Pumped Hydroelectric Storage

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Abstract

Pumped hydroelectric storage (PHS) is the most established technology for utility-scale electricity storage and has been commercially deployed since the 1890s. Since the 2000s, there have been revived interests in developing PHS facilities worldwide. Because most low-carbon electricity resources (ex. wind, solar, and nuclear) cannot flexibly adjust their output to match fluctuating power demands, there is an increasing need for bulk electricity storage due to the calls to mitigate global warming. This entry introduces the PHS technology, the pros and cons, its history, and the prospect.

1. Introduction:

PHS is the only widely adopted utility-scale electricity storage technology. As of 2009, there are hundreds of PHS stations operating with total capacity of 127 GW worldwide [1]. Japan currently has the largest PHS capacity in the world. Table 1 shows the installed PHS capacities in major countries.

Table 1. Installed PHS capacities.

Country	Installed PHS Capacity (MW)
Japan	25,183
USA	21,886
China	15,643
Italy	7,544
Spain	5,347

Germany	5,223
France	4,303
Austria	3,580
United Kingdom	2,744
Switzerland	1,655
Poland	1,406
Belgium	1,307
Czech	1,147
Luxemburg	1,100
Portugal	1,029
Slovakia	916
Bulgaria	864
Latvia	760
Greece	699
Croatia	293
Ireland	292
Sweden	45

(Sources: EU member states [2], USA [3], Japan [4], China [5])

A PHS facility is typically equipped with pumps/generators connecting an upper and a lower reservoir (Figure 1). The pumps utilize relatively cheap electricity from the power grid during off-peak hours to move water from the lower reservoir to the upper one to store energy. During periods of high electricity demand (peak-hours), water is released from the upper reservoir to generate power at higher price.

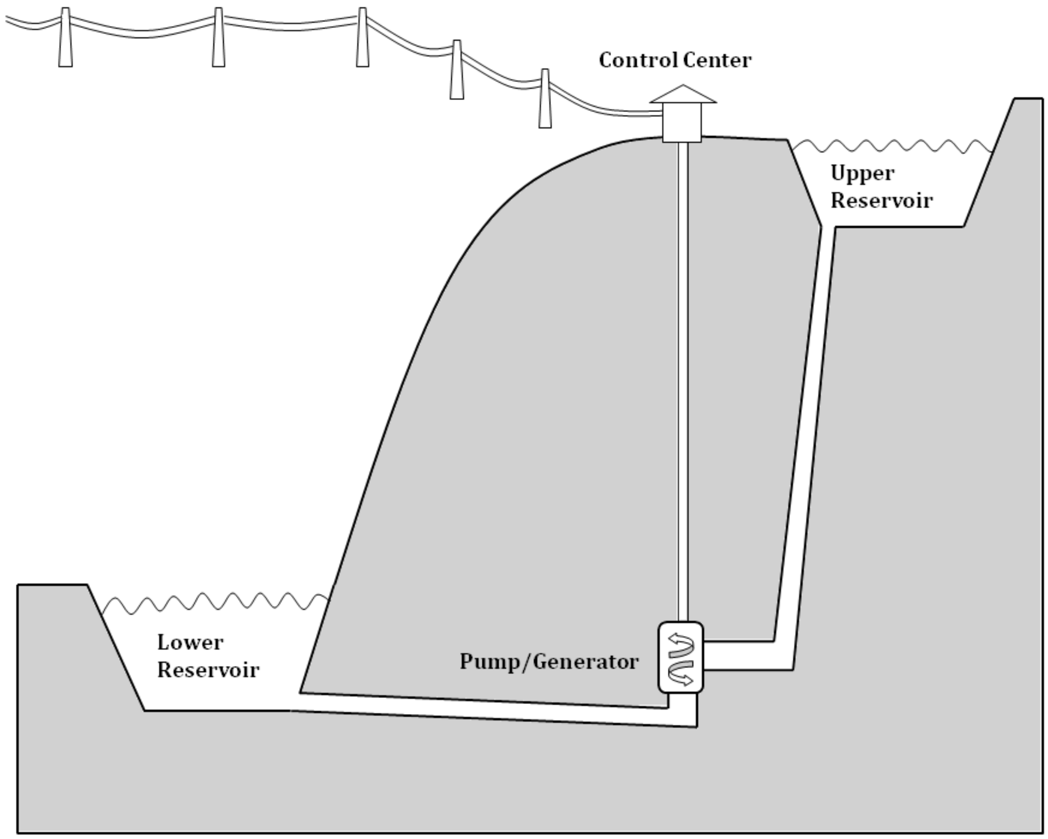

Figure 1. PHS Diagram.

There are two main types of PHS facilities: (1) pure or off-stream PHS, which rely entirely on water that were previously pumped into an upper reservoir as the source of energy; (2) combined or pump-back PHS, which use both pumped water and natural stream flow water to generate power [6]. Off-stream PHS is sometimes also referred to as closed-loop systems. However, some may define closed-loop more strictly as entirely isolated from natural ecosystem.

The efficiency of PHS varies quite significantly due to the long history of the technology and the long life of a facility. The round-trip efficiency (electricity generated divided by the electricity used to pump water) of facilities with older designs may be lower than 60%, while a state-of-the-art PHS system may achieve over 80% efficiency.

2. Significance of Bulk Electricity Storage in a Carbon-constrained World

Most low-carbon electricity resources cannot flexibly adjust their output to match fluctuating power demands. For instance, nuclear power plants best operate continuously and their outputs cannot be ramped up and down quickly. Wind and sunshine are intermittent and therefore the operators of wind turbines and solar power devices have little control over the schedule of electricity output. Utility-scale electricity storage to maintain balance and prevent blackouts remains a significant challenge to a de-carbonized power system.

PHS provides the most proven and commercially viable solution to the aforementioned barrier. It serves to stabilize the electricity grid through peak shaving, load balancing, frequency control, and reserve generation. Currently there is only one alternative technology, i.e. compressed air energy storage (CAES) that can provide bulk energy storage at similar scale to PHS. Unlike PHS, the deployment of CAES is extremely rare. As of 2010, there are only two operating CAES facilities in the world [7].

In recent years, due to increasing concern for global warming and the call to de-carbonize electricity, there has been increasing commercial interest in PHS [8]. Developers are actively pursuing new PHS projects around the world. An additional 76 GW PHS capacity worldwide is expected by 2014 [1]. China has the most aggressive plan. The Chinese government has identified 247 potential PHS sites with total capacities of 310 GW and expects to increase its PHS installation to 50 GW by 2020 [5]. Although Japan already has the highest density of PHS installation in the world, Japanese power companies are continuing to develop more PHS plants. The share of PHS in the total hydroelectric power capacity in Japan is still growing [4].

3. Pros and Cons

By storing electricity, PHS facilities can protect the power system from outages. Coupled with advanced power electronics, PHS systems can also reduce harmonic distortions, and eliminate voltage sags and surges. Among all kinds of power generators, those peak-load generators typically produce electricity at much higher costs than the base-load ones. PHS provides an alternative to peaking power by storing cheap base-load electricity and releasing it during peak hours.

There are several drawbacks in PHS technology. The deployment of PHS requires suitable terrains with significant elevation difference between the two reservoirs and significant amount of water resource. The construction of a PHS station typically takes many years, sometimes over a decade. Although the operation and maintenance cost is very low, there is a high upfront capital investment, which can only be recouped over decades.

Environmental impacts are also serious concerns and have caused many cancellations of proposed PHS projects. Conventional PHS construction sometimes involves damming a river to create a reservoir. Blocking natural water flows disrupt the aquatic ecosystem and the flooding of previously dry areas may destroy terrestrial wildlife habitats and significantly change the landscape. Pumping may also increase the water temperature and stir up sediments at the bottom of the reservoirs and deteriorate water quality. PHS operation may also trap and kill fish. There are technologies to mitigate the ecological impacts. Fish deterrent systems could be installed to minimize fish entrapment and reduce fish kill. The water intake and outlet could be designed to minimize the turbulence. An oxygen injection system could also compensate for the potential oxygen loss due to warming of the water because of pumping. In some cases, the PHS system may serve to stabilize water level and maintain water quality [7]. The potential impacts of PHS projects are site-specific and must be evaluated on a case-by-case basis. Governments usually require an environmental impact assessment before approving a PHS project.

4. Historical Development

The earliest PHS in the world appeared in the Alpine regions of Switzerland, Austria, and Italy in the 1890s. The earliest designs use separate pump impellers and turbine generators. Since the 1950s, a single reversible pump-turbine has become the dominant design for PHS [9]. The development of PHS remained relatively slow until the 1960s, when utilities in many countries began to envision a dominant role for nuclear power. Many PHS facilities were intended to complement to nuclear power for providing peaking power.

In the 1990s, the development of PHS significantly declined in many countries. Many factors may have contributed to the decline. Low natural gas prices during this period make gas turbines more competitive in providing peaking power than PHS. Environmental concerns caused the cancellation of several PHS projects and significantly prolonged the permitting process. Power sector restructure in some countries likely also contributed to this slowdown. During the 1990s, several countries started to restructure the power sector by unbundling generation and transmission. The nature of PHS falls into the gray area between generation and transmission [10]. Because the net electricity output of PHS operation is negative, a PHS facility usually cannot qualify as a power generator. Although PHS provides crucial load-balancing and ancillary services to the grid and reduces the needs for transmission upgrades, PHS facilities do not typically qualify as transmission infrastructure. For instance, in the United States, the Federal Energy Regulatory Commission denied a request from a proposed PHS project to be categorized as a transmission facility for purposes of rate recovery [11]. The regulations for PHS vary from country to country. For example, in China, PHS is considered a transmission facility and the Chinese government charges the state grid corporations with the primary responsibility for developing PHS and allows them to recover costs of PHS through transmission tariffs [5].

5. Prospects

In recent years, in addition to the worldwide revived interests in developing conventional PHS projects, many developers are also proposing new approaches. Japan pioneers in utilizing seawater PHS. The Okinawa seawater PHS station, which has commenced operation in 1999, is the world's first seawater PHS system [12]. A similar seawater project has been proposed in Ireland. Researchers had proposed the possibility of utilizing an underground cavern as the lower reservoir for a PHS project since the 1970s [13]. The commercial interests in developing underground PHS have surged in recent years in the United States. Several developers have received preliminary permits to study the feasibility of building underground PHS facilities at their identified sites [7]. There are also projects in the United States proposed to use groundwater and recycled wastewater for PHS [7].

Many existing PHS facilities were built many decades ago and therefore were equipped with outdated and inefficient technology. There is a significant potential in increasing PHS capacity simply by renovating and upgrading the existing PHS facilities. In addition, many existing conventional hydropower stations could be re-engineered to add pump-back units and become combined PHS stations.

Although PHS may be an essential enabling technology for de-carbonizing electricity, the political will to mitigate carbon dioxide or to remove regulatory barriers for PHS is far from certain. The price of natural gas is also a key determinant in the future of PHS. Because PHS is essentially a peak-load technology, which competes directly with gasfired power, low natural gas price would render PHS uncompetitive. The vision of de-carbonizing electricity and how PHS fits into that vision will like vary from country to country.

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