CHAPTER 7

Technological advances in prospecting sites for pumped hydro energy storage

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7.1 Introduction

Global energy demand is increasing rapidly as the world's population grows, posing a threat to society and the environment (Hussain, Rahman, Sivasengaran, & Hasanuzzaman, 2019). One of the human systems, most immediately affected by climate change, is energy usage. In predicting the future energy demand for a variety of energy sources, there exists the interaction of several factors of uncertainty including population increase, economic growth, differences in the sectoral blend of economies, individual and organizational behavior, as well as the rate of technology advancement (van Ruijven, De Cian, & Sue Wing, 2019). The art of predicting future energy demands has become a central part of every national policy analysis as far as energy-related factors and constraints are concerned (Rosenberg, Lind, & Espegren, 2013). According to the sixth intergovernmental panel on climate change assessment report, anthropogenic activities on the globe are causing an increase in temperature, and thus by the end of the century, the world is most likely to suffer from the associated negative climate change impacts. The most prominent element contributing to climate change is the emission of greenhouse gases, with carbon dioxide (CO_2), from the combustion of fossil fuels, being the most significant contributor (Masson-Delmotte et al., 2021; York, 2016).

Due to the intermittent nature of renewable energy (RE) sources, the mismatch between demand and supply continues to be a major difficulty for the penetration of RE sources. This situation is, of course, surmountable with energy storage solutions. Electrochemical, pumped hydro, and compressed air are some of the technological options for energy storage. However, batteries that consist of regenerative fuel cells and rechargeable batteries are considered the most suited and cost-effective solutions for sustainable RE technologies (Hussain et al., 2019; Leung et al., 2012).

A fifth of the global energy generation is hydropower. Hydropower is the primary source of energy supply for about 55 countries as well as

being the only domestic energy source for many countries. As a result, its current contribution to electricity generation is far bigger than that of any other RE source, and its prospects, particularly in developing nations, are enormous (Yuksel, 2010). An enhanced environmental benefit harnessed from hydropower is linked to the fact that there is neither consumption nor contamination of the water resource during energy generation. Profits from the sale of power generated from hydropower plants could be used to fund several social amenities and interventions such as drinking water supply systems, agricultural irrigation projects, navigational infrastructure, recreational amenities, and ecotourism (Yuksel, 2010; Yüksel, 2010).

7.2 Pumped hydro energy storage

Pumped hydroelectric energy storage (PHES) utilizes the elevational difference and hence the potential energy of water that has been pumped from a lower elevation reservoir to a higher elevation reservoir. In moving the water from a lower to a higher reservoir, the technology makes use of a cheaper off-peak source of power to effect pumping. To ensure profitability, power is thus generated from the activities of a turbine by allowing the raised water in the higher reservoir to return to the lower elevation reservoir during peak demands when electricity cost is high. Reversible turbine/generator assemblies serve as a pump or a turbine, depending on the situation (see Fig. 7.1). The method is considered to be the most cost-effective way of storing massive quantities of electrical power, although capital costs and geographical constraints are major deciding factors. Almost every PHES power plant's design depends heavily on the site's characteristics. If the geography and geology of the area are favorable, a site with sufficient water is considered excellent for the establishment of a PHES plant. Table 7.1 provides the various typologies of PHES.

The site selection process, being the first stage in implementing a project, is critical throughout the PHES plant's life cycle. It is critical to choose the right construction site to maintain economic, social, and environmental benefits. Choosing an unreasonable site may substantially impede the construction process, resulting in additional cost overruns and affecting peaking capacity (Ding, Duan, Xue, Zeng, & Shen, 2015).
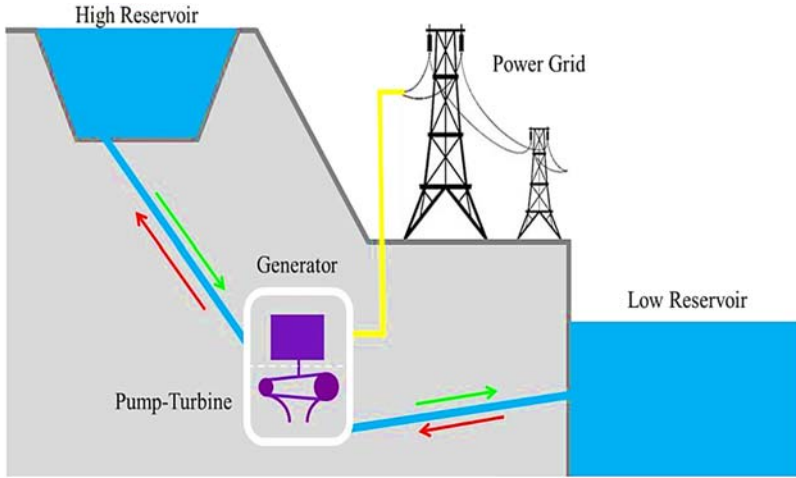
Figure 7.1 A schematic view of a typical pumped hydroelectric energy storage illustrating the direction of water flow at various modes (Zhu & Ma, 2019). *Zhu, B. S., & Ma, Z. (2019). Development and prospect of the pumped hydro energy stations in China. Journal of Physics: Conference Series, 1369(1), 012018.*

Table 7.1 Pumped hydroelectric energy storage topologies (Andrade, Kelman, Cunha, de Albuquerque, & Calili, 2020).

Typology	Description
T1	This makes use of two existing reservoirs connected to one or more penstocks in addition to a powerhouse which forms a pumped hydropower storage (PHS) scheme
T2	This is composed of an existing lake/reservoir connected to a newly built reservoir. The newly built reservoir is often constructed on a flat area with excavation and embankments or a valley or even sometimes depression
T3	This is composed of a greenfield pumped hydropower storage constructed within valleys, close-by dams, depressions, or hilltops
T4	This sea–based system makes use of the sea as a lower reservoir connected with a new one. Alternatively, the system may be composed of higher elevation basin reservoir linked to cavern as a lower elevation reservoir
T5	This multi–reservoir system makes use of the combination of pumped hydropower storage and conventional plants
T6	This system has a lower reservoir that receives adequate inflows from a major river
T7	This type utilizes an abandoned mine pit reservoir similar to the T2 arrangement

7.3 Potential sites for pumped hydroelectric energy storage

7.3.1 Traditional (conventional) river-based pumped hydroelectric energy storage

Many extant greenfield pumped hydropower storage systems were created in tandem with traditional river-based hydropower plants. Two reservoirs at varying heights but located not far from each other are formed. The lower reservoir is usually huge and on a major river, while the upper reservoir is smaller and situated further up on the same river or in a high-tributary or parallel valley. A substantial amount of water from the river goes through the system, creating power, before flowing down to the river. The recycling of water between the two reservoirs provides an avenue for energy storage. Pumping is done by purchasing electricity at periods when prices are not expensive, such as when demand is low or when other sources of power are abundant. Generation generally takes place during periods of peak demand and high prices. The system of buying power at a low cost and using it to generate power, which is in turn sold at a higher price, is what is termed arbitrage (Blakers, Stocks, Lu, & Cheng, 2021).

7.3.2 Off-river (closed-loop) pumped hydro systems

River-based pumped hydro systems account for nearly all extant pumped hydro systems. There are significant environmental and social concerns to damming or changing the dynamics of rivers in many regions. Alternative techniques of establishing pumped hydro systems do not cause large changes to river dynamics. One option is to use subterranean tunnels and powerhouses to connect existing reservoirs (such as old mining sites) that are near together. Surface disruption is minimal when handled with care and the construction period is reduced compared to river-based PHES (Blakers et al., 2021).

7.4 Factors to consider in the pumped hydroelectric energy storage site selection

7.4.1 Geographic and engineering factors

Locating a site for PHES can be a daunting task even for the most experienced engineers. It proceeds with a suitable assessment of the site for PHES. The primary requirement is that the site where the PHES is to be

situated should store an adequate volume of water compared with the quantity of materials (e.g., rock) used for the reservoir wall construction. Also, there should be a high altitude difference ("head") between the paired site. The requirement for PHES, however. goes beyond reservoir identification, existing/possible constraints, and technologies assessment, as depicted in Fig. 7.2. Social, economic, and environmental factors play a significant role in site selection for PHES as presented in Fig. 7.3 and are discussed below.

7.4.2 Environmental factors

Many environmental factors affect PHES including:
- Implementing a pumped hydro project may involve an alteration to either the daily water level or the water flow rate or both. Any of the scenarios would have a deleterious influence on the aquatic environ-ment within a reasonable distance of the project area.
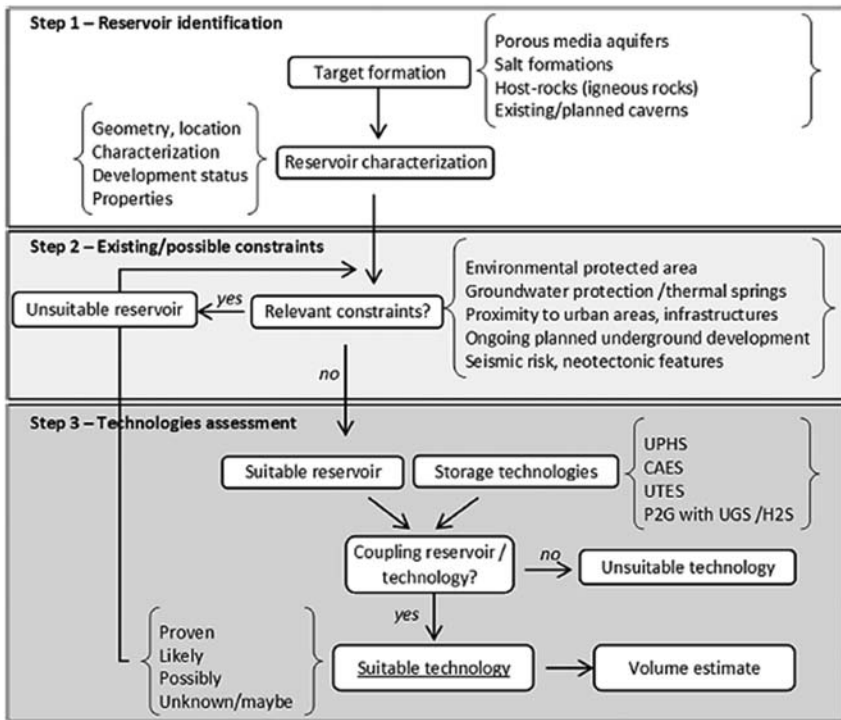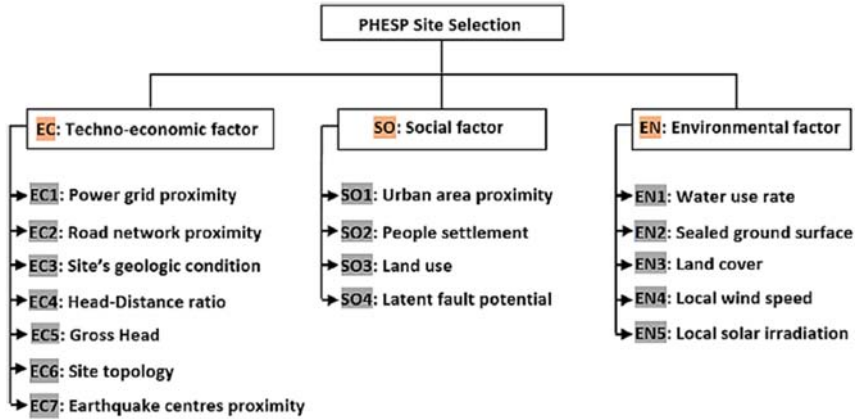

Figure 7.2 Reservoir selection (Carneiro, Matos, & van Gessel, 2019).

Figure 7.3 Factors for site selection of pumped hydroelectric energy storage (Nzotcha et al., 2019).

- Sealed ground surface: This refers to a previously dry land surface that will be inundated to create a man–made reservoir with known environmental impacts (e.g., modifications in soil humidity, animal movement).
- Land cover: The quantity of vegetation to be inundated as a result of the formation of the reservoir, as well as the accompanying carbon dioxide (CO_2) release, has a significant environmental impact.
- Local solar irradiation: Connecting the PHES to a local solar farm as a stand–alone unit (Nzotcha, Kenfack, & Manjia, 2019) would reduce losses by avoiding extensive transmission lines connecting the two systems.
- Local wind speed: Following recent trends, the process of choosing a location for a pumped hydro project could be influenced by the need to reduce transmission losses or obtain reliable power from a stand–alone wind farm (Coburn, Walsh, Solan, & McDonnell, 2014).

7.4.3 Economic factors

- Nearness to power lines: When a PHES project is situated close to power lines, it results in reduced initial investment as well as power losses, thus resulting in improved efficiency and economic returns.
- Access to road network: Implementing a PHES project requires access to the project site as well as the conveyance of equipment and materials transportation. As a result, building closer to existing road networks is more cost-effective.

- The geological condition of the site: The site's lithology generally dictates the cost involved in siting reservoirs and other crucial infrastructure. Furthermore, unless a reservoir lining is planned, the plant's roundtrip efficiency will be harmed by the high soil permeability.
- The head–distance ratio: In PHES, this is the proportion of the gross head to the horizontal distance between the two reservoirs. It specifies the span of the water conveyance and thus the associated cost.
- The gross head is the difference in elevation between the lowest and highest water levels in the upper and lower reservoirs. This is an important feature of PHES sites since it limits their capacity.
- The complexity of the civil works involved: This factor also generally has a massive impact on the total cost of the PHES project to be implemented.
- Seismic considerations: In areas where seismic vibrations are prevalent, there will be the need to implement measures to forestall unwanted incidents. This will thus impact the economic returns on the PHES project.

7.4.4 Social factors

- Nearness to an urban area: PHES may serve as a site for tourist attraction and hence it is beneficial for the project site to be situated near an urban area. However, because a PHES consumes a large portion of the land surface area, the plant should not compete with other important land uses such as an urban extension. In such instances, there is the need to maintain a safe distance.
- Settlement: Sometimes, there may be the need for permanent or temporary settlement of people and facilities to pave way for a PHES project. Detailed accounting and evaluation of people and facilities to be affected are required in such situations.
- Land use: The implementation of a PHES project will also need to take into consideration the possibility of interfering with cultural or socioeconomic human activities.
- Potential for a new latent fault: Constructing a high–altitude artificial reservoir could expose nearby communities to a new latent fault, such as downstream flooding.

7.5 Models for pumped hydroelectric energy storage suitability modeling/mapping

As suitable site selection of PHES requires consideration of multiple social, techno–economic, and environmental factors, a multicriteria analysis is

often required for its evaluation by incorporating each of the necessary factors identified above. A typical example of multicriteria decision-making (MCDA) for PHES site selection is shown in Fig. 7.4 and proceeds in three macro steps: (1) defining the problem, (2) decision-making, and (3) recommendation. The problem statement includes the following stages:

- Criteria definition: This refers to the identification and definition of a set of social, techno-economic, and environmental factors on which the evaluation is to be performed. This forms the three Sustainable Development (SD) pillars for PHES site selection.
- Alternative consideration: This represents options available to compare with the proposed PHES for optimal decision-making. The alternatives can be similar PHES with slightly varying characteristics of the social, techno-economic, and environmental factors.
- PHES MCDM problem model: This refers to a matrix of alternatives and the criteria for PHES site selection. Alternatives differ from each other by the numeric or categorical values of their evaluation criteria.
- Data collection and pre-processing: This refers to the collection of raw data on criteria and pre-processing for use in MDCM process. A criterion's values may be numeric or categorical and must be determined for each alternative under consideration.
- Quantification models: This refers to the different models used to get a quantitative description of the attributes, which are being measured for the PHES site evaluation. Quantitative models may be formulas or the use of conversion scale to convert categorical variables into numeric variables, etc.

The problem definition often ends with an MCDM problem matrix with a numerical input of criteria values for each alternative. The MCDM matrix at this stage has two major issues: (1) all criteria usually have different units and (2) use of linguistic terms sometimes to describe some criteria. These two issues make it impossible to compare any two criteria and the entire MCDM matrix which is crucial to getting a performance matrix.

This problem is solved by normalizing or standardizing the criteria values to enable the direct comparison between any two criteria. Normalization or standardization convert criteria values between 0 and 1, allowing the setup of a real performance matrix required for the second step of the MCDM approach.

The second phase involves the use of the performance matrix and preference estimation rules to determine the most preferred criteria from
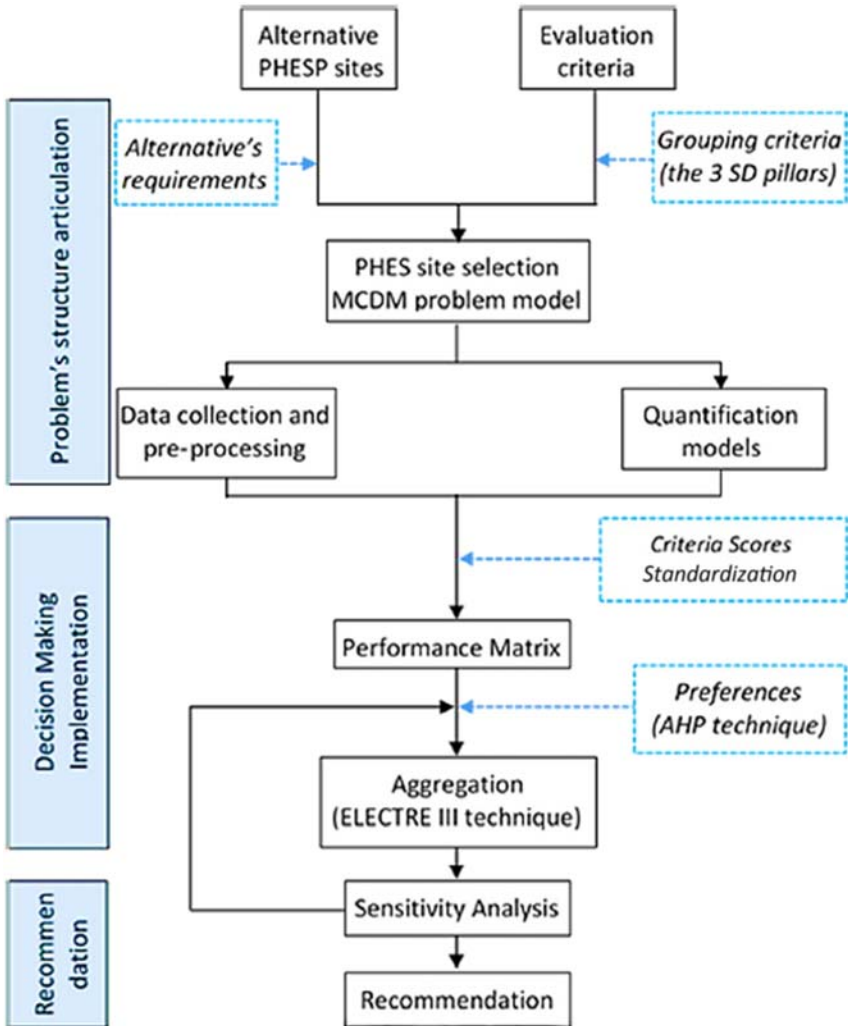
Figure 7.4 A typical example of multicriteria decision-making for pumped hydroelectric energy storage site selection (Nzotcha et al., 2019).

the least desired criteria for PHES site selection. The process is usually in three forms: (1) weight estimation of each criterion, (2) building a preference matrix using the performance matrix and the estimated weights, (3) aggregating each alternative's criteria to determine the most preferred PHES alternative.

The Analytical Hierarchical Process (AHP), designed in Saaty and Vargas (2001), has often been used for estimating weight and optimal

selection PHES and MCDA of storage energy systems (Kotb et al., 2021; Nzotcha et al., 2019; Olabi et al., 2021). After weight estimation with AHP, ranking of the alternatives by ELECTRE III through (1) computation of concordance matric, (2) computation of discordance matrix, (3) computation of credibility matrix, (4) ascending reorder and descending, and (5) ranking of the alternatives. The sensitivity analysis, which is often the last stage, involves several iterations and priority adjustments aimed at providing a ranking that is based on better PHES sustainability criteria.

7.6 Environmental impacts of pumped hydroelectric energy storage on prospective sites

7.6.1 Land requirements

The implementation of a PHES project may result in the inundation of a vast proportion of land that could have otherwise served other purposes. An off-river PHES with the following typical characteristics, viz., 400 m head, 90% generation efficiency, 85% usable water volume, and 20 m depth, will require about 12 hectares of land for both the upper and lower reservoirs per GWh of storage (Blakers et al., 2021).

7.6.2 Water requirements

Also, PHES projects may be seen as a potential threat to water supply security as a result of the quantity of water required to satisfy the storage for the initial fill as well as evaporation requirements. For instance, the energy storage volume required for a 27 GWh per million people is equivalent to 27 kl/person. This was the underlining reason for the failed implementation of the proposed Storm King Mountain PHES, which was intended to augment the energy supply of New York (Blakers et al., 2021).

7.6.3 Impact on fishery industry and aquatic habitat

PHES may result in inimical consequences to the fish industries and the aquatic habitat as a whole due to the likelihood of fish entrapment and oxygen depletion. This problem of fish entrapment can however be minimized with the use of fish deterrent systems and careful adjustment to the pumping schedule, as in the case of Russell hydropower station. Also, oxygen depletion in the aquatic environment is often caused by the warming of the water due to pumping operations associated with PHES. However, this challenge of oxygen deficit can be ameliorated with the

implementation of an oxygen injection system. Oxygen level fluctuations in the aquatic environment generally impact algae and fish growth (Nestler, Don Dennerline, Weeks, Don Degan, & Sykes, 1999).

Notwithstanding these negative impacts, PHES projects may also be used as avenues to enhance aeration in situations where perennial drought conditions cause oxygen level fluctuations (Yang & Jackson, 2011).

7.6.4 Cultural, historical, and scenery impacts

The siting of PHES projects may also bring untold destruction to several historical and cultural monuments as well as beautiful natural scenes. This was one of the major concerns of stakeholders and environmentalists against the Storm King Mountain PHES, which was never implemented (Birkland, Madden, Birkland, Mapes, & Roe, 2006).

7.6.5 Other environmental factors

Other environmental impacts may also be associated with the construction of roads, pipes, or tunnels for water conveyance, a powerhouse and switchyard, and high voltage transmission lines.

7.7 Addressing the environmental impacts

Modern PHES projects are currently undergoing a technological evolution to attenuate much of the negative environmental impacts associated with their construction and operation. This technological evolution is making use of new methodologies such as the use of off-stream systems, abandoned quarries, and mines as well as underground reservoirs and groundwater systems. For instance, the off-stream approach eliminates river daming, thus resulting in fewer impacts on the aquatic environment whilst the use of abandoned quarries, mines, and underground reservoirs minimizes the consequences on existing water bodies, though this requires an extensive scientific evaluation to fully comprehend the peculiar hydrological/environmental interaction associated with each project. Furthermore, the use of groundwater resources, instead of surface water resources, results in minimal adverse impacts on fish. Even more enhanced environmental benefits such as aquatic life protection and water quality improvement will be harnessed with the proposed use of wastewater for off-stream PHES projects. This proposed design will come along with a specially designed pumping scheme that promotes aeration whilst the

storage could serve as an extended aerobic biological treatment. Also, the need for frequent power transmission upgrades will be reduced with this proposed initiative, since wastewater treatment plants are often located near densely populated cities, which are also characterized by high energy demand (Yang & Jackson, 2011).

7.8 Conclusion

As the global community advocates for more RE sources in the generation mix, the need for energy storage interventions such as PHES will continue to remain crucial. This is expected to foster the growth and development of the PHES industry. The selection of PHES is based on several factors: geographic, social, economic, and environmental. Due to the number and complexity of factors considered for this purpose, a MCDA model is often used during the selection process. From our study, it is observed that the implementation of a PHES project may come with several environmental concerns, that is, land and water requirements, impacts on the fishery industry, aquatic habitat, cultural, historical as well as natural scenery. However, we also observed that much of these concerns are being addressed with improvement in PHES technology.

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