climate change is a critical and urgent issue. In order to leave a livable environment for future generations, it is foreseen to focus and implement this system, which provides fully renewable environmentally friendly storage at great powers. It will be able to contribute to Turkey in terms of cost, frequency regulation and water needs. The intermittent nature of renewable resources requires longer storage usage. With this storage, both the continuity of the energy will be ensured and the supply-demand balance will be ensured. The drop height, hydraulic slope, network connection and geological structure of hydroelectric reservoirs in Turkey are suitable for the installation of these solar connected pumped hydro storage facilities.

2. Material and Method

There has been an increased interest in renewable energy sources to reduce carbon dioxide absorption and fossil fuel use. However, electrical energy storage systems were needed to ensure the stability and reliability of the electricity grid and to use renewable energy resources efficiently due to the intermittent nature of renewable energy resources [16]. This need; This can be met either by the implementation of conventional storage hydroelectric power plants or by the implementation of other energy storage systems that can keep fossil fuel power plants in reserve so that they can be commissioned within minutes. Popular uses include fossil fuel generators, batteries, flywheels, supercapacitors and compressed air systems. Storage of electrical energy is necessary for better use of renewable energy resources through electricity transmission and distribution infrastructure [17]. 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, rotary reserve. In addition, energy storage systems can contribute to the stabilization of peak loads and in this way reduce generator failures. The amount of energy stored can play an important role in balancing the peak load. The capacity factor of the base generating units can be increased in this way, it is also a positive factor for the use of stored energy at a low price. In addition, energy balance is very important in power systems. This balance also emphasizes that it requires keeping the frequency at 50 Hz. This is made possible by smart grid integration. Energy storage systems can also contribute to the stabilization of peak loads, thus reducing generator failures. Energy storage systems are an important key to adapting to the diversity of new technology, changing consumer habits and actions, and the changing mechanism of electricity generation and distribution in recent years.

Energy storage technologies are developing day by day. Among the popular ones are fossil fuel generators, batteries, flywheels, supercapacitors. 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. Flywheels store kinetic energy. Pumped hydro storage and compressed-air energy storage is used as potential energy storage.

2.1. Compressed air energy storage

The oldest compressed air energy storage (CAES) plant was built in 1978 in Hundorf, Germany. It is planned to come cross the highest energy needs and allow a nuclear power plant to maintain a constant capacity factor [18]. Compressed air storage compressors are used to compress air and store it in an underground or aboveground piping system [19]. It can provide above 100 MW of energy with a single unit. When there is low power demand, the compressor is operated and the ambient air is compressed and stored in the underground impermeable caverns, and electricity is produced by operating the turbines with compressed air at times of need. The energy produced from electricity or a different source is stored in large air tanks [20]. Efficiency varies between 70% and 89% as it is related to compressor and turbine efficiencies. It can self-discharge. It has a useful life of about 40 years [18] When the power generation cannot meet the load demand, the stored compressed air is released and the heat released by the combustion of fossil fuel or the heat gained as a result of the compression process can be converted into electrical energy by heating it with a heat source and applying it to turbines as a pressure [19]. Energy storage with compressed air can be used from small scale to large scale power capacity. It can also be integrated into a large-scale power plant that includes grid applications for load shifting, voltage and frequency control. Disadvantage; It is difficult to find suitable geographical areas with underground natural caves. The system is incineration with the use of fossil fuels.

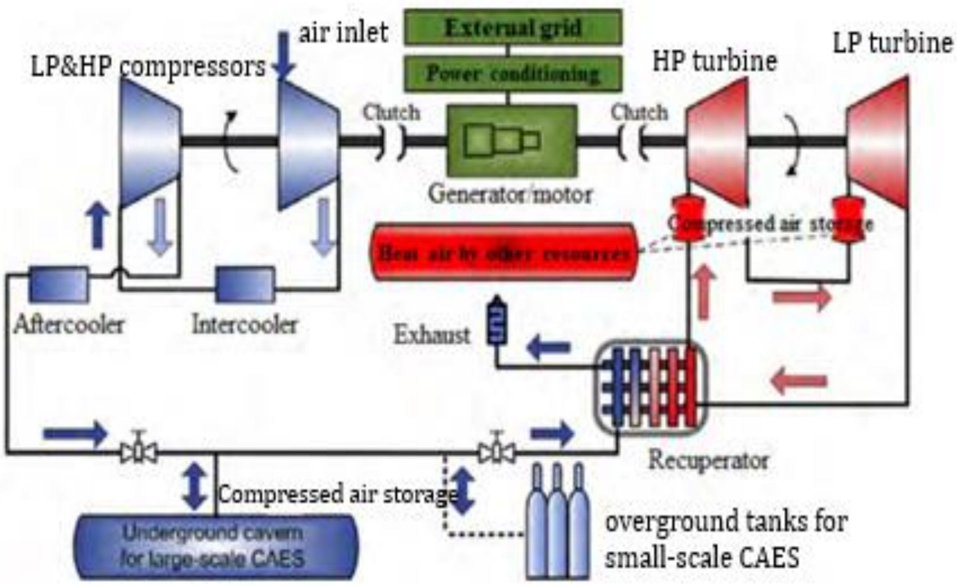

Figure 1. Compressed air of principle scheme [21]

2.2. Pumped hydro storage

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 [22].

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 [23]. In pumped storage hydroelectric power plants, there are 2 reservoirs, the upper and lower reservoirs. River, natural lake, dam, sea or artificial pool are chosen as reservoirs.

Figure 2 shows the schematic of pumped hydro storage. Pumped hydroelectric storage power plants provide storage as potential energy by pumping water from the lower reservoir to the upper reservoir [24]. When the energy demand is rise, electrical energy is produced by reducing the water accumulated in the upper reservoir to the lower reservoir [25]. 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 [26]. 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 [27]. 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 [28]. Pumped storage is classified three main categories [29]:

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

Semi-open: consists of an artificial or modified reservoir and a lake or river dam in continuous mode.

An open system (back pumping) is a system in which there is a continuous flow of water from both the upper and lower reservoirs. Most of the lands are far from the river when the terrain is 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, 37]. A combination of high head, low separation of reservoirs, and low dam wall volumes result in relatively low capital costs

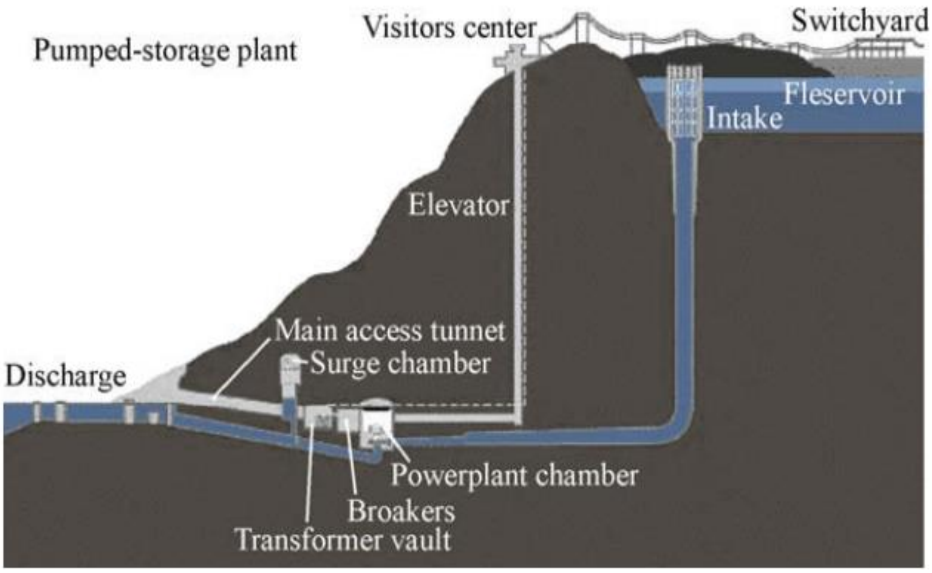

Figure 2. Pumped hydroelectric storage diagram [27]

Table 1 shows the advantages, disadvantages and usage areas of mechanical energy storage methods, pumped hydro storage and compressed air storage, which are used in high-power systems and provide potential energy storage.

Table 1. Mechanical energy storage methods advantage, disadvantage and usage area [29]

Mechanical Energy Storage Technology	Advantage	Disadvantage	Usage Area
Pumped Hydro Storage	High capacity, low unit energy cost	The need for large and private space	Time shift energy applications, Integration of large-powered renewable energy sources
Compressed-air Storage	High capacity, low unit energy cost	Large underground space needed, additional fuel cost	Time shift energy applications, Integration of large-powered renewable energy sources

2.3. Solar Powered Pumped Hydro Storage

In PV solar energy, a storage is needed due to the fact that the sun is not continuous, only for daytime production. Pumped hydroelectric storage (PHES) uses mechanical storage to maximize solar energy use and prevent outages [30]. A continuous supply of electricity can be provided by this solar-connected pumped hydro storage. In addition, the integration of pumped hydro storage with solar also supports supply and demand balance.

During low demand, the pumping process and hydroelectric generation are done during peak demand. Therefore, consumption during off-peak hours is covered by the sun. In the remaining period, power generation is completed from hydro if insufficient solar production is confirmed. Excess solar energy that is not used for consumption in the system is used for storage. In this way, the purchase prices of electricity from the grid are likely to decrease [31].

The working principle of the hybrid PHES can be briefly explained as follows. As shown in Figure 3, when solar generation is higher than energy demand, the excess energy is used to pump water from a lower reservoir to an upper reservoir. Storing energy in the form of gravitational potential energy of water (charge/pumping mode, Figure 3a). When energy generation is needed, water is permitted to flow back down through the turbines and the stored energy is transferred to the load (production mode, Figure 3b) [32].

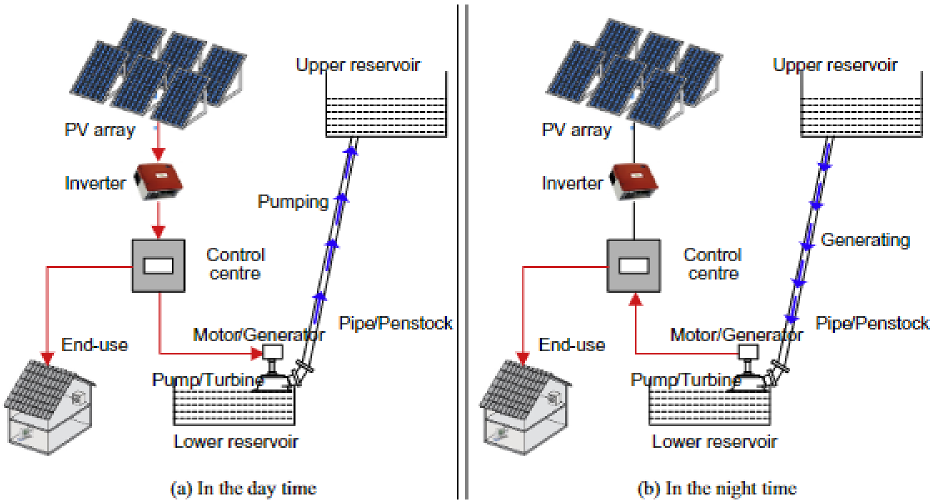

Figure 3. System schematic of a solar connected pumped storage system

System modeling is a critical step before system design, simulation and optimization.

2.3.1. Energy model of the system components

The studied system consists of different stages that can convert solar radiation into hydro potential energy. First, the photovoltaic cell system works as an energy source. The output of the first stage is processed by a dc-dc converter to feed and electromechanical pump-hydro stage. It follows from this that the pumping system is able to raise a column of water through a water recovery pipe from the bottom to the upper reservoir [33].

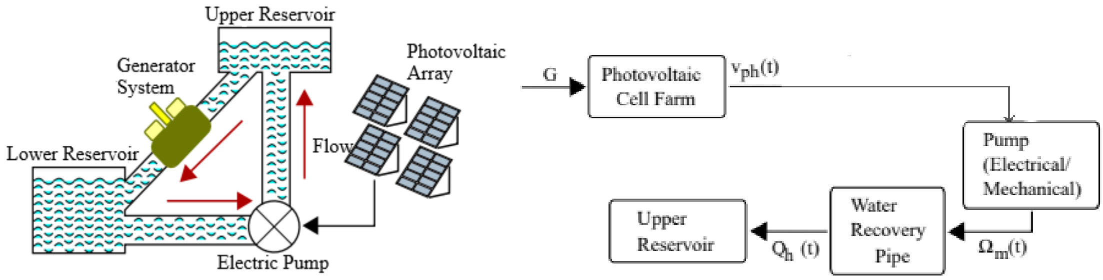

Figure 4. a) Model of the solar-powered pumped-hydro system for energy storage b) System blog diagram

The complete system is illustrated in Figure 4a with a more detailed block diagram given in Figure 4b, where the inputs and outputs of each of the subsystems (domains) are presented. In Figure 4b we see that the system has as input the current due to the sun's G radiation and as output the hydraulic flow Qc. A solar cell, also known as a photovoltaic cell, is an electronic system that converts solar energy into electricity using the photovoltaic effect.

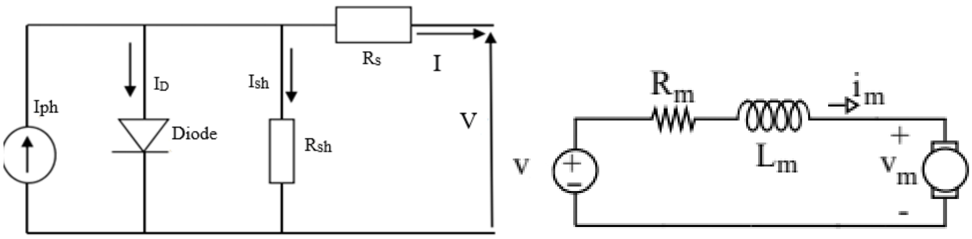

Figure 5. Photovoltaic cell circuit diagram and Pump circuit diagram

A single diode PV circuit diagram is used in the solar model. V output will be the pump voltage. The relationship between the outputs current (I) and voltage (V) of the PV panel for a single unit is expressed as follows [34, 35].

$$I = I_{Ph} - I_0\left(e^{\frac{V+IR_s}{aV_T}} - 1\right) - \frac{V+IR_s}{R_{sh}} \tag{1}$$

A pump is defined electrically and mechanically to store water from the bottom to the upper reservoir. First, the equivalent circuit for the electric field is shown in Figure 5. Inductance Lm stores kinetic energy and in Figure 4 the dynamics of the system is described.

$$L_m \dot{i_m} = -R_m i_m + v - v_m \tag{2}$$

According to the Biot-Savart Law, the magnetic flux can be expressed as:

$$\emptyset_m = L_m i_m \tag{3}$$

The dynamics of the system, the q_m related to charge storage in the circuit are used. q_m is expressed as the ratio of magnetic flux to inductance.

If we make mathematical modeling to determine the hydroelectric power;

The power output from the hydro system is rely on the condition of the water tank due to precipitation and previous pumped storage. The water stored within one hour will be used to generate power when the power from the PV is not sufficient to meet the load demand [12]. It will be used to generate hydroelectricity during rainy hours. It is divided by 3600s to run continuously for 1 hour. Hydroelectric output can be expressed with Equation 4 and 5.

$$Q_r(t) = \frac{R_{rain} \cdot dt_{rain} \cdot A_{catch} \cdot \tau_{catch}}{36 \times 10^5} \tag{4}$$

$$P_H(t) = \rho \cdot g \cdot Q_r(t) \cdot (h - h_f) \cdot \tau_{Ho} \tag{5}$$

$$Q_{pump}(t) = \frac{P_{excess}(t) \cdot \tau_{pump}}{\rho \cdot g \cdot (h - hf)} \tag{6}$$

$$V_m(t) = (Q_{pump}(t) \times 3600) + (R_{rain} \cdot dt_{rain} \cdot A_{catch})/1000) \tag{7}$$

Where Qr denotes the water flow rate enters to hydro turbine in m^3/s, Qmax is the maximum limit of water flow to be used in hydro turbine in m^3/s, Q_{pump} is the pumped water flow rate in m^3/s, R_{rain} indicate rain in millimeters (mm), dt_{rain} represents the rainfall time duration in number of minutes in an hour. A_{catch} is the accumulate area in m^2, V is the effective volume of water in the upper reservoir. τ_{catch} is the efficiency of rainfall basin, ρ means water density (1000 kg/m^3), h shows the gross water head in m, hf is head loss due to friction in m, and τ_{Ho} is the overall efficiency of hydropower system.

In PV solar energy, a storage is needed due to the fact that the sun is not continuous, only for daytime production. A continuous supply of electricity can be provided by this solar-connected pumped hydro storage. In addition, the integration of pumped hydro storage with solar also supports supply and demand balance.

During low demand, the pumping process and hydroelectric generation are done during peak demand. Therefore, consumption during off-peak hours is covered by the sun. In the remaining period, power generation is completed from hydro if insufficient solar production is confirmed. Excess solar energy that is not used for consumption in the system is used for storage. In this way, the purchase prices of electricity from the grid are likely to decrease [36]. In order to make the energy management very well in system design, the output power estimations of the PV system are made by methods such as ANN and Fuzzy Logic. The planning and operating process of the power system are a good measure to increase the reliability of these systems. These performance values are examined for the processes of meeting the load demand for hybrid renewable systems. This is due to the power imbalance of the hybrid renewable energy source. Optimization methods are used to correct this. While optimizing the reliability of the system, the process is taken as a constraint or a target to be achieved. The value of the reliability index (IR) can be checked using optimization methods to find the optimal size of the hybrid renewable resource's configuration.

3. Conclusion

There is a need for new studies in the field of energy storage in order to ensure the efficiency of existing energy sources and to meet the energy need in a healthy way. This need can be met with new studies to be carried out in the field of energy storage by using developing technological opportunities. However, it is important to consider environmental factors, low cost and high efficiency in such studies. Among the energy storage systems, the pumped hydroelectric storage system and compressed air storage from mechanical storage systems provide frequency and voltage stability. 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. The use of large rivers as sub-reservoirs increases efficiency by providing a large increase in the amount of water, while it is also used for hydroelectric power plants. It is predicted that pumped storage can meet the hourly energy needs with its integration with the PV solar energy system. A brief review of the solar coupled hybrid pump hydro storage system is given. As a result of these investigations; It is said that optimization methods are used to solve the solar problems of the hybrid system and as a result, the ANN model is better. It is stated that this hybrid system provides a good balance in situations where supply-demand variability is high. The hybrid system can generate and store electricity at low cost in a standalone solution that faces climate change and reduces its carbon footprint.

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Author contributions

Ayşenur Oymak: Conceptualization, Methodology, Software **Mehmet Rida Tür:** Data curation, Writing-Original draft preparation, Software, Validation. **Nouha Bouchiba:** Visualization, Investigation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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