OVERVIEW OF PUMPED HYDROELECTRICITY STORAGE SYSTEM TO PRODUCE CLEAN ENERGY

Tawsif Hossain Chowdhury

Abstract**—**With steadily increasing the prices of fuel and growing concerns over the environment, the energy from renewable resources, particularly hydro energy is becoming very popular throughout the world. However, the main shortcoming of hydropower is its inconsistent water flow from the source. This uncertainty has ignited a renewed interest in Pumped Hydroelectric Energy Storage plants. Pumped storage systems today are considered one of the most effective methods to overcome the regular water variability problem. In this report, the introduction of pump storage facilities is investigated along with its technical and economic feasibility.

Keywords**—**Renewable Energy, Pumped Storage Energy, Hydroelectricity, Clean Energy, Economic Analysis.

I. INTRODUCTION

PUMPED storage hydropower (PSH) is one of the customized forms of conventional hydropower technology to store energy and generate electricity. There is a significant number increase in hydroelectric pumped storage systems in the last 20-30 years which has given electricity utility companies the flexibilities to meet the daily extra demand when needed with the capabilities of a quick startup [1]. More often this scheme is used during the high demand period of electricity. Typically, a pumped storage project is designed to have 6 to 20 hours of generation during peak hours [2]. So that the big power generation units like nuclear units can operate in their baseload mode.

II. HISTORY OF PUMPED STORAGE HYDROPOWER

Thought-out the history of mankind, we can see that Humans have been trying to harness water to perform work. Gradually humans learned how to generate electricity using water. The evolution of the modern hydropower turbine began in the mid-1700s. But the idea of Pumped-storage hydropower came on the scene in the late 1900s. The first Pumped storage hydro plant was constructed in Switzerland; it started operations in 1909 [3]. The Rocky River Plant was the first major pumped storage hydroelectric plant in the USA, starts operation in 1929 [1]. Several pump storage plants were built between the 1960s to the late 1980s. The major reason was due to the oil crises in the early 1970s [4]. Earlier plants were very basic; each plant consists of a motor and pump on one shaft and a turbine on the separate shaft. In 1956, the Tennessee Valley Authority commissioned the first reversible pump (Hiwassee Unit 2). After that, a huge development in technology and materials has been seen to not only improve the overall efficiency but also allow increasingly more units to be constructed for higher demand [5].

T. H. Chowdhury is with the Department of Electrical and Electronic Engineering, Southeast University, Tejgaon I/A, Dhaka, Bangladesh (E-mail: *thchowdhury @seu.edu.bd*).

III. EVALUATION OF PUMPED STORAGE HYDROELECTRICITY

A pumped storage hydro plant can be considered as a mechanical storage mechanism, which stores potential energy from water by raising it against gravity in a big reservoir. Electricity is generated by employing the gravitational differences between two water storage reservoirs [6].

A typical conventional PSH system consists of two reservoirs known as the upper reservoir and the lower reservoir as shown in Fig. 1. These two are connected by a penstock (a connecting pipe) that carries water from one reservoir to another. These two reservoirs must be positioned at different altitudes.

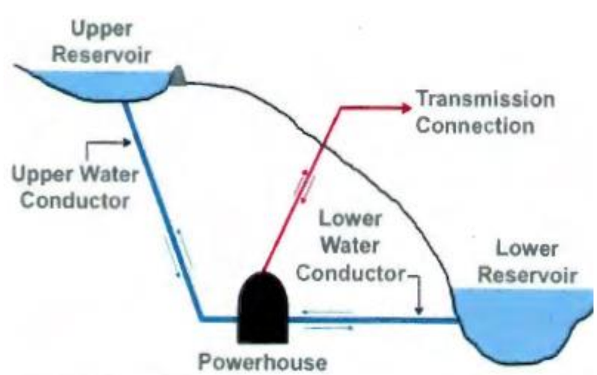

Fig. 1. Typical PSH Configuration [5]

The plant also consists of a powerhouse with a pump/turbine and a motor/generator and a transmission connection with the main power grid as shown in Fig. 2 that illustrates the whole process of PSH to generate the power. When the upper reservoir releases the water, energy is generated by the downward flow which is designed to flow through the high-pressure shafts that are linked with the turbines.

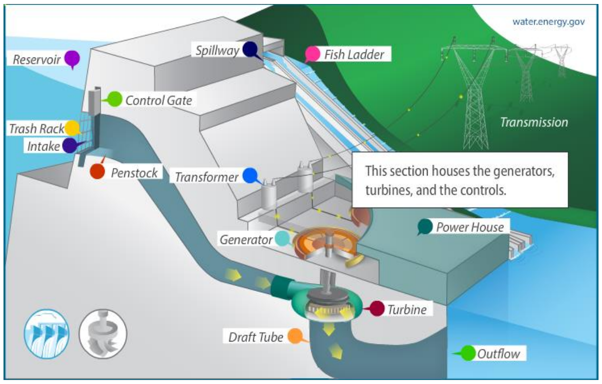

Fig. 2. The electricity generation process of PSH [7]

Finally, the turbine starts to rotate the shaft which consequently rotates a series of magnets past copper coils in a generator to produce electricity. From the generator room, transmission lines carry electricity to the end-users/clients. [7].

During off-peak hour usually, when demand is at its lowest, the pump motors are powered by National Grid electricity to pump back to the upper reservoir using the same system. Pump storage generation offers a critical backup facility during periods of excessive demand on the national grid system. Figure 3 shows the pumping and generation hour on top of the daily load curve. Besides, PSH also provides power system management capabilities such as voltage balancing, frequency stability, and black starts [4, 8].

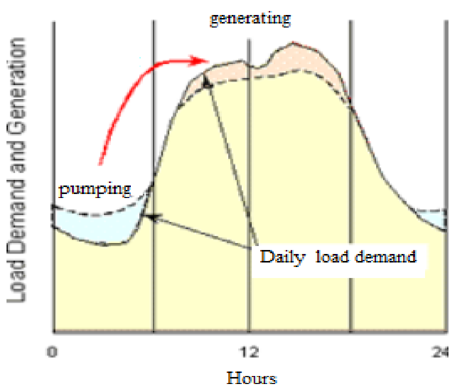

Fig. 3. Load demand (pumping) and generation [12]

Depending on the particular geologic and hydrologic constraints, pump storage hydro plants can be implemented in various ways. PSH projects in most cases use natural lakes or large rivers at high altitudes, or water reservoirs of existing conventional hydro facilities as their reservoirs.

PSH plants that are constantly connected to naturally flowing water from a hill or river are known as 'open-loop' projects. On the other hand, a 'closed-loop' PSH system can be constructed separately from a naturally free-flowing river or lake. An advantage of this application is that there is the least interaction of aquatic life, which also reduces the environmental impacts and concerns [5].

A. Closed Loop

The closed-loop PSH contains two different reservoirs that are isolated from a free-flowing water source. Typical construction of closed-loop PSH system can be seen in Fig. 4. Comparatively, closed-loop systems have much lower impacts on environments. Because, after the initial filing of the reservoirs, minimum make-up water is only required to offset evaporation or seepage losses. Therefore, it greatly reduces aquatic issues like fish passage, sediment migration, etc. The water reservoirs can be artificial or natural. Off-site water sources, as well as gray water, can be considered to fill initially, and evaporation makeup water. Since the closed loop system does depend on the river or lake water, it can be built near the grid with the right topographical features with less transmission loss [9].

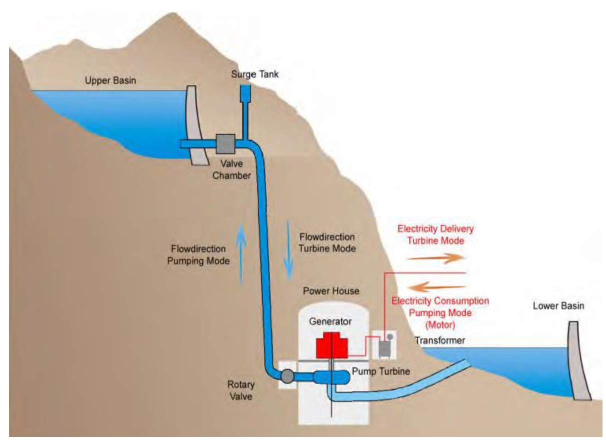

Fig. 4. Closed-loop pumped storage plant arrangement [3]

B. Open Loop

Virtually maximum existing pumped storage projects are open-loop systems. It uses the free flow of water from the upper reservoir. The Okinawa Yanbaru Seawater Pumped Storage Power Station (Japan, commissioned in 1999) is an example of such an open loop plant where the sea is used as the lower reservoir [10]. In the open-loop system, we have to deal with various issues like water temperature, minimum water flow, drought, fish passage, etc. [3]. Figure 5 shows an open-loop system in which water is released in nature after the power generation.

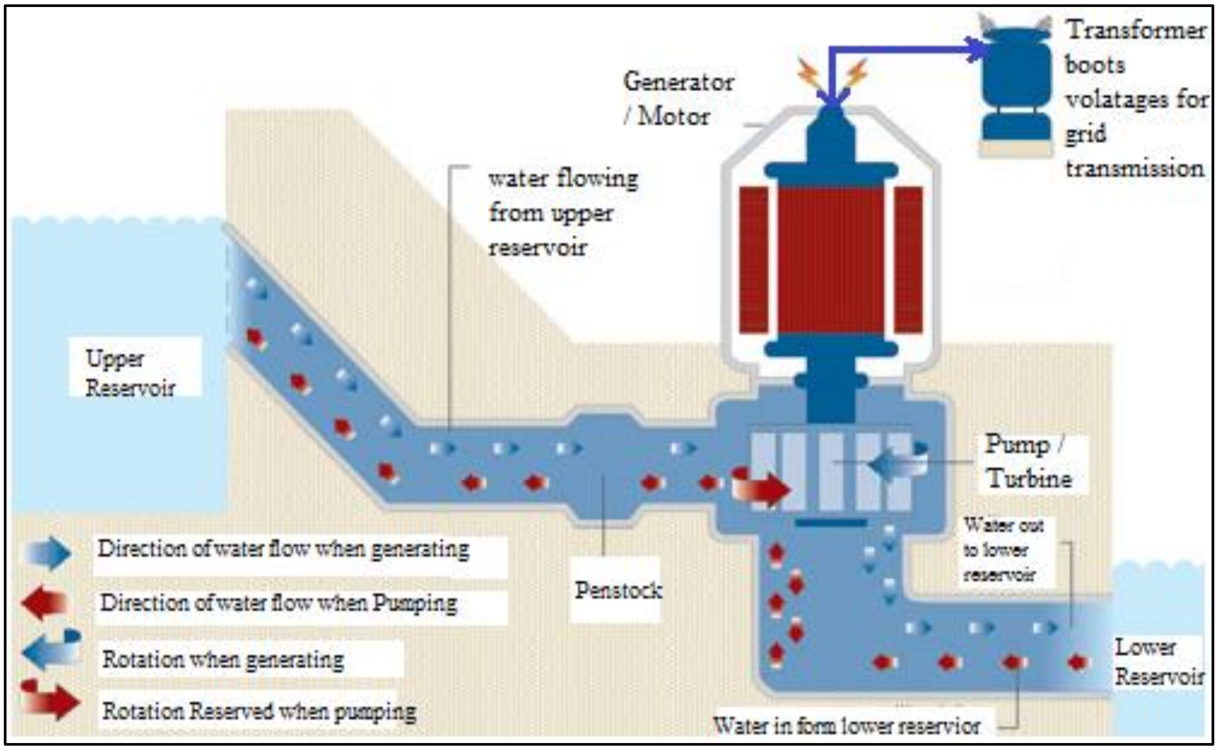

Fig. 5. Open-loop pumped storage hydropower plant arrangement [7]

The present worldwide capacity of pumped storage is about 140 GWe. Figure 5 shows the names of the plants which has the largest capacity to generate power through the pumped hydro method. Approximately 45 GWe of pumped storage capacity is stalled in the European Union region. Whereas in Asia, Japan (30 GWe) and China (24 GWe) are the leading countries for pumped hydropower electricity generation. In the northern American region, U.S.A. has around 38 pumped hydroelectric facilities that contribute just about 2 percent (20 GWe) of the country's total electrical generation. This amount is comparatively small compared with Europe's (nearly 5%) and Japan's (about 10%) [12]. Table 1 shows the list of the largest ten such power stations in various parts of the World [13].

TABLE I
THE LIST OF 10 LARGEST STATIONS [14]

Plant Name	Country	Capacity (MW)
Bad Creek Hydroelectric Station	USA	1,065
Bailianhe Pumped Storage Power Station	China	1,200
Baoquan Pumped Storage Power Station	China	1,200
Bath County Pumped Storage Station	USA	3,003
Blenheim-Gilboa Hydroelectric Power Station	USA	1,160
Castaic Power Plant	USA	1,566
Coo-Trois-Ponts Hydroelectric Power Station	Belgium	1,164
Čierny Váh Pumped Storage Power Plant	Slovakia	735.16
Dinorwig Power Station	UK	1,728
Drakensberg Pumped Storage Scheme	South Africa	1,000

Table 2 shows the generation capacity through PSH in 2014 of several countries and the world as a whole. United States of America and Japan are among the highest amount of energy generating countries [12].

TABLE II
PUMPED STORAGE HYDRO PRODUCTION IN 2014 [13]

Country/Region	Energy (GWh)
World	113770
USA	20054
Japan	21601
China	13200
Germany	5857
India	4949
Austria	3826
Spain	3801
UK	2883

IV. TYPES OF TURBINE

Two types of turbines are used in a pumped storage hydro plant; impulse turbines and reaction turbines.

Generally, impulse turbines are used for a higher head and relatively lower flow of water. Water is thrown through a nozzle directed towards the turbine blades, which push the turbine to rotate. In this case, the water will hit the nozzle with a great velocity from the height. Two to six nozzles are distributed uniformly around the turbine surface. Pelton turbine and Cross-flow turbines are the most commonly used impulse turbine.

With relatively low head and higher water flow, it is recommended to use reaction turbines. The conversion of energy conversion from water does not occur at atmospheric pressure, as it does in the case of an impulse turbine. The pressure of water continuously changes as it strikes the turbines and transfers energy. The most popular reaction turbine in the market is the Kaplan and Francis turbines. Blades can be adjustable in the Kaplan turbine. This is a propeller-like water turbine. Adjustment of the angle of the propeller blade can lead to high efficiency. Wicket gates are also adjustable over a wider range of head and flow [14].

The Francis turbine's inlets are made spiral-shaped and this shape helps to guide blades to direct the water tangentially onto the turbine runner to produce high speed. Adjusting the blades helps to achieve higher efficiency over a various range of head and flow. Francis turbines are the most commonly used turbines that are used in pumped storage plants [14].

V. Cost

The cost per kWh unit may be a little bit on the higher side if compared to other renewable energy sources. But still, the setup cost and efficiency of the PSH overcome the cost issue. Table 3 shows the cost comparison per kWh among all renewable sources in 2018. Table 3 shows the cost comparison per kWh among all renewable sources in 2018 [15-16].

TABLE III
COST OF PER UNIT OF RENEWABLE ENERGY [16-17]

Power Plant Type	Cost $/kWh
Wind	0.056-0.127
Solar PV	0.085
Concentrating solar power	0.185
Geothermal	0.072
Biomass/Bioenergy	0.062
Hydro	0.047
Pumped Hydro	0.175

The setup cost of a pumped-storage hydroelectricity plant depends on various matters like geographic placement; labor cost etc. here is a brief overview of cost estimation. Below is the table of cost and efficiency of storage technologies [17]. Table 4 represents the per kW energy cost of PSH of a matured plant. The costs are in the US dollar rate of the year 2013.

TABLE IV
COST AND EFFICIENCY OF PUMPED STORAGE TECHNOLOGY [18]

Technology	Maturity	Cost ($/kW)	Cost ($/kWh)	Efficiency	Cycle	Response Time
Pumped Hydro	Mature	1,500-2700	138-338	80%–82%	no	Seconds to Minutes

The primary cost estimate for the pumped storage plant with a small capacity of 250 MW is $5,595/kW. This cost includes mainly engineering structural cost and power distribution/management cost. For this type of technology and power plant configuration, design differences, local technical support, location environmental issues, labor cost, productivity differences, and the increase in overheads associated with the power transmission have also been taken into consideration.

VI. Conclusion

Although traditional pumped-storage hydroelectricity is considered a 100% source of renewable energy. The main reason behind this is that during the transfer of water from its lower reservoir to the upper reservoir, this system requires electricity from the national grid during the off-peak hour. But if the power for pumping this water can be managed from another renewable source like solar/wind, then pumped storage hydro plant can be considering as 100% renewable energy plant. PSH shows a great prospect and can become a reliable substitute option for gas turbine/coal plants in many countries. Studies have found that 15GW PSPs with a storage capacity of 96GWh replace up to 13GW from gas power plants in a 60% scenario. In the UK, PSH is used to meet the extra demand during peak period as it has a black start (can run at zero loads) and quick-start capability compare to other power plants [19].

References

[1] Dames and Moore. "*An Assessment of Hydroelectric Pumped Storage,*" The U.S. Army Engineer, USA, 1981. [Online] Available: *https://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/IWR019-000001-000517.pdf.*

[2] Energy Storage Association. "*Pumped Hydropower,*" Washington, USA, 2016. [Online] Available: *www.energystorage.org/energy-storage/technologies/pumped-hydroelectric-storage.*

[3] M. Michael, M. Debbie, T. Kelly. "*Challenges and Opportunities for New Pumped Storage Development,*" 2014. [Online] Available: *http://www.hydro.org/wp-content/uploads/2012/07/NHA_PumpedStorage_071212b1.pdf.*

[4] N. Dorji, "*Wind Following with Pumped Hydroelectric Energy Storage in New Brunswick,*" MSc. Thesis, University of Rajasthan, India, 2004.

[5] F Upton, "*Pumped storage and potential hydropower from conduits,*" US Department of Energy, 2015. [Online] Available: *https://www.energy.gov/sites/prod/files/2015/06/f22/pumped-storage-potential-hydropower-from-conduits-final.pdf.*

[6] O. Torres, "*Life cycle assessment of a pumped storage power plant,*" MSc. Thesis, Norwegian University of Science and Technology, 2011.

[7] IEA Technology Cooperation Programme, "*Hydropower, bioenergy, CSP and geothermal,*" 2016. [Online] Available: *https://www.iea.org/reports/renewables-2020/hydropower-bioenergy-csp-and-geothermal#hydropower.*

[8] Engie, "*First Hydro Company,*" [Online] Available: *https://www.fhc.co.uk/en/about/.*

[9] J. I. Pérez-Díaz, M. Chazarra, J. García-González, G. Cavazzini, and A. Stoppato. "Trends and challenges in the operation of

pumped-storage hydropower plants," *Renewable and Sustainable Energy Reviews*, vol. 44, pp.767-784, 2015

[10] Energy Storage Association, "*Surface Reservoir Pumped Hydroelectric Storage,*" Washington, USA, 2016. [Online] Available: *http://energystorage.org/energy-storage/ technologies/surface-reservoir-pumped-hydroelectric-storage.*

[11] M. A. Tilahun, "*Feasibility Study of Pumped Storage System for Application in Amhara Region, Ethiopia,*" MSc. Thesis, Royal Institute of Technology, Sweden, 2009.

[12] A. Whiteman, J. Esparrago, T. Rinke and I. Arkhipova, "Renewable Energy Statistics 2016," *The International Renewable Energy Agency* (IRENA), Abu Dhabi, UAE, 2016. [online] Available: *https://www.irena.org/-/media/Files/IRENA/ Agency/Publication/2016/IRENA_RE_Statistics_2016.pdf*.

[13] Wikipedia, '*Pumped-storage hydroelectricity,*' 2016. [Online] Available: *https://en.wikipedia.org/wiki/Pumped-storage_hydroelectricity*.

[14] V. Koritarov and L. Guzowski, "*Modeling Ternary Pumped Storage Units,*" 2013. [Online] Available: *https://ceeesa.es.anl.gov/projects/psh/ANL_DIS-13_07_ Modeling_ Ternary_Units.pdf*.

[15] H. Anuta, P. Ralon and M. Taylor, "Renewable Power Generation Costs in 2018," *The International Renewable Energy Agency* (IRENA) Abu Dhabi, UAE, 2018. [Online] Available: *https://www.irena.org/-/media/Files/IRENA/Agency/ Publication/2019/May/IRENA_Renewable-Power-Generations-Costs-in-2018.pdf.*

[16] T. Kelly, "*A Study - How the Cost of Storage per MWh Varies with Different Storage Technologies and Different Applications,*" Intertek, 2017. [Online] Available: *https://www.intertek.com/blog/2017-10-06-grid-scale-energy/*.

[17] Ecofys, "*Energy Storage Opportunities and Challenges,*" 2014. [Online] available: *https://energyexemplar.com/wp-content/ uploads/ecofys-2014-energy-storage-white-paper.pdf.*

[18] I. Táczi and Intern, "Pumped Storage Hydroelectric Power Plants: Issues and Applications," *Energy Regulators Regional Association* (ERRA), 2016. [Online] Available: *https://erranet.org/wp-content/uploads/2016/07/Research-Paper_Pumped-Storage-HPPs_final_2016_eng_1.pdf*.

[19] C. Yang, "Pumped hydroelectric storage," *Storing Energy, Elsevier*, 2016, pp. 25-38.

Tawsif Hossain Chowdhury was born in Dhaka, Bangladesh on 17 December 1988. He received the BSc. degree in Electrical and Electronic Engineering from American International University Bangladesh (AIUB) in 2012. In 2017, he completed his MSc. degree in Renewable Energy and Resource Management from the University of South Wales, the UK under the Commonwealth Shared Scholarship.

Currently, he is working as a lecturer in the Department of Electrical and Electronic Engineering of Southeast University, Dhaka, Bangladesh. Previously, he worked at Robi Axiata Ltd. as a project coordinator. He also worked as assistant manager, operations at Sheba ICX (Integrated Services Ltd.). In the last two years, he has published two peer-reviewed research articles in national journals and three in international journals including one in Elsevier. His research interests include renewable energy sources, tandem solar cell, isolated micro-grid design, waste to fuel, waste management.