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Pumped hydro energy storage system: A technological review

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ABSTRACT

The pumped hydro energy storage (PHES) is a well-established and commercially-acceptable technology for utility-scale electricity storage and has been used since as early as the 1890s. Hydro power is not only a renewable and sustainable energy source, but its flexibility and storage capacity also make it possible to improve grid stability and to support the deployment of other intermittent renewable energy sources such as wind and solar. As a result, a renewed interest in PHES and a demand for the rehabilitation of old small hydro power plants are emerging globally. With regard to PHES, advances in turbine design are required to enhance plant performance and flexibility and new strategies for optimizing storage capacity and for maximizing plant profitability in the deregulated energy market. In the early 2000s, this technology has again emerged as an economically and technologically acceptable option for peak load shaving and wind and solar energy storage for power quality assurance. Furthermore, renewable energy sources due to their fluctuating nature cannot maintain or regulate continuous supply of power and hence require bulk electricity storage. The present study aims at reviewing the existing global PHES capacities, technological development, and hybrid systems (wind-hydro, solar pv-hydro, and wind-pv-hydro) and recommending the best possible options. The review explores that PHES is the most suitable technology for small autonomous island grids and massive energy storage, where the energy efficiency of PHES varies in practice between 70% and 80% with some claiming up to 87%. Around the world, PHES size mostly nestles in the range of 1000–1500 MW, being as large as 2000–3000 MW. On the other hand, photovoltaic based pumped storage systems have been used for very small scale (load of few houses) only.

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Nomenclature

CSP	concentrated solar thermal power
ESS	energy storage system
GW	gigawatt
MPT	micro-pump turbine
MW	megawatt
PHES	pumped hydroelectric energy storage
PV	photovoltaic
RES	renewable energy sources
VER	variable energy resources
WP	wind power
WPD	wind power density

1. Introduction

The adverse effects of globally changing climatic conditions due to human interference in the natural eco-system of the life cycle have led people to minimize such activities which are leading the planet towards destruction. People from different walks of life have realized the consequences of using fossil fuels and are developing and utilizing clean and renewable sources of energy. These sources of energy include wind, solar photovoltaic, solar thermal, geothermal, hydroelectric, biofuels, biomass, wave, tidal, etc. Of these, wind and solar sources have taken the lead due to their technological maturity and commercial acceptance. The global deployment and investment of these sources are increasing year to year as can be seen from the literature. Furthermore the high cost of generation, dependence on fossil fuels and environmental considerations have been a powerful driver for increasing the exploitation of the renewable energy potential during the last decades [1,2].

The present review aims at understanding the existing technologies, practices, operation and maintenance, pros and cons, environmental aspects, and economics of using pumped hydroelectric energy storage (PHES) systems to store energy produced by wind and solar photovoltaic power plants.

According to the latest update, global investment in the development and utilization of renewable sources of power was 244 b US$ in 2012 compared to 279 b US$ in 2011, Weblink1 [3]. Fig. 1 shows the trend of installed capacities of renewable energy for global and top six countries. At the end of 2012, the global installed renewable power capacity reached 480 GW, while China remained the world leader with 90 GW contribution followed by USA and Germany with 86 and 71 GW installed capacities, respectively. In the global capacity of 480 GW, the contribution of EU-27 is 210 GW and that of BRICS countries (Brazil, Russia, India, China and South Africa) 128 GW. Global wind power installed capacity increased by 12.4% to more than 318 GW in 2013 due to greater participation by China and Canada, as shown in Fig. 2. However, installations slowed down in 2013 to about 35.5 GW, almost 10 GW less than the installation in 2012, Weblink2 [4]. China's installed wind capacity was 75.3 GW at the end of 2012 and it reached 91.4 GW in 2013. The other major contributor to wind power capacity, Canada, added 1.6 GW of new capacity. Europe's installed wind capacity rose to almost 121.5 GW in 2013 compared to 110 GW at the end of 2012. The world's cumulative PV installed capacity surpassed 100 GW mark, achieving just over 102 GW at the end of 2012, Weblink3 [5], as depicted in Fig. 3. The global cumulative PV installed capacity in 2011 was 71 GW. This capacity is capable of producing as much annual electrical energy as 16 coal power plants or nuclear reactors of 1 GW capacity each. Each year these PV installations save more than 53 million tons of CO_2 equivalent greenhouse gases entering into the atmosphere. The

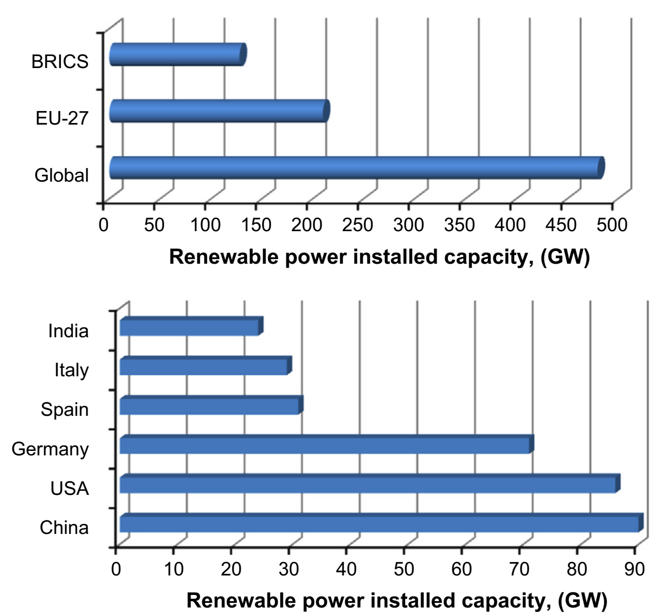

Fig. 1. Renewable power capacities in the world, EU-27, BRICS, and six countries at the end of year 2012 [3].

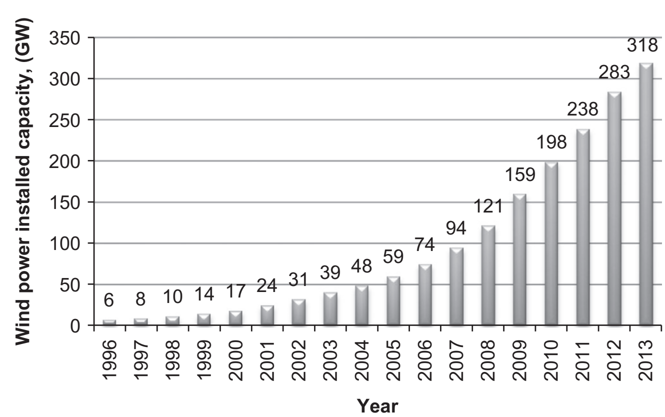

Fig. 2. Cumulative global wind power installed capacity growth [4].

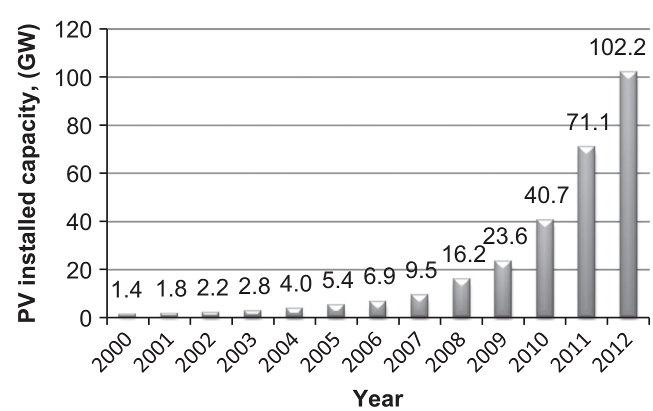

Fig. 3. Global cumulative solar photovoltaic installed capacity [5].

total hydro installed capacity reached 990 GW in 2012 compared to 960 GW in year 2011, an increase of 3.12%, Weblink1 [3].

Usually, the renewable energy sources are naturally intermittent with different degrees of intermittency. Solar energy is less intermittent compared to wind, as wind velocity is highly fluctuating meteorological parameter. This fluctuating nature of the clean energy sources has an adverse effect on the power production directly, becoming a challenge for regular and uninterrupted supply of power to the end user and for grid stability. Hence, bulk energy storage option is an answer and has already been recognized as a means of reducing fossil fuel demand and environmental degradation [6,7]. In case of isolated island grids where technical limitations are imposed by conventional generating units and the limited size of the systems, energy storage option is considered to be the most effective means to increase the wind penetration [8–11].

Suitable energy storages in bulk are required to minimize the wind energy wastage, safeguard the investors' interest, and establish wind power as an electricity generation source. Electrical networks usually keep 8–10% extra capacity in addition to the capacity on line to cope up with immediate power requirements, [12]. The provision of PHES in isolated grids, like those found in islands, seems to be a promising option to address both high electricity production cost and continuously increasing power demand encountered in these areas [6,7,13,14]. Caralis et al. [14] examined the ability of the Greek power system to absorb renewable power and the necessity of pumped storage systems. Results showed that for the gradual increase of variable output of renewable energy sources (RES), pumped storage is required. However, the feasibility of pumped storage systems was not proved in the intermediate scenarios of RES integration. A favorable and realistic way to introduce pumped storage in island systems is based on the concept of PHES comprising of wind farms and storage facilities, operating in a coordinated manner [15–21]. For these reasons, energy storage systems which are able to recover the rejected wind energy [22–26] under economically effective terms [23,27] are widely applied, achieving maximum exploitation of wind energy at both national [28] and community level [29] applications.

Sullivan et al. [30] examined the US power system and found that storage can lead to more installed wind power, to make it sufficiently valuable. Swider [31] studied the addition of compressed air energy storage (CAES) to an endogenous investment model. The study showed that, at certain levels of wind power and capital costs, CAES can be economic in Germany for large-scale wind power deployment, due to variable nature of wind. Yin et al. [32] proposed a micro-hybrid energy storage system consisting of a pumped storage plant and compressed air energy storage. The hybrid system acting as a micro-pump turbine (MPT) included two tanks, one open to the air and the other subjected to compressed air. The MPT utilizes excess power from the grid to pump the water, which in turn compresses the air, and eventually the energy is changed into internal energy of the air. The energy in the air is then released to drive water passing through the MPT to generate power when the power supply from the grid is insufficient.

Meibom et al. [33] discussed the benefits of using thermal storage for wind integration, while Mathiesen and Lund [34] examined various technologies for wind integration, showing that thermal storage can be very useful. Ummels et al. [35] studied the effect of storage on system operation over one year in the Netherlands. It was found that, though storage became more viable for the system with increasing levels of wind power, it never proved to be the best option for the system examined. Pumped storage plants provide a means of reducing the peak-to-valley difference and increasing the deployment of wind power, solar photovoltaic energy and other clean energy generation into the grid [36]. Pumped storage plants represent the most mature approach among the peaking power sources and thus are one of China's major investments for the future. According to Zeng et al. [37], for large-scale development of clean energy sources, such as wind power that is highly intermittent, the need for peaking capacity in the system increases greatly.

In the present scenario, development of efficient and environmentally safe energy storage system (ESS) is an important issue to be addressed to safeguard the society from natural disasters. Demand for ESS is increasing for all types of applications, such as remote area power supply systems (e.g. offshore platforms, telecommunication installations), stressed electricity supply systems, emergency back-up, mobile applications and finally for grid connected large renewable energy power plants. The supply of electric power to remote areas is becoming more attractive due to advancements in the photovoltaic (PV), concentrated solar thermal power systems (CSP) and wind power generation technologies beside the development of ESS. According to Lee and Gushee [38] massive electricity storage is the critical technology needed for the renewable power if it is to become a major source of base load dispatchable power. They further indicated that energy storage systems cost constitute about 30% of the total renewable power supply system cost. In addition, according to the recent estimates by electricity storage association (ESA) and KEMA, more than 100,000 incremental jobs will be created by 2020 in the energy storage sector [39].

2. Pumped hydroelectric energy storage (PHES)—Definition

Pumped hydroelectric energy storage stores energy in the form of potential energy of water that is pumped from a lower reservoir to a higher level reservoir. In this type of system, low cost electric power (electricity in off-peak time) is used to run the pumps to raise the water from the lower reservoir to the upper one. During the periods of high power demand, the stored water is released through hydro turbines to produce electric power. Reversible turbine/generator assemblies act as pump or turbine, as necessary. Typical conceptual pumped-hydroelectric-storage (PHES) systems with wind and solar photovoltaic power options for transferring water from lower to upper reservoir are shown in Figs. 4 and 5, respectively. The technique is currently the most cost-effective means of storing large amounts of electrical energy, but capital costs and the presence of appropriate geography are critical decisive factors. The design of almost every PHES power plant is highly dependent on the site characteristics. A site having sufficient water available is said to be good for the development of PHES plant, if the topography and geology of the area are favorable.

Pumped storage is generally viewed as the most promising technology to increase renewable energy penetration levels in power systems and particularly in small autonomous island grids. The wind and pumped-storage systems, called hybrid power stations, constitute a realistic and feasible option to achieve high renewable penetrations, provided that their components are properly sized. The PHES system is a hydroelectric type of power generation system used in power plants for peak load shaving. Pumped-storage schemes currently provide the most commercially important means of large-scale grid energy storage and improve the daily capacity factor of the generation system.

The relatively low energy density of PHES systems requires either a very large body of water or a large variation in height. Pumped storage is the largest-capacity form of grid energy storage available and as of March 2012. As reported by the Electric Power Research Institute (EPRI) PHES accounts for more than 99% of bulk storage capacity worldwide, representing around 127 GW [40]. The global PHES capacities of different countries are summarized in Table 1 [41]. In 2009, the global PHES capacity was around

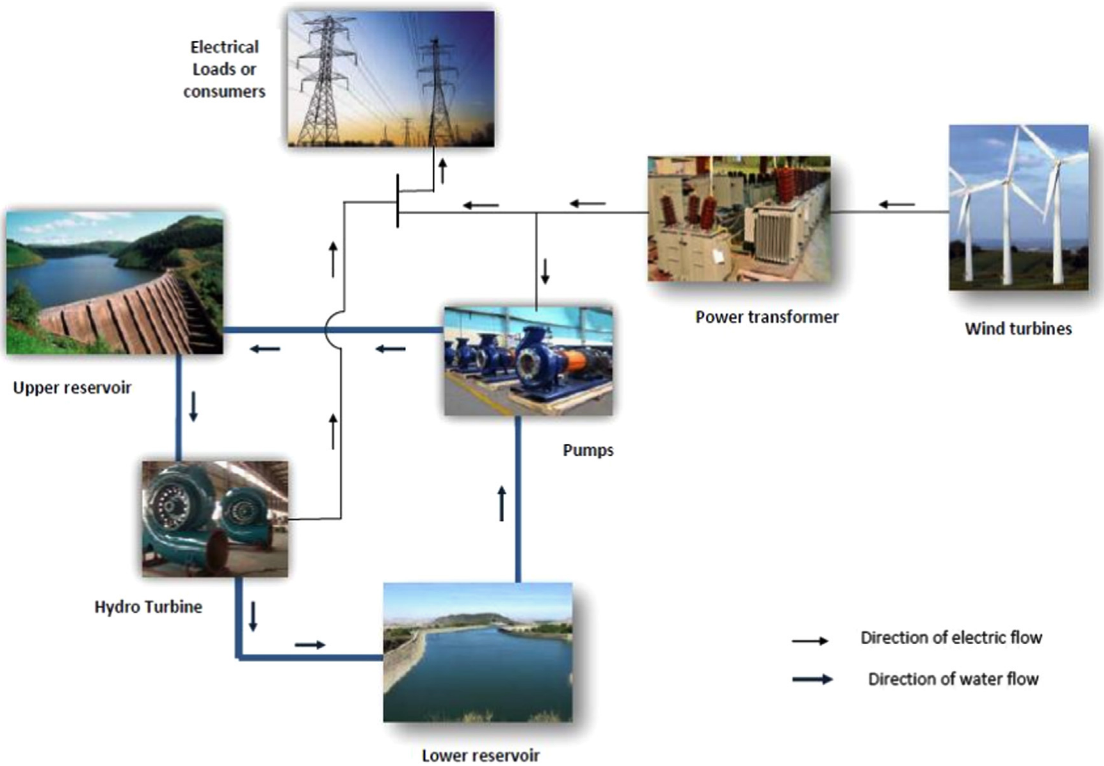

Fig. 4. Conceptual wind power based pumped hydroelectric storage (PHES) system.

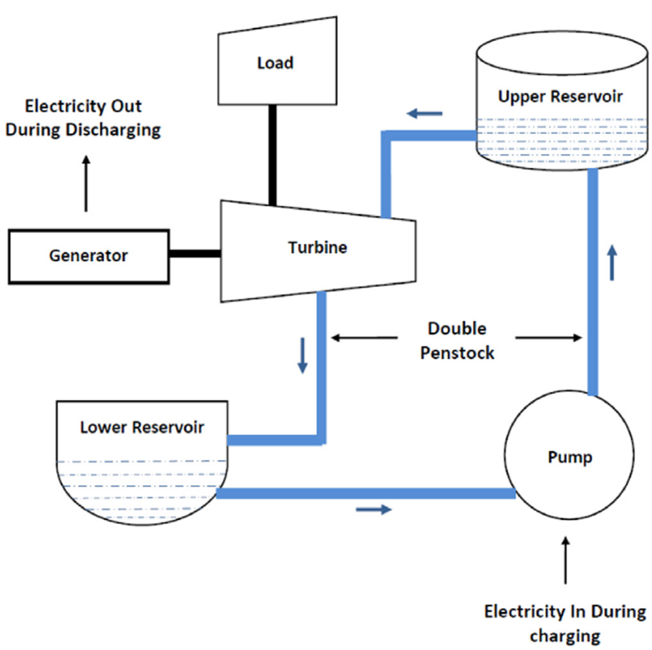

Fig. 5. Conceptual solar PV power based pumped hydroelectric storage (PHES) system.

Table 1
Summary of PHES installed capacities of the world and different countries at the end of year 2009.
(*Source*: US Energy Information Administration 2012).

North America			22 GW
Canada	0.2	United States	22.2
Central & South America			1
Argentina			1
Europe			44 GW
Austria	4.4	Luxembourg	1.1
Belgium	1.3	Norway	1.4
Bulgaria	0.9	Poland	1.4
Croatia	0.3	Portugal	1.0
Czech Republic	1.1	Serbia	0.6
France	4.3	Slovakia	0.9
Germany	6.7	Spain	5.3
Greece	0.6	Sweden	0.1
Ireland	0.3	Switzerland	1.8
Italy	7.5	United Kingdom	2.7
Eurasia			2 GW
Lithuania	0.8	Russia	1.2
Africa			2 GW
Morocco	0.5	South Africa	1
Asia & Oceania			33 GW
Austria	1	Korea, South	4
Japan	25	Taiwan	3
World			104 GW

100 GW. The energy efficiency of PHES varies in practice between 70% and 80% [40,42–44] with some claiming up to 87%, [45].

According to the rated power of PHES, these systems can be classified into large, small, micro, and pico. The PHES having installed capacity from a few hundred kW to more than 10 MW are generally known as big plants, although there is no official definition of large hydroelectric power stations. A small pumped hydroelectric energy storage may have a capacity of up to 10 MW maximum, but again, there is no such standard definition or very clear cut capacity range. The third category of PHES is micro which may have a capacity of up to 100 kW. Such type of plants can provide power to isolated or small communities and may also be connected to grids where wind and other renewable sources of energy are being used. The term pico size PHES is used for plants of installed capacities of less than 5 kW. These are used to store the energy produced from wind or solar photovoltaic systems for remote communities where the power requirement is only for a few.

3. Why pumped hydroelectric energy storage (PHES) plants?

Renewable and clean energy sources such as wind, solar, wave, tidal, biomass, municipal waste, etc., are intermittent in nature and hence lack in producing continuous and nameplate capacities. Of these, wind is highly fluctuating meteorological parameter and changes on hourly, daily, weekly, monthly, and annually [46]. So, to hook wind power with the grid and assure quality power supply, large energy storage systems are required. Solar radiation is, however, better known sources of energy and is less fluctuating but only works during daylight hours. From power quality point of view solar energy provides relatively more reliable power and can be committed and managed. In this case, relatively smaller energy storage systems can be useful to provide continuous and quality power. According to Hino and Lejeune [47], pumped hydroelectric storage plants have several advantages, such as (1) flexible start/stop and fast response speed, (2) ability to track load changes and adapt to drastic load changes, and (3) can modulate the frequency and maintain voltage stability. All these imply that PHES plants are useful tools in the electricity system as pointed out by Nazari et al. [48] and Mitteregger and Penninger [49]. Kear and Chapman [50] conducted a survey and found that pumped hydro was seen by most as prohibitively costly, but was almost universally viewed as technically capable of providing renewable support and peak power adequacy. In the modern world, with growing awareness among people, clean and renewable sources of energy are being encouraged and used globally. Keeping in view these growing trends of using intermittent sources of energy, there is and there will be a greater need for flexibility in the modern energy transmission and distribution systems. With regard to a large integration of wind power to electricity network, a number of issues [51–58], described below, are required to be addressed:

- Grid capacity and voltage profile should not exceed the specified limits.
- Network congestion.
- Impact of variable energy resources (VER) on bulk power transmission due to wind integration.
- Handling of harmonics created by the addition of wind on the grid.
- Transient stability performance of the system for normal and contingency conditions and determination of power transfer levels restricted by a stability constraint due to the addition of the VER interconnections.
- Handling changes in network impedances due to wind farm connection to the grid and then its effects on the remote control-signals.
- Protection issues of grid protection equipment on the grid due to wind power addition on the network.
- Stability problems in grids may occur due to dynamics behaviors of wind farms connected to the grids.
- Capital investment assessment may be needed to mitigate adverse system impacts, if any, including equipment, transmission lines, and special/high speed protection system.

All of these issues and others may be handled, in general, by using bulk energy storage systems that include mechanical systems (pumped hydro, compressed air energy storage (CAES), flywheels), electrical systems (capacitors and ultra-capacitors, superconducting magnetic energy storage (SMES)), and chemical/electrochemical systems (metal-air, flow batteries, Li-ion battery, NaS battery, hydrogen energy storage), [59].

Considering the above issues, Weisser and Garcia [53] stated that there should be no technical issues for instantaneous wind penetrations of up to 20% on an electric grid. However, Lundsager et al. [42] stated that a maximum of 25–50% wind penetration may be feasible within the electricity sector and also reported that the feasibility of very high wind penetrations decreases dramatically when the size of the electricity grid increases from 100 kW to 10 MW. For a 100 kW grid a wind penetration of 80% is feasible, but for a 10 MW grid a wind penetration of only 20% is feasible [42]. The authors concluded that the primary reason for this dramatic reduction in the feasible wind penetrations was due to the lack of energy storage on the grid [42]. Bakos [60] concluded that a storage capacity for the energy required for 1–3 days duration is necessary to obtain wind penetrations above 90%. PHES is the largest and most mature form of energy storage available and therefore, it is likely that PHES will become more important within energy-systems as renewable energy penetrations increase. The efficiencies of pumped hydro plants lie in the range from 70% to 80% [61]. The price of a storage reservoir varies significantly depending on the local geography—quoted numbers lie between 1 and 20$/kW h for storage capacity and 600–1000$/kW for the turbines ([61,62]). Although the benefits of PHES are usually recognized, it is widely believed that suitable locations to construct PHES facilities are becoming rare [63].

4. Global PHES plant sizes and trends

PHES is the only proven large scale (4100 MW) energy storage scheme for power system operation, Sivakumar et el. [64]. The increasing trend of installations and commercial operation of these schemes has been noticed in recent years, Deane et al. [103]. Worldwide, there are more than 300 installations with a total capacity of 127 GW [12,98]. In addition, with the present capacity, it is expected that another 76 GW will be added by 2014 worldwide [12]. Many countries have realized the feasibility of this technology and are planning for the addition of PHES to the power system, especially to facilitate the use of renewable energy sources. In India, at present there are 11 pumped storage schemes operational with an installed capacity of 4804 MW and another 1000 MW capacity plant is under construction, [64]. Moreover, the first pumped storage plant in India was commissioned in 1980–1985 [65], and 56 potential sites were identified suitable for the development of pumped storage schemes, with a probable installed capacity of 94,000 MW [66].

Punys et al. [67] studied PHES plants operating all over the European Union (EU) based on key statistical indicators found in the European Hydropower database (HYDI). In 2010, all over the EU, there were approximately 140 operational PHES plants (with installed capacity exceeding 19.5 GW), 84 of them were mixed-type PHES. The largest number of PHES was found in Germany (31), Italy (21) and Austria (19). The largest number of mixed PHES was in Austria (19), Italy (14) and Germany (11). In Austria, Bulgaria, Portugal, Romania and Sweden, all PSPs are mixed type. Only pure PSPs are installed in Belgium, Ireland, Lithuania, Luxemburg and Slovenia. There are no installed PSPs in Estonia, Hungary, Cyprus, Latvia and Malta. In China, PHES has met a booming period for the last 10 years. Currently, 24 PHES stations have been built with an installed capacity of 16.95 GW, while government's target of 2020 is 50.02 GW, [68]. Ming et al. [68] provided an overall review of China's PHES development, with a detailed (i) presentation of the installed capacity, (ii) distribution of existing and proposed PHES stations, (iii) description of 4 typical stations for the practical functions of PHES in power grids, (iv) analysis of the management mode and the price mechanism of PHES operation, and (v) identification of the barriers in PHES development in China.

5. PHES site selection criteria and methodologies

Technically feasible, commercially and socially acceptable site selection for PHES is a critical issue and needs continuous attention of researchers to find out more accurate, yet simple and economical methods and tools for the identification and selection of feasible sites. Furthermore, with the passage of time, the availability of technically and economically feasible sites is becoming scarce [69]. Hence new and effective ways and methods have to be thought and brought about. Connolly et al. [70] developed a computer program that can scan a terrain and identify if there are any feasible PHES sites in there. This program has proven helpful in identifying feasible locations for PHES [70].

6. Historical development of PHES technologies

The earliest PHES in the world appeared in the Alpine regions of Switzerland, Austria, and Italy in the 1890s. The earliest designs used separate pump impellers and turbine generators. Since the 1950s, a single reversible pump-turbine has become the dominant design for PHES [71]. The development of PHES remained relatively slow until the 1960s, when utilities in many countries began to envision a dominant role for nuclear power. Many PHES facilities were intended to complement to nuclear power for providing peaking power.

In the 1990s, the development of PHES significantly declined in many countries. During this period low prices of natural gas made gas turbines more competitive in providing peaking power than PHES. Environmental concerns caused the cancellation of several PHES projects and significantly prolonged the permitting process. The nature of PHES falls into the gray area between generation and transmission [72]. As the net electricity output of PHES operation is negative, a PHES facility usually cannot qualify as a power generator. Although PHES provides crucial load-balancing and ancillary services to the grid and reduces the needs for transmission upgrades, PHES facilities do not typically qualify as transmission infrastructure. Recently, Ardizzon et al. [73] provided an overview of the prospects of pumped-hydro energy storage and small hydro power plants in the light of sustainable development. Advances and future challenges in both turbine design and plant planning and management were proposed. PHES and hybrid wind/solar-PHES were illustrated and discussed, and limits and peculiarities of the new design strategies were outlined for both PHES and small hydro power plants based on computational fluid dynamics results.

7. Wind pumped hydroelectric energy storage (W-PHES) plants

Pumped storage has been considered suitable for improving the intermittent wind power output [74], but its utilization has severe geographic restrictions [75]. So current research is mostly carried out for the energy system in regions with islands and mountains [76–79], focusing on the economic operation of pumped storage related to wind power [80]. However, the pumped storage is used to clip and fill wind power gaps rather than participate in power generation scheduling. With respect to the complementarities of wind and other energy, it has been reported that the combination of solar and wind produces less variability in production than that produced on its own [81]. The wind power and PHES integrated power systems are known to be the most economically and technically competitive technology in different geographical areas [82–84].

A major advantage of these hybrid plants is the improvement of the dynamic security of non-interconnected power systems through the introduction of the hydro turbines [85]. The combined use of wind energy with PHES is considered as a means to exploit the abundant wind potential, increase the wind installed capacity and substitute conventional peak supply. So far, the optimum sizing of pumped storage facilities in similar applications has been the subject of relatively few studies [86–89]. Brown et al. [86] optimized the size of pumps and reservoirs for maximum exploitation of the wind potential of an island, using a linear programming method. However, with the aid of dedicated optimization tools based on evolution algorithms, Kapsali et al. [87] presented a detailed design of a pumped hydro-storage system (see Fig. 6) for the recovery of the energy rejected by wind farms in the non-interconnected Greek islands Lesvos and Crete. The recovery of rejected wind energy by pumped storage was examined by Anagnostopoulos and Papantonis [88] for the interconnected electric power system of Greece, where the optimum pumped storage scheme was investigated to combine an existing large hydroelectric power plant with a new pumping station unit. In a recent study Katsaprakakis et al. [89] optimized the size of a combined wind-hydro pumped storage system for the case of the isolated power system of Karpathos–Kasos, where the operation of the system was based on the condition of guaranteed energy supply to the local grid on a daily basis during the peak load demand hours.

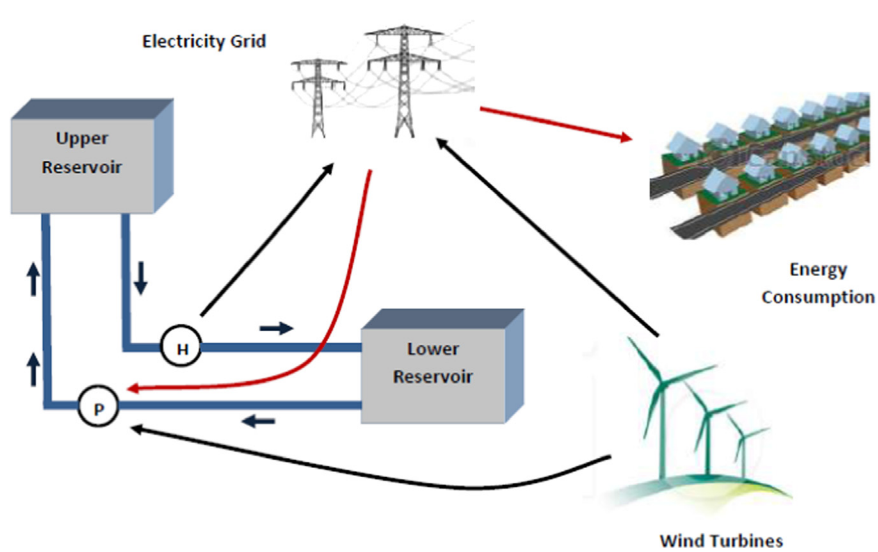

Fig. 6. Pumped hydroelectric energy storage system integrated with wind farm [87].

Katsaprakakis et al. [90] attempted the development of seawater pumped storage systems in combination with existing wind farms for the islands of Crete and Kasos. An optimal design of a system consisting of an energy tower (ET), pumped storage and seawater desalination plant was presented by Omer et al. [91]. The energy tower is a power plant project, which uses hot dry air and seawater to produce electricity. The hybrid system leads to an increase of 14% in the annual net profit, compared to the sum of profits from optimally designed stand-alone systems [91]. Connolly et al. [92] investigated large-scale energy storage integration of fluctuating renewable energy by using the Irish energy system, PHES, and wind power as a case study. In total three key aspects were investigated in relation to PHES: operation, size, and cost. From the results it was evident that PHES can increase the wind penetration feasible on the Irish energy system and also reduce its operating costs.

Reuter et al. [19] reviewed renewable based technologies in a specific policy context. By employing a real option approach, they provided an additional insight into the specific characteristics of renewables and their associated uncertainties, considering the market effects on investment decisions. The prices of the model were determined endogenously by the supply of electricity in the market and by exogenous electricity price uncertainty. The inclusion of market effects allowed capturing the full impact of public incentives for companies to invest in wind power and hydro pumped storage installations. Caralis et al. [82] made an analysis of wind energy with PHES in three specific islands and showed that there is a significant market for such systems in Greece; and its development cost is competitive to the fuel cost of local power stations in autonomous islands. Dursun and Bora [83] investigated the potential of hydropower and wind energy in Turkey, emphasizing the possible contribution of wind-hydro pumped storage systems in meeting Turkey's electric energy demand.

One way to reduce the electricity production cost is to increase the contribution of renewable energy sources (RES) to the islands' energy balance, with special focus given on the development of wind power applications, which is proved to be a economically and environmentally friendly technology [53,93]. On the other hand, the intermittent nature of the wind and fluctuations of daily and seasonal electrical load demand in these regions lead to strict wind energy penetration limits [94–95] mainly due to existing technical barriers which protect the autonomous electrical grids from possible instability problems. Consequently, under the current legislative frame, it is difficult to achieve higher than 15% wind energy contribution in autonomous electrical networks [96] unless economically viable energy storage techniques [27,97,98] that are able to exploit the excess wind energy amounts produced by local wind farms [22–25,99] are implemented. Katsaprakakis et al. [98] investigated the introduction of PHES systems in isolated power production systems with high thermoelectric production and wind energy rejection. The introduction of PHES in Crete yields to almost 10% annual electricity production cost reduction [98]. The annual wind energy rejection was nullified. The investment payback period was found to be less than 5 years. However, the introduction of PHES in Rhodes lead to only 1.85% reduction in annual cost of electricity production [98].

Kaldellis et al. [13] applied a methodology in Lesbos island, Greece for sizing of PHES systems to exploit the excess wind energy produced by local wind farms which otherwise be rejected due to electrical grid limitations. The study showed that in Lesbos Island a total of 10% annual curtailment of the total wind power production from 30 MW installed capacity wind farm could be achieved with the addition of 10.5 MW PHES. According to Bueno and Carta [24], a 20.40-MW wind farm, 17.80-MW modular pumping station and 60.00-MW hydroelectric power station have no negative impact on either the reliability of the electrical system or consumer satisfaction. This system resulted in an increase of wind power penetration of 1.93% annually (52.55 GW h/year). Additionally, the proposed pumped hydroelectric energy system would result in fossil fuel saving of 13,655 MT/year and a reduction in CO_2 emissions into the atmosphere of 43,064 MT/year. Within the general guiding framework of a policy for the promotion of clean and renewable energy, PHES systems represent an enormous and as yet barely explored potential [24]. Kapsali and Kaldellis [100] examined the economic viability of a wind-based PHES system (wind-hydro solution) to be connected to the local electrical grid of an Aegean Sea island, Lesbos, with guaranteed energy amounts during the peak load demand periods. Based on the maximization of the project's net present value, the optimum system configuration was proposed, while many other feasible solutions were revealed. According to the results obtained the implementation of this project demonstrated excellent technical and economic performance, while at the same time renewable energy source (RES) contribution was doubled reaching almost 20% of the Lesbos island electrical energy consumption.

Varkani et al. [101] reported that the integration of PHES with wind farms in mainland of Spain increased the profitability of the integrated system and minimized the wind energy losses. A neural network technique was used to predict the wind energy one day ahead for the efficient management of wind and PHES integrated power system. Katsaprakakis et al. [102] studied the feasibility of maximizing the use of wind power in combination with existing autonomous thermal power plants and wind farms by adding pumped hydroelectric energy storage in the system for the isolated power systems of the islands Karpathos and Kasos located in the South-East Aegean Sea. The study [102] proved the economic feasibility of small scale wind powered pumped storage systems, not taking into account the undoubted environmental benefits. A detailed techno-economic survey of new and existing PHES projects across Europe has been provided by Deane et al. [103], while Yang and Jackson [104] presented the opportunities and barriers related to the utilization of PHES for the US.

Connolly et al. [105] compared three practical operation strategies (24 optimal, 24 prognostic, and 24 historical) to the optimum profit feasible for a PHES facility with a 360 MW pump, 300 MW turbine, and a 2 GW h storage utilizing price arbitrage on 13 electricity spot markets. The results showed that 97% of the profits can be obtained from a PHES facility if the energy storage is optimized based on the day-ahead actual or very accurate electricity prices. Otherwise, the predicted profit could reduce significantly and even can turn into a loss. Finally, over the 5-year period investigated (2005–2009) the annual profit from the PHES facility varied by more than 50% on five out of six electricity markets considered. Considering a 40-year lifetime of PHES, even with low investment costs, a low interest rate, and a suitable electricity market, PHES is a risky investment without a more predictable profit. Steffen [106] analyzed the current development and evaluated the revenue potential as well as possible barriers for the development of PHES and stated that the prospects for new pumped-hydro storage plants have improved, even though profitability still remained a major challenge.

Murage and Anderson [107] investigated the benefit of optimally integrating wind power with pumped hydro storage in Lake Turkana Wind Power project, Kenya. The simulation results showed that the daily wind power pattern does not match the daily load pattern and hence the introduction of pumped hydro storage reduced the system's total power output shortage by 46%. The integration of pumped hydro storage with the wind farm was found to increase the expected daily revenue of the wind farm by over 10 thousand dollars.

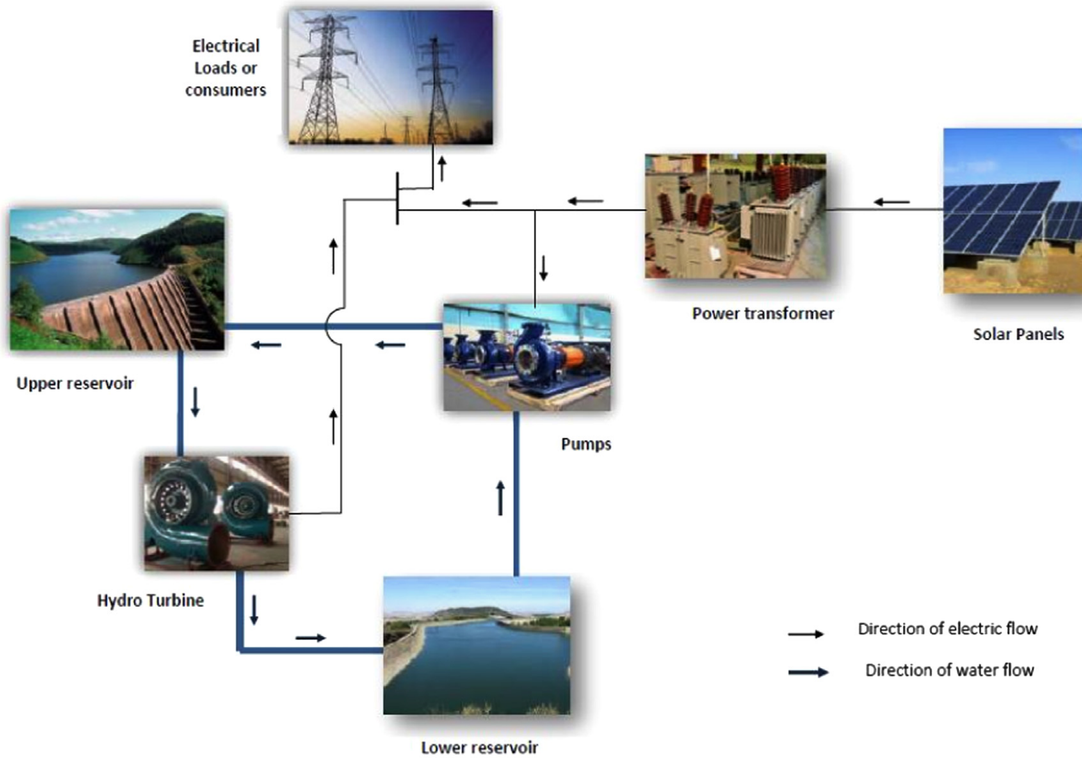

Fig. 7. A conceptual solar photovoltaic based PHES.

8. Solar photovoltaic pumped hydroelectric energy storage (PV-PHES) plants

The energy from the sun is intermittent in nature and also available only during day time. Hence, to make its best and continuous use, an energy storage system which can store the energy when excess energy is available and then use the stored energy when it is not available. A photovoltaic based PHES is shown in Fig. 7. The power produced by the PV panels is transmitted through the grid and the extra energy during off peak hours is used to pump the water from a lower reservoir to an upper. The water from the upper reservoir is released through hydraulic turbines to produce energy during peak load hours. This sub-section presents the review of existing, if any, and the theoretical studies reported in the literature on photovoltaic based pumped hydroelectric energy storage systems.

Ma et al. [108] presented a study of the PHES system in combination with solar photovoltaic energy penetration for small autonomous systems in remote areas. The authors developed mathematical models for the major components, system reliability and economic criteria for benchmark and optimization. The study demonstrated that the proposed model and optimization algorithm are effective and can be used for other similar studies in the future. Javanbakht et al. [109] evaluated the transient performance of a small-scale plant consisting of a photovoltaic and a pumped hydroelectric storage system. The proposed system included two six-pulse converters interconnected through a DC link, to which the PV plant was interfaced via a single-stage bidirectional boost converter. The electrical system of the pumped hydroelectric storage plant consisted of a squirrel-cage induction machine supplied by the machine side converter and the hydraulic system included separate turbine and pump units. A scaled linearized model was adopted to represent the elastic water column and surge tank. Simulation results showed the transient performance of the plant during pumping and generating cycles of the complete system. Tao et al. [110] presented the results of a solar photovoltaic based pumped hydroelectric storage system.

Margeta and Glasnovic [111] proposed a hybrid power system consisting of photovoltaic energy generation in combination with pumped hydroelectric energy storage system to provide a continuous energy supply. This creates a new type of sustainable hybrid power plant which can work continuously, using solar energy as a primary energy source and water for energy storage. Junhui et al. [112] proposed a standalone renewable power system to solve the energy and water shortage in remote areas with abundant solar energy. The system utilizes a photovoltaic panel as the main energy source and a battery pack as the energy storage device to smooth the fluctuation of solar power and to mitigate load transients and variations. In addition, a hydro storage system is used for water storage and also for supplying extra electric power via a hydro-turbine generator.

In an earlier study, Margeta and Glasnovic [113] analyzed a possibility of upgrading hydroelectric power plant with solar photovoltaic generator. The authors used the example of hydro energy plant Zavrelje/Dubrovnik in Croatia as a paradigm of renewable energy exploitation. The results of the study confirmed that the proposed solution of hybrid PV-PHES system is natural, realistic, and very promising. Margeta and Glasnovic [114] also presented the characteristics of a hybrid photovoltaic (PV) power plant and PHES to achieve sustainable production of green electric energy comparable to that of conventional energy sources.

Margeta and Glasnovic [115] analyzed the hybrid solar and hydro system that can provide continuous power supply and the possibilities of its implementation in Europe and areas with similar climate. The authors developed a mathematical model for selecting the optimal size of the PV power plant as the key element for estimating the technological feasibility of the overall solution. The study established that apart from the total head, solar radiation, hydro accumulation size and the natural water inflow have the biggest effect on the calculated power of the hybrid power plant. The results clearly showed a wide range of implementation of the solar photovoltaic and pumped hydroelectric storage hybrid system from relatively cold climates to those abundant in solar energy. Glasnovic and Margeta [116] presented the main features of a hybrid power plant comprised of the modified reversible hydroelectric power plant operating together with the photovoltaic power plant. The feasibility and characteristics of the hybrid power plant were tested on electric energy supply of the island of Vis in Croatia. It has been established that the system is real, feasible and can be installed very successfully at different locations and can vary in size.

Manolakos et al. [117] presented the outcome of the implementation of a stand-alone photovoltaic plant in which battery storage was partially replaced by a micro-hydraulic system. The plant was installed on Donoussa Island in the Aegean Sea, Greece to cover basic electricity needs of the remote village of Merssini (13 houses). Lighting, TV-set and refrigerator were considered as the basic electricity needs for each house. The photovoltaic array consisted of 300 photovoltaic modules of 60 W_p each, for a combined 18 kW_p total installed power. The micro-hydraulic system consisted of a water pump of 6 kVA and a water turbine coupled with a DC generator of 7.5 kW and two identical water reservoirs of 150 m^3 capacity each. During the day, the load was satisfied directly from the photovoltaic generator through an inverter while any energy surplus was directed to the pump for pumping water from the low level reservoir to the upper level reservoir. During the night, water is released to the lower reservoir to generate energy using hydraulic turbine. There is also a battery bank of 186 cells of 2 V nominal voltages in series, with a total capacity of 100 A h.

9. Wind, solar, and photovoltaic pumped hydroelectric energy storage (W-PV-PHES) plants

The use of wind-hydro hybrid schemes for power production in islands or isolated regions appears to be the best solution to overcome the problem of wind energy storage and penetration to the grid [58,118–122]. Nowadays PHES in conjunction with renewable energy sources (RES) such as wind and solar photovoltaics [123–126] are being used for desalination of sea water. Due to the intermittent nature of RES, a storage system is usually required to guarantee the desalination unit operation during unfavorable weather conditions. Pumped storage in hybrid wind-hydro power production plants has been studied applying numerical design optimization methodologies in some previous studies [97,127]. Anagnostopoulos and Papantonis [97] presented a numerical methodology for optimum sizing of the various components of a reversible hydraulic system designed to recover the electric energy that is rejected from wind farms due to imposed grid limitations. The results showed that a well optimized design may be crucial for the technical and economic viability of the examined system.

Papaefthymiou and Papathanassiou [128] investigated the possibility of obtaining optimum sizes of major components, (hydro turbines, pumps, wind farm, reservoirs), of a PHES operating in an island system. Genetic Algorithms (GAs) were applied for the optimization and a real isolated island power system. Spyrou and Anagnostopoulos [129] developed a computer algorithm to simulate the entire plant operation and to perform economic evaluation of the investment. The results demonstrated the performance, the role and the contribution of each subsystem along with the production and economics of the complete plant. Vieira and Ramos [130] presented an optimization model for the determination of best hourly operation for 1 day, according to the electricity tariff, for a pumped storage system with water consumption and inlet discharge. Wind turbines were introduced into the system and a

Fig. 8. Aerial view of Okinawa 30 MW capacity sea water pumped storage plant [133].

comparison with the normal water supply operating mode was done, and the energy cost savings with hybrid solution were calculated. He [131] presented a simulation model for the evaluation of the operational benefits of Tianhuangping pumped storage hydro-plant in the Shanghai electrical network. The study showed the efficiency improvement of the overall units and the increase of peak load capacity due to the addition of pumped hydro power plant in the network. Specifically, Tianhuangping plant provided an average coal consumption decrease of 5.1 g/kW h and an additional 600 MW peak capacity for the Shanghai electrical network [131].

10. Seawater pumped hydroelectric storage power plants

There is currently only one seawater pumped-storage hydro system operating in the world, located at the northern coast of Okinawa Island, Japan [132]. The system began operation in 1999 and has the potential to generate up to 30 MW of power. The hydropower plant has a total head, the vertical distance, or drop, between the intake of the plant and the turbine, of 136 m and the upper reservoir is located just 600 m from the coast. It has an octagonal planar shape with its maximum width of 252 m Yoko and Yosuke [132]. Its maximum depth is 25 m and its effective storage capacity is 564,000 m^3. An aerial photograph of the Okinawa sea water pumped storage plant is shown in Fig. 8 [133]. The Dead Sea Power Project (DSPP) [134] is a tunnel and hydropower project that can produce 1500 to 2500 MW of clean and renewable electric energy. The penstock from the reservoir to the Dead will be designed to provide for 800 cm/s flow, enough to power 2500 MW hydro turbine generator capacity. In this project, the water from the Red Sea will flow below the sea level through a 72 km tunnel to a reservoir above Qumran. Surge chambers will be constructed in the penstock near the hydropower plant to prevent water hammering from the sudden closure of a water gate. The steep shoreline will limit the length of the draft tubes exiting the turbines and increase the efficiency of the plant. The value of such electric energy will be maximized by power generation during peak demand times. Planned operation of the project can fill the Dead Sea to the desired level within seven years of operation. After that, the continued operation of the hydropower plant will be enabled by the development of additional desalination capacity to supply the water needs of the region.

In Glinsk [135], Ireland, there is a proposal for a 480 MW seawater pumped-storage hydro plant. This plant would be able to accept approximately one-third of the excess electricity generated by the 5000 MW of wind turbines expected to be in operation by 2020 according to Ireland's energy plan. This plant is expected to work as follows: the facility will accept power, primarily excess wind power during off peak night time hours or when the generation exceeds demand, and use it to pump seawater to the upper reservoir situated on the top of Glinsk Mountain. The stored energy will be returned to the grid through turbines for use during peak times in the morning and evening, or generation emergencies. This will significantly reduce the national need for imported fossil fuels that are required to keep gas, coal, and oil fired power stations running. The proposed 6 GW h energy storage will accept a power flow of up to 1500 MW from wind farms for storage.

Storing electricity at the bottom of the ocean is the new concept from the German engineer Rainer Schramm [136] and could be very effective with an efficiency of around 80%, comparable to conventional energy storage systems. This energy storage system makes use of the pressure differential between the seafloor and the ocean surface. In the new design, the pumped storage power plant turbine will be integrated with a storage tank located on the seabed at a depth of around 400–800 m. The way it works is: the turbine is equipped with a valve, and whenever the valve is opened water flows in and turns the turbine. This turbine then turns the generator which finally produces the electricity. A typically-sized system will be able to produce around 300 MW, for a time period of about 7–8 h, enough to power about 200,000 British households. At strong wind conditions, excess electricity can be sent subsea to pump water out of the storage tanks. In periods with little wind, energy can be obtained from this underwater plant instead. The same can be applied to solar generation: the pumped storage power station can contribute to constant electricity production at night time when there is no sunshine to run a solar power plant. The flexibility extends not just to the turbine and tank sizes, but also to the depth the system is installed at.

A seawater pumped storage power project is proposed to meet the peak demand in East Java [137]. The proposed East Java seawater pumped storage power project is located near the Watangan Mountain in Lojejer Village Wuluhan County Jember Province of East Java State. This project is expected to have the plant capacity of 800 MW with 242 m^3/s maximum discharge of seawater and 389.4 m effective head by connecting the upper pond placed near the top of the mountain and the Indian Ocean as the lower pond by around 1900 m long waterway. The dam for upper pond will be funneled type rock-fill dam faced by asphalt concrete with around 47 m height and with around 5900,000 m^3 effective water storage. The waterway will consist of around 850 m long headrace tunnel and 1050 m long tailrace tunnel. The generating duration is designed to be 6 h maximum per day. The energy produced is expected to be transmitted to Paiton–Kediri transmission line through the newly constructed 80 km transmission line. The energy for pumping the sea water will be obtained from Paiton Thermal Power Plant through the transmission line.

Recently, Kotiuga et al. [138] conducted a pre-feasibility study of a seawater pumped storage system and showed that a 1000 MW pumped storage plant, that could generate power for 8 h, would eliminate the need for 1000 MW thermal plants burning heavy fuel oil. The study identified a number of potential sites and ranked them using multi-criteria analysis (MCA) based on geological conditions; environmental and social impacts, capital cost and economic viability; as well as access to the transmission grid. The study further emphasized that mitigation of corrosion effects from seawater may be a major issue and may become a significant cost factor. To identify candidate seawater sites, topographic studies were made of the whole coastline from Aqaba to the Yemen border, approximately 1800 km [138]. The screening of potential sites was made using the head limit of 800 m, and L/H of less than 20. Three alignments in the Gulf of Aqaba were identified that met the basic criteria. This provided the initial conclusion that the Gulf of Aqaba offered the most potential for economic pumped storage development. In terms of construction access, the preferred site of these three, referred to as the Magna site (XS-1) was selected on the basis of better topography in the powerhouse/tailrace areas. The Magna site with 1000 MW installed capacity will consist in 4 turbines, each of 250 MW, head 755 m, L/H of 4.64, turbine discharge of 165 m^3/s, upper reservoir storage of 5 h^2 m (total), and reservoir dam of 80 m high × 350 m crest length.

10.1. Discussion

Electrical energy storage is an important area for optimal utilization of renewable sources of energy generation through existing electrical transmission and distribution infrastructure in all parts of the globe. It has been argued by many researchers [5–38] through experience, experimental work, and modeling studies that the throughput of renewable sources of energy will increase with usage of bulk energy storage options. It has been established that a favorable and realistic way to introduce pumped storage in island systems is based on the concept of hydroelectric power storage operating in a coordinated manner [15–21]. Furthermore, the usage of bulk energy storage systems has been proven to reduce wastage of renewable energy generation and specially wind energy by 10% [22–26].

The undergoing review proved that pumped hydroelectric storage plants have several advantages such as flexibility to start/stop, fast response speed, capability to track load changes, adaptability to drastic load changes, modulating the frequency and maintaining voltage stability. Though PHES systems were seen by most researchers and developers as prohibitively costly, but are universally viewed as technically capable of providing renewable support and peak power adequacy. A large number studies, more than 35, have reported that wind power and PHES integrated power systems are the most economically and technically competitive technologies in different geographical areas. The combined use of wind energy with PHES is considered as a mean to exploit the abundant wind potential, increase the wind installed capacity and substitute conventional peak supply.

Whereas sea water PHES is concerned, only one 30 MW capacity plant is operational in Japan. There are some other projects in different stages of feasibility studies and evaluations, such as Dead Sea Power Project of 2500 MW capacity, pumped storage plant of 1000 MW capacity in Saudi Arabia, and 480 MW capacity PHES in Ireland. The Dead Sea Power Project plant will also compensate the depleting water level of the Dead Sea. Another 800 MW installed capacity pumped hydroelectric energy storage plant is under consideration in East Java, Indonesia.

10.2. Concluding remarks

An extensive review of pumped hydroelectric energy storage (PHES) systems is conducted, focusing on the existing technologies, practices, operation and maintenance, pros and cons, environmental aspects, and economics of using PHES systems to store energy produced by wind and solar photovoltaic power plants.

It has been agreed by the scientific community that massive electricity storage is the critical technology for the renewable power, if it is to become a major source of base load despicable power. Among all existing storage technologies, PHES is the most suitable technology for small autonomous island grids and massive energy storage both technological maturity and economical compatibility over the lifespan of the project. The energy efficiency of PHES varies in practice between 70% and 80% with some claiming up to 87%. The largest PHES stations are in the range of 2000 to 3000 MW installed capacities around the globe. However, PHES sizes in the range of 1000 MW to 1500 MW are more common. Globally, the typical sizes of turbines were found to be 300 to 400 MW in larger PHES.

The main purpose of PHES is to utilize excess energy from the grid during off peak hours or the excess energy produced by wind farms or solar photovoltaic power plants to pump the water from the lower reservoir to the higher reservoir and then release the water from the higher reservoir to the lower through the hydraulic turbines to produce energy during peak load hours. In this way, the wastage of energy from either of the three sources can be minimized and the excess energy can be optimally utilized.

According to the studies and experiences reviewed, there should be no technical issues for instantaneous wind penetrations of up to 20% on an electric grid. However, a maximum of 25–50% wind penetration may be feasible within the electricity sector. Furthermore, it is reported in the literature that the feasibility of very high wind penetrations decreases dramatically, when the size of the electricity grid increases from 100 kW to 10 MW. For a 100 kW grid a wind penetration of 80% is feasible, but for a 10 MW grid a wind penetration of only 20% is feasible.

On conventional pumped storage development most experience has been developed by USA, Japan, Ukraine, Germany and France. It is worth to mention that the USA and Japan provide about 40% of the total storage capacity through pumped hydroelectric storage systems. The available data from existing projects showed that single-stage reversible pumped storage units are now being designed for up to about 800 m head, and in the next decade this limit is expected to increase to about 900 m. Higher heads may be developed using multiple stage arrangements.

The photovoltaic based pumped storage systems were found in the literature, but for very small applications such as load of a few houses. However, the theoretical framework and modeling studies were reported in the literature.

Experience of pumped storage using seawater is limited to a single project in Japan, the 30 MW Okinawa project with a head of 136 m. A much larger PHES plant, with about the same head, is at the conceptual study stage in Ireland. No direct information was found on the cost of erosion protection needed for a seawater plant, or the overall reliability and life of such protection.

The other parameter of interest was the relation between the head (elevation difference between upper and lower reservoirs) and the distance between reservoirs (approximately the overall water conduit or tunnel distance). Clearly, the shorter the distance in relation to the head the more cost effective the layout is. Comparison of this parameter (L/H) showed that plants being developed were almost always with a ratio of less than 10. Thus, for a maximum head of 800 m, the maximum distance between the upper and lower reservoirs should be less than 8 km.

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