Hydropower and seasonal pumped hydropower storage in the Indus basin: pros and cons

Julian David Hunt a,b,*, Giacomo Falchetta c, Simon Parkinson a, Adriano Vinca a, Behnam Zakeri a,d, Edward Byers a, Jakub Jurasz e, Emanuele Quaranta f, Emmanuel Grenier g, Amaro Olímpio Pereira Junior h, Paulo Sergio Franco Barbosa i, Roberto Brandão j, Nivalde José de Castro j, Paulo Smith Schneider k, Lara Werncke Vieira k, Andreas Nascimento b, Yoshihide Wada a

a International Institute for Applied Systems Analysis, Vienna, Austria
b Federal University of Espírito Santo, Brasil
c Fondazione Eni Enrico Mattei, Milan, Italy
d Sustainable Energy Planning Research Group, Aalborg University, Denmark
e Wrocław University of Science and Technology, Wroclaw, Poland
f European Commission Joint Research Centre, Water and Marine Resources Unit, Ispra, Italy
g International Commission on Large Dams, Paris, France
h Interdisciplinary Centre for Energy Planning (NIPE), University of Campinas, Brasil
i Energy Planning Program, Federal University of Rio de Janeiro, Brasil
j Interdisciplinary Centre for Energy Planning (NIPE), University of Campinas, Brasil
k Electric Sector Study Group, Federal University of Rio de Janeiro, Brasil
l Mechanical Engineering Program, Federal University of Rio Grande do Sul, Brasil

ARTICLE INFO

Keywords:
Hydropower
Seasonal Pumped Hydropower Storage
Energy Storage
Water Management
Indus Basin

ABSTRACT

The Indus basin has a large hydropower untapped potential for electricity generation and to regulate the Indus river flow, which could reduce flooding events and provide water supply during drought periods. In this paper, a computational module is developed to localize potential sites for hydropower generation and seasonal pumped hydropower storage (SPHS). The levelized costs for hydropower generation in the basin with conventional dams are as low as 12 USD/MWh; the cost of energy storage is 1 USD/MWh. In case of SPHS plants, the cost of energy storage is 2 USD/MWh. It can be concluded that the conventional hydropower potential is, for the moment, less expensive than SPHS, but its potential in the Indus basin is limited to 26 GW with hydropower costs below 50 USD/MWh and its reservoirs have a short lifetime due to the high sedimentation rates of the basin. SPHS would be an interesting alternative to complement the hydropower potential adding long-term water and energy storage with fewer sediments, social and environmental impacts. Given that the region has the highest potential and lowest costs for SPHS in the world, it could become a major player on seasonal and pluri-annual energy storage in Asia and globally.

Introduction

Over the last decades, the world has been undergoing a boom in hydropower dam construction. Currently, at least 3,700 major dams, each with an installed hydropower capacity of more than 1 MW are either planned or under construction, primarily in countries with emerging economies. For example, in Europe 8,507 dams are planned to be built, and 278 are under construction, especially in the Balkan region. A total of 2,396 planned, and 77 currently under construction are located in protected areas [1]. The new dams installed worldwide are forecasted to increase the global hydroelectricity capacity from the current 1,200 GW to about 1,700 GW [2]. These dams often contribute to fulfilling broader socio-economic objectives: Pakistan and Ethiopia are examples for which the expansion of hydropower could close the gap for electricity access in the future [2,3].

The Indus basin still has a large hydropower potential to be...
developed due to its high altitudes in the upper Indus region and large water availability. It is very demanding to use water efficiently because the region still faces one of the biggest water management challenges worldwide. This is due to population growth and rapid urbanization, industrialization, and environmental degradation, lack of water storage infrastructure, or inefficient water use due to water losses in outmoded irrigation systems and poverty [4–7]. Groundwater is highly extracted, which reduces the groundwater level and further increases electricity demand for irrigation [4,8]. In addition, water scarcity and flooding also are aggravated by climate change [3]. Another issue that has been brought forward is the high volume of sedimentation in the upper Indus Basin, which increases the challenges for building dams in the region because they will rapidly fill up the reservoir with sediments. This was one of the main reasons why the Tarbela dam has already undergone three height extensions since its construction [4,9,10].

From a hydrological point of view, the Indus river is subject to highly seasonal inflows. This is because the snow and ice masses stored in the mountains of the upper Indus basin during the winter period melt during the summer, which considerably increases the flow of the river and its tributaries. Additionally, the thaw period coincides with the monsoon rainfalls, which also considerably increases the water flow in the rivers. This consequently leads to very seasonal river discharge patterns, regular flooding events during the summer and droughts during the winter.

Research has been carried out to better describe the basin and to analyze the availability of water resources, climate change impacts and possible water management solutions. Charles et al. [11] developed a methodology for forecasting seasonal streamflow in the upper Indus basin of Pakistan. Latif et al. [12] analyzed the precipitation time series and temporal variability of snow cover. Hasson et al. [13] assessed the runoff in two catchments of the upper Indus Basin by using a semi distributed hydro-glacial model. Faiz et al. [14] assessed the impact of precipitation variability in the stream flow of the Hindu Kush, Himalayan and Karakoram River basins of Pakistan. Immerzeel et al. [15] analyzed the precipitation in the upper Indus basin, taking into account glacier mass balances and runoff analysis. Nepal et al. [16] reviewed the impact of climate change on the hydrological regime of the Indus. Anjum et al. [17] analyzed spatial, temporal variability of snow cover. Hasson et al. [18] prevailed climatic trends and runoff response from the upper Indus Basin.

In addition, several studies have been carried out with the objective of estimating the hydropower and energy storage potential of the Indus basin. For instance, Zhou et al. [19] presented an exploitable potential for hydropower in Pakistan of 108 TWh per year, mainly located in the Indus Basin. Other studies estimate a feasible hydropower potential of about 60 GW [20–25]. This is significantly higher than the estimated hydropower installed capacity of 17 GW expected by 2040, to supply a yearly demand of 64,728 GWh in Pakistan [26]. The levelized costs of electricity (LCOE) estimated for hydropower in Pakistan range from 24 USD MWh–1 to 84 USD MWh–1 [23]. Hagler Bailly Pakistan investigated technical design, hydology, climate, sedimentation management, environmental impact and the impacts on fisheries of medium size hydropower projects in Pakistan [27]. Hunt et al. show that the Indus basin is the world region with the largest and cheapest potential for seasonal and pluri-annual energy storage [28].

The research gap that the paper covered is to estimate the costs and potential for hydropower, water storage, long-term and short-term energy storage in the Indus Basin. The key innovation and contribution of the paper lies in the comparing the hydropower and the SPHS potential of a region, focusing particularly on water and energy storage of the reservoirs. It calculates the costs of conventional hydropower dams and SPHS plants for the Indus basin with the intention of finding the most suitable technologies for the development of the hydropower potential and water management solutions for the Indus Basin.

**Methodology**

The methodology implemented in this paper is based on a Global Model for Seasonal Pumped Storage Analysis presented in [28]. This model has been upgraded to include hydropower plants and is now called “Global siting of hydropower and SPHS projects model”. Other methods used for estimating global hydropower potential are [19,
however these methods assume that the plants are run-off-the-river and do not estimate their water and energy storage capacity. One recent study investigates the global potential for PHS and assumes the construction of two reservoirs in a closed loop for daily and weekly operation. They found a global potential of $23 \times 10^6$ GWh in more than 600,000 plants, but the project sizes appear to be impractical or infeasible for seasonal storage or water storage and do not include detailed cost analysis or water availability [34,35]. We have not included these closed loop sites because they are designed to store only energy and we are looking at energy and water storage solutions in this paper. Other studies have been developed to find the potential for PHS projects in Europe [33,36,37], and Iran [38], however, these are regional models also do not include costs. GIS models have been created to find daily and weekly pumped hydropower storage plants [34,38–42], there is only one model that looks at SPHS [28]. Given that the water and energy storage volume for daily and weekly PHS plants is not so large, these models do not estimate the benefits that the SPHS plants would have on the operation of the hydrological basin. Refer to the

Figure 2. Water storage costs with (a) hydropower plants and (b) SPHS plants; hydropower generation costs with (c) hydropower plants and (d) SPHS plants; long-term energy storage costs (e) hydropower plants and (f) SPHS plants.
water to an upper reservoir has not been assessed for the Indus basin. Having a considerable impact on the overall river flow.

There will be water available to fill up the storage reservoir without storage reservoirs, according to water availability. This guarantees that project costs. The hydrological data were used to restrict the size of the project.

Cost range description of each main affluent of the Indus basin.

| River    | Water Storage (USD m$^{-3}$) | Hydropower Long-term energy storage (USD MWh$^{-1}$) | Short-term energy storage (USD MWh$^{-1}$) |
|----------|-----------------------------|---------------------------------------------------|------------------------------------------|
| Indus    | 0.001 - 0.03                | 12 - 47                                           | 1 -                                      |
| Jhelam   | 0.01 - 0.05                 | 29 - 46                                           | 7 -                                      |
| Chenab   | 0.005 - 0.04                | 19 - 35                                           | 2 -                                      |
| Sutlej   | 0.005 - 0.05                | 12 - 50                                           | 1 -                                      |
| Kabul    | 0.001 - 0.04                | 47 - 102                                          | 1 -                                      |
| Kumar    | 0.001 - 0.02                | -                                                 | 1.2 -                                    |

Seasonal Pumped Hydropower Storage

| River    | Land cost (billion USD)     | Electrotechnical cost (billion USD) | Miscellaneous costs (billion USD) | Dam cost (billion USD) | Turbine cost (billion USD) | Reservoir level (m) | Dam height (m) | Dam length (km) | Generation capacity (GW) | Storage volume (km$^3$) | Hydropower generation (TWh) |
|----------|-----------------------------|------------------------------------|----------------------------------|-----------------------|--------------------------|---------------------|----------------|----------------|------------------------|---------------------------|---------------------------|
| Indus    | 0.011                       | 0.071                               | 0.007                            | 0.522                 | 0.071                    | 105                 | 75             | 50             | 0.797                  | 3.462                     | 0.131                     |
| Jhelam   | 0.035                       | 0.158                               | 0.002                            | 0.553                 | 0.017                    | 150                 | 150            | 100            | 0.239                  | 3.549                     | 1.125                     |
| Chenab   | 0.028                       | 0.056                               | 0.002                            | 0.300                 | 0.024                    | 200                 | 200            | 150            | 0.317                  | 1.324                     | 3.785                     |
| Sutlej   | 0.012                       | 0.070                               | 0.002                            | 0.030                 | 0.007                    | 250                 | 250            | 200            | 0.317                  | 1.808                     | 1.234                     |
| Kabul    | 0.006                       | 0.182                               | 0.002                            | 0.028                 | 0.008                    | 300                 | 300            | 200            | 0.952                  | 5.612                     | 5.349                     |

Details of the cheapest hydropower projects presented in Table 2.

- Costs are subsequently estimated, divided between dam, tunnel, excavation, and reservoir engineering.
- The site selection model is divided into nine main stages (Figure 1 and Table B.7). For each land grid cell (point under analysis (PUA)), the model searches for rivers with sufficient discharge (higher than a yearly average of 100 m$^3$ s$^{-1}$) within 1 to 30 km of distance from a potential SPHS site, which consist of the tunnel length (Figure 1 (c)). If a large river is found, the model attempts to build dams of 50, 100, 150, 200 and 250 meters height, along 4 axes (N-S, W-E, NW-SE, NE-SW) and with a maximum length of 7.2 km in the PUA (Figure 1 (d)). If the topography allows the construction of such dams, it verifies whether the PUA is the lowest point of the dam (if it is not, the process stops with the intention of not repeating the same project) (Figure 1 (e)). Using the surrounding topography and observing limits to the maximum flooded area of the reservoir, the model identifies the side of the dam that results in a reservoir (Figure 1 (f)). Subsequently, the reservoir water level is varied to determine the flooded area vs. level and storage volume vs. level curves (Figure 1 (g)).

Developing hydropower projects takes substantially less time and the model is much simpler than finding SPHS projects. The main difference between both is that the hydropower model does not have to look for other rivers to extract water (Figure 1 (c)), instead it only develops projects on rivers with yearly average river flows higher than 100 m$^3$ s$^{-1}$. Additionally, the cost estimation does not include tunnel and excavation costs.
tunnel, powerhouse excavation, pump-turbine, electro-technical equipment and land costs [45,48]. In the analysis, the water storage capacity of the SPHS projects is limited according to the water availability of the main river. If the storage capacity is much higher than the amount of water available, the estimated cost of storage tends to infinity, as the reservoir will never fill up.

Cost estimation

The costs of water and energy storage service calculated in the Estimate Storage Cost stage vary according to the annual river flow, the seasonal and inter annual variation. These hydrological parameters have the main purpose to guarantee that there will be sufficient water in the river to be stored in the upper reservoir. The variation of the water and energy storage (with and without cascade) costs with the water available for storage is presented in equations (1), (2) and (3), respectively. The cost for additional short-term energy storage costs is presented in equation (2).

\[
C_W = \begin{cases} 
C_p \frac{W_R}{W_S} & \text{if } W_R < Q_A \\
C_p \frac{W_R}{2Q_A} & \text{if } Q_A < W_R < 2Q_A \\
C_p \frac{2Q_A}{W_R} & \text{if } W_R > 2Q_A
\end{cases}
\]

(1)

\[
C_{Eww} = \frac{C_p}{E_{Rbw}} \begin{cases} 
W_S = W_R & \text{if } W_R < Q_A \\
W_S = Q_A + 0.5W_R & \text{if } Q_A < W_R < 2Q_A \\
W_S = 1.5Q_A & \text{if } W_R > 2Q_A
\end{cases}
\]

(2)

\[
C_{Ewoc} = \frac{C_p}{E_{Rwo}} \begin{cases} 
W_S = W_R & \text{if } W_R < Q_A \\
W_S = Q_A + 0.5W_R & \text{if } Q_A < W_R < 2Q_A \\
W_S = 1.5Q_A & \text{if } W_R > 2Q_A
\end{cases}
\]

(3)

where, \(C_W\) is the cost of water storage in USD km\(^3\), \(C_p\) is the cost of the project (i.e. dam, tunnel, turbine, electrical equipment, excavation and land) in USD, \(Q_A\) is the yearly water available for storage in km\(^3\), which is 50% of the annual river flow in the river section under analysis, \(W_S\) is the water storage capacity adjusted by the water availability in km\(^3\), and \(E_{Rbw}\) and \(E_{Rwo}\) are the energy storage costs for the water and energy without and with cascade, respectively.

Figure 3. Description of the proposed SPHS plants. (a) Topography of the upper Indus basin, (b) Marwa, (c) More and (d) Spiti SPHS plants.
Table 4
Details of selected SPHS projects presented in Figure 2.

| Suggested name | More | Marwa | Spiti |
|----------------|------|-------|-------|
| River          | Indus| Chenab| Sutlej |
| Latitude (°)   | 33.3735| 33.5569| 31.9061 |
| Longitude (°)  | 77.9143| 75.7854| 78.5983 |
| Altitude where the dam is located (m) | 4635 | 2003 | 3002 |
| Altitude of the river, lower reservoirs (m) | 3875 | 1156 | 2608 |
| Minimum generation head (m) | 790 | 917 | 394 |
| Dam height (m) | 100 | 200 | 200 |
| Dam length (km) | 1.2 | 1.8 | 1.035 |
| Generation capacity (GW) | 1.0 | 1.0 | 1.0 |
| Storage volume (km³) | 2.6 | 4.24 | 17.77 |
| Energy storage without cascade (TWh) | 5.42 | 10.57 | 21.53 |
| Energy storage with cascade (TWh) | 20.13 | 23.49 | 100.02 |
| Yearly river flow (km³) | 5.24 | 5.48 | 6.58 |
| Land requirement (km²) | 67.23 | 43.08 | 136.23 |
| Tunnel length (km) | 24 | 21 | 12 |
| River discharge (m³ s⁻¹) | 33.24 | 34.77 | 39.91 |
| Dam cost (billion USD) | 0.26 | 0.77 | 0.66 |
| Tunnel cost (billion USD) | 0.45 | 0.43 | 0.35 |
| Excavation costs (billion USD) | 0.05 | 0.05 | 0.06 |
| Pump turbine cost (billion USD) | 0.08 | 0.08 | 0.08 |
| Miscellaneous costs (billion USD) | 0.01 | 0.01 | 0.01 |
| Electrotechnical cost (billion USD) | 0.17 | 0.17 | 0.17 |
| Land cost (billion USD) | 0.11 | 0.02 | 0.06 |
| Total construction costs (billion USD) | 2.26 | 3.07 | 2.78 |
| Water storage costs (USD m⁻³) | 0.14 | 0.20 | 0.02 |
| Energy storage costs without cascade (USD MWh⁻¹) | 73.89 | 81.22 | 13.41 |

where,

$$C_{GW} = \frac{C_{GW}}{G}$$

where, $C_{GW}$ is the cost of long-term energy storage excluding the cascade in USD MWh⁻¹, $W_b$ is the water storage capacity of the reservoir developed in the model in km³, $E_{Res}$ and $E_{Roc}$ are the energy storage capacity of the reservoir developed in the model with and without cascade in MWh, respectively, $C_{GW}$ is the cost of long-term energy storage including the cascade in USD MWh⁻¹.

Results

The results from the hydropower and SPHS plants siting computer model presented in this paper are divided in water storage, generation, long-term energy storage, and short-term energy storage cost. These outputs are presented in maps, capacity curves and a description of the costs.

The hydropower water storage cost varies from 0.001 to 0.05 USD m⁻³, while SPHS varies from 0.015 to 0.05 USD m⁻³ (Figure 2 a, b). Worth noting that hydropower dams have a greater land requirement in comparison to SPHS. Analyzing the capacity curves in Figure 2b, the cost of water storage starts small with a small addition to the overall water storage potential. This is because of the possibility of the construction of effective, low altitude and short dams. After reaching the 300 km³ capacity mark, there are several projects that store a lot of water with a higher cost, due to the requirement of larger and more expensive dams. Conventional hydropower generation cost varies from 12 to 50 USD MWh⁻¹, a low cost in comparison to SPHS (Figure 2 c, d) hydropower generation which varies from 50 to 300 USD MWh⁻¹. The wide range of cost variation for SPHS is a result of its highly sensitive to the topography, distance to a river, and water availability. The cost for hydropower suddenly increases after 20 GW installed capacity because the hydropower potential in the Indus and Sutlej rivers finishes and the cost of hydropower in the other rivers is higher. Hydropower long-term energy storage costs and SPHS (Figure 2 e, f) varies from 1 to 50 and 2 to 50 USD MWh⁻¹, respectively. Considering the high volume of sedimentation in the upper Indus Basin, SPHS plants have the advantage to provide additional energy and water storage for the basin with low sedimentation rates. Table 2 presents the cost range description of each main affluent of the Indus basin.

Table 3 details the cheapest hydropower projects presented in Table 2. It presents all the details of the dams that are estimated by the model described in Section 2. It turns out that the cheapest proposed projects for the Chenab and the Kabul reservoir were already built. This is convenient as it helps verifying the quality of the model results.

Figure 3.

Table 4 provides details of selected SPHS projects presented in Figure 4 and Figure 2. The project proposed for the Indus basin is located upstream of the Tso Kar salty lake. The upper reservoir would be filled with fresh water from the Indus river and from precipitation and ice melted from the mountains, that would end up in the Tso Kar lake. If there is an interest to maintain the Tso Kar salty lake with its current volume, some of the water from the upper reservoir would have to flow to the lake. The More, Chenab and Sutlej SPHS plants have large reservoirs and storage volumes, and their seasonal operation is combined with the existing hydropower generation in cascade to optimize the
hydropower generation and water supply. Figure 4 presents the location of projects described in Table 3 and Table 4. The required transmission lines are presented in Table C8. The largest transmission line required would be 335 km for the More SPHS, which is not very large, however, the harsh weather and terrain increases installation costs.

The short-term energy storage cost with SPHS plants (Figure 5) presented a range of 0.24 to 0.6 billion USD GWh\(^{-1}\). The cheapest alternatives for short-term energy storage can be seen in the middle of the Indus river and in the Beas river basin. Given the rapid reduction in battery prices, short-term energy storage solutions should be located close to the demand. Thus, the developments of daily and weekly PHS plants should be focused on the Beas river basin, which is close to Ludhiana and Chandigarh in India. Note that the potential for short-term energy storage is as high as 500 GW. This is because, in short-term energy storage, the water used for regeneration is re-used several times during the pumping and generation cycles.

Figure 6 (a) shows the costs of the different components of the proposed SPHS projects by the computer model. The costs of tunnel and electromechanical components are significantly higher than the costs of the dam. This is because the model assumes that all projects have a 1 GW installed capacity, which is higher than the installed capacity required to store water seasonally in the upper reservoir. Thus, if the main objective of the SPHS is to store energy and water seasonally, it would be advisable to reduce the installed capacity of the plant to 500 or 250 MW depending on the site of the reservoir. Figure 6 (b) shows that the critical components of the hydropower project costs are the dam, electromechanical equipment and turbine.

Discussion

Water demand and climate vulnerability

More importantly than energy generation, water is crucial for crop irrigation and food production in Pakistan. The main benefits of building storage reservoirs in the upper Indus basin is related to the regulation of the river flow, which prevent floods and stores water for the winter or years with lower than average rainfall. The main challenges in building hydropower and SPHS reservoirs is the increase in evaporation, which could lower the river flow downstream. Another challenge of regulating the river, is that water for irrigation is mostly required during the summer to produce mainly rice, maize, sorghum, millet, sugarcane and cotton [49]. Regulating the flow of the Indus river, without policies to adapt to new agriculture techniques could result in energy and water conflicts in the future.

Climate change is expected to increase average temperatures in the lower Indus basin, which increases the potential of the air that reaches the upper Indus basin to precipitate. This is expected to increase the frequency of flood events in the region [50] and increase the sedimentation rates of the rivers. SPHS plants can lower the impacts of climate change by providing seasonal storage services, while the conventional hydropower dams, would be partially empty to store river flow surges resulted from floods in the future.

High river sedimentation

Hydropower plants in the Indus basin have high rates of sedimentation in the region, which increases maintenance costs and shortens the lifetime of the reservoir, as they are usually filled with sediments within a few decades [4,9,10,51]. SPHS plants could have substantial benefits in the Indus basin because their reservoirs are limited to a small catchment area, and thus the sedimentation rates are substantially smaller and the reservoirs can last for hundreds of years.

SPHS plants in series

This section presents proposals for hydropower and SPHS arrangements that could be considered for the Indus basin based on the analysis carried out in the paper. The first proposal is the combination of two SPHS systems with one connection to the Indus River plant (Figure 7). The project consists of a 41 km tunnel for the Jalkol reservoir until the first powerhouse with a 1440 m generation head, and a 31 km tunnel for the Palas reservoir that connects to the Indus River with the second powerhouse, with a 920 m generation head. The high pumping/generation head denotes it can generate and store large amounts of energy with little water and land requirements. Comparing with the Kaprun site in Austria, the distance from the Leiter Glaisier to the Kaprun lower reservoir (Figure 7 (b)) is 35 km and the total generation head is around 1100 meters, which results in a tunnel efficiency index of 31.4 (1100 m generation head / 35 km tunnel). The proposed Jalkol reservoir has an index of 40.7 (2320 m generation head / 57 km tunnel) and the Palas

Figure 6. (a) Cost of SPHS projects with long-term energy storage, (b) cost of hydropower projects with generation. The range shows the values between 5% and 95% of the sample data, with the bars for between the first and third quartile. The line on each bar shows the median of each range.
Figure 7. Proposal of a combination of two SPHS system with one connection to the Indus River.

Figure 8. SPHS system with the powerhouse connected to reservoir and catchments on both sides of the river.
reservoir has an index of 46.5 (1440 m generation head / 31 km tunnel), which are both superior to the Kaprun project in Austria. Note, however, that pumped-storage plants have limitations in head of around 1,400 meters. Plants with higher heads are not commonly designed and produced, thus, are not currently available in the market due to the very high pressures involved.

**SPHS plants in both sides of the river**

Given the very steep terrain in the Upper Indus Basin, another arrangement of SPHS that could be implemented in the Indus Basin and provide a combination of hydropower and water storage is the possibility of developing two reservoirs, one on each side of the river, as shown in Figure 8. With the increase in capacity, the relative costs of the turbines, generator and excavation would be lower. Another possibility is to store water from one reservoir into the reservoir on the other side of the river if one of them is full. This would only be possible if the water level from the full reservoir is higher than the water level of the empty reservoir, so that the water could flow naturally under gravity from one reservoir to the other. The main benefit of catching water from both sides of the river is that it increases the water availability for the plant, which increases the power capacity of the turbine, generators, and substations, reducing overall costs. It also allows for the creation of only one large storage reservoir up the mountains to store water from both sides of the mountain. This reduces the need for building two reservoirs on each side.

**Seawater closed loop SPHS plant**

This paper only analyzed the potential for energy storage with open loop SPHS types. This type of plant is more convenient because it also stores water for the dams in cascade. However, due to the very large potential for efficient reservoir construction in the region, and the mountainous topography, closed loop SPHS plants can also be built. Given that the water in closed loop systems is reused innumerable times, the energy storage potential of the region is very large. An example of a closed loop SPHHR project can be built between two existing lakes, as shown in Figure 9. It is estimated that this project can store 4.4 TWh of energy but could be increased to 10 TWh if additional water from the Indus Basin is added to the system. The main challenges of this project are the saltwater corrosion in the turbines, and the low temperatures that can freeze the water in the tunnel and damage the turbine. The advantage is that the energy storage process has no impact on the flow of the Indus river. Another interesting arrangement for the region that was not considered is to build pump-back PHS plants. These are conventional dams built in the main river with reversible pump turbines. This arrangement is interesting because, if the inflow of the dam is low, the pump/turbines can be used for energy storage instead of hydropower generation. This significantly increases the flexibility of the plant. Pump-back PHS require the lower reservoir to always reach the upper reservoir dam.

**Future role of SPHS**

Batteries and hydrogen are rapidly gaining the market for energy storage [53]. Pumped hydro storage will have to reinvent itself to remain competitive. Bloomberg predicts that the use of batteries for grid storage in 2030 will be 280 GW, which will surpass the global capacity of PHS plants [54]. With a battery cost expected to fall under 100 US $/kWh in 2024 and around 60 US$/kWh in 2030 [55], batteries will soon be cheaper than PHS plants with daily storage cycles. Regarding long-term energy storage (GWh), hydrogen will be an important competitor for PHS as the global network of production and distribution of hydrogen develops [56]. For instance, a full liquid hydrogen tanker with a volume of 267,000 m\(^3\) (the size of a large LNG tanker) stores 415 GWh or 17 GWd of electricity, assuming that the efficiency to transform the hydrogen into electricity is 70%. This is equivalent to the energy stored on a monthly or seasonal PHS plant. This would significantly reduce the viability of seasonal PHS plants in countries that will rely on imported hydrogen in the future. Given that the overall efficiency for

---

*Figure 9. Possible closed loop project with existing salty lakes [52]*
energy storage with batteries (90%) is higher than PHS plants (70-85%), and the efficiency of hydrogen (30-60%) is lower than PHS plants. It is likely that batteries will become more competitive than PHS for short-term energy storage to complement the generation from renewable energy sources, such as solar and wind power [57–60]. However, PHS will be more competitive than hydrogen for long-term energy storage. Thus, in the future, monthly and seasonal PHS plants will become more common than daily and weekly PHS plants. The Indus Basin having the lowest cost for long-term energy storage, has the potential to become the world’s future long-term energy storage hub.

Conclusion

This article presented the results for the Global siting of hydropower and SPHS projects model in the Indus river basin. It is estimated a hydropower potential of 26 GW exists in the Indus basin, with an energy storage cost ranging between 12 and 50 USD MWh\(^{-1}\), offering a vast and cheap energy storage potential, due to its appropriate topographical formation for the construction of effective storage reservoirs. It found that the levelized costs for hydropower generation in the basin with conventional dams are as low as 12 USD MWh\(^{-1}\); however, the cost of energy storage is 1 USD MWh\(^{-1}\) and the cost of water storage is 0.001 USD m\(^{-3}\). In case of SPHS plants, the cost of energy storage is 2 USD MWh\(^{-1}\) and the cost of water storage is of 0.015 USD m\(^{3}\).

Given the large potential low cost for energy storage of the Indus basin, the region has the potential to become a major player in seasonal, and pluri-annual energy storage for Asia; a similar role as the Alps are used for energy storage in Europe. If an hydrogen economy is implemented worldwide, the Indus region could play an important role used as a cheap, stationary, long-term energy storage option for a globally integrated hydrogen economy.

Author Contributions

Conceptualization, J.H.; methodology, E.B.; formal analysis, G.F., L.V.; investigation, S.P.; data curation, A.V.; writing—original draft preparation, J.H.; writing—review and editing, B.Z.; visualization, J.J.; project administration, P.S.; funding acquisition, A.N., Y.W., N.C.; resources, E.Q.; software, E.G.; validation, A.P.J.; formal analysis, P.B.; supervision, R.B.; All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank for the funding from the IS-WEL (GEF and UNIDO). This research was also funded by the National Agency of Petroleum, Natural Gas and Biofuels (ANP), the Financier of Studies and Projects (FINEP) and the Ministry of Science, Technology and Innovation (MCTI) through the ANP Human Resources Program for the Oil and Gas Sector (PRH-ANP / MCTI, in particular PRH-ANP 53.1 UFES, for all the financial support received through the grant.

Appendix A: Seasonal pumped hydropower storage (SPHS)

We investigate two alternatives to regulate the flow of the Indus River for hydropower generation: First, using conventional dams, which are built in the cross sections of the main river (Figure A.10 (a)). Second, SPHS plants, which are artificial reservoirs off the main river, with some or minor natural inflow (Figure A.10 (b) and (c)). Given that conventional hydropower dam is a widely developed technology, this section will focus on introducing the state-of-the-art of the SPHS concept.

Hydropower generation in high mountain locations using SPHS plants is not a new technology. Especially in mountainous regions of developed countries, SPHS’s have been applied, for example, in Austria [62–65], Switzerland [66–69], Norway [70,71], Sweden [72,73], Australia [74] and USA [73,75]. Basically, a SPHS consists of building a reservoir off to the major river at higher altitudes and a power/pumping station to generate hydropower or to fill up the reservoir. Famous examples of SPHS built in Austria, are the Kaprun and Malta hydropower systems [76,77]. These plants were built with the main objective of storing the melted water from glaciers on the top of the mountains and generating electricity. In addition, the use of dams to store water coming from the increase ice melting due to the future climatic scenario is a topic that is starting to be investigated from the scientific literature [78]. These pump-turbines reservoir are used to store energy when the price for electricity is low and generate electricity during high price periods [79]. Typically, the pump storage plants utilize the daily price spread (i.e., high prices during peak hours around noon and low prices during the night) to maximize revenues. More recently, the increased use of new renewable energy sources (i.e., wind and solar) in Europe requires energy balancing, which is partly provided by these storage systems. Furthermore, the pump turbines are also used to fill up the upper reservoir during the spring or summer, when there is not enough rain or snow to re-fill the upper reservoirs by natural inflows [80]. This practice is advantageous in countries where the costs of electricity during the summer is lower than in the winter, like in Europe. In summary, SPHS plants act as a combination of conventional hydropower plants and pumped storage plants [81].

Table A.5 presents the main characteristics of the pump storage and the aspects that could be relevant for the Indus Basin. SPHS could increase the energy security in Pakistan and could make a valuable contribution to the insertion of intermittent renewable energy sources in the country. Furthermore, the flexibility could provide the balancing energy that is needed. Water security can also be substantially improved with the implementation of SPHS.

![Figure A.10. Operation of (a) conventional hydroelectric plants (b) SPHS during periods of high-water availability (c) SPHS during periods of low water availability. Note that the same legend is used in other figures [61].](image-url)
| Characteristics of the seasonal pumped hydropower storage technology related to the needs of energy and water storage. |
|---------------------------------------------------------------|
| **Challenges** | **Deploying seasonal pumped hydropower storage (SPHS)** |
| Energy storage | Increase water and energy storage in water basins to regulate the river flow and increase hydropower generation. |
| Highly seasonal hydropower generation | Hydropower, solar and wind generation usually do not have the same seasonal generation profile as the demand for electricity. Natural Gas is an option for flexible electricity generation, however, it is a fossil fuel based source of energy and emits CO₂. A seasonal storage option should be considered by countries that intend to considerably reduce CO₂ emissions. |
| Store excess water during periods of high hydropower generation and reduce spillage. | |
| Goal for CO₂ emissions reduction | Countries in high latitudes have a strong seasonal solar power generation profile. Seasonal storage allows energy to be stored in the summer and generate electricity during the winter, when there is lower solar generation. |
| Increase in solar power generation in countries at high latitudes | Countries in mid and high latitudes tend to have a seasonal electricity demand profile. For example, they can consume more electricity in the summer for cooling or during the winter for heating purposes. Typically, the peak national grid demand can be two to three times as high as the minimum demand [89]. |
| Seasonal demand variations | With the electrification of the heating sector in countries at high latitude, the demand of electricity during the winter will increase even further. |
| Electrification of the heating sector | Reduction in fluctuation of electricity prices with fossil fuel prices and supply. |
| Low energy security | Large part of the generation capacity of a country is on stand-by for energy security reasons. The number of stand-by plants would reduce if seasonal pumped-storage is implemented. |
| Reduction in fluctuation of electricity prices with renewable energy availability, especially hydropower. | Costs of oil and diesel based electricity generation for island electricity generation might be higher than the combination of renewable sources and energy storage. |
| Low power plant capacity factor | SPHS plants can store water on higher ground away from the river, in cases where along the river is infeasible. |
| Island electricity generation | Water storage in reservoirs with high level variation considerably reduces evaporation rates due to higher volume to area ratio. |
| Inappropriate topography | SPHS projects have much smaller sedimentation rates than conventional dams due to the smaller catchment area. |
| High evaporation rates | Damming a major river for storage would result in higher environmental and social impact than damming a small tributary river. SPHS allows water storage without fragmenting the ecosystem of a main river, assuming that a cascade of hydropower plant is not installed in the river. The implicit comparison to conventional reservoir dams tends to minimize seasonal pumped-storage environmental impacts or disadvantages. |
| High storage reservoir sedimentation | Storing water in a SPHS reservoir parallel to the river allows for a better control of the water quality in the reservoir, as it would not be directly affected by the fluctuations in water quality in the main river. Usually, the water quality of a river deteriorates when the river flow is low and there is not enough water to dilute the pollutants in the water. In these low water availability periods, the SPHS plant will not pump water from the river. Water will be pumped into the river when the river flow rate is higher and the pollutants in the water are more dissolved. This will contribute to maintaining a better water quality in the reservoir. If the SPHS is still required to provide short term energy storage, another small reservoir can be built close to the river, however, water from the lower reservoirs would not be exchanged with the river water to maintain the water quality in the SPHS reservoir. |
| Lower environmental and social impacts | SPHS plants can be used in combination with conventional flood control mechanisms to improve their efficacy. This combination consists of allowing the reservoirs on the main river to operate with low levels as the long-term storage is provided by the SPHS reservoir parallel to the river. So that when the flooding river flows reach the dam in the river, it will be nearly empty and can store large parts of the flood waters. This combination guarantees that the system will store water and energy seasonally and that the dam in the river will have available storage volume to contain the flood. |
| Better water quality control | The improvement in water management resulting from a SPHS plant would reduce the chances that a waterway runs out of water [94]. |
| Flood control | SPHS projects can be combined with an interbasin transfer project to increase the water security of a region or provide balancing between watersheds. |
| Transport with waterways | Pakistan has a vast network of channels. As the lower Indus basin is a sedimentary basin, the water percolates in the channels and enhances the recharging the groundwater of the basin. If the seasonal variation in the water flow in the lower Indus basin is reduced, the channels will have water for longer times and can increase groundwater recharge. This is convenient in Pakistan as it lacks infrastructure to distribute water resources. |
| Interbasin Transfer | Increase the water storage capacity in regions where conventional storage reservoirs are not a viable alternative. |
| Groundwater recharge | SPHS reservoirs are usually several meters above the level of the river, which contributes to lowering the temperature of the water released by the plant. The operation of the SPHS plant contributes to reducing the temperature of the river flow. River temperature is an important driver for aquatic ecosystem health. |
| Water security | Earthquakes are not unlikely in the region and pose a high risk due to the potential of dam failure. The magnitude of the earthquakes that may be induced by hydropower reservoirs can be estimated by equations in [96]. There is no study in the literature estimating the risk of SPHS reservoirs. Given that the reservoir of SPHS plants are placed on the top of a mountain or hinterlands, and not in a valley, they might be more susceptible to earthquakes. |
| Potential issues resulted from SPHS plants | |
| Temperature change | |
| Earthquakes | |
Appendix B: Global siting of hydropower and SPHS projects model

The shortcoming and the way forward for the improving the model are the inclusion of transmission costs, the costs the land and for relocating people from where the reservoirs would be built. Due to the large
computation time, the topographic resolution used was 15”, which limits the minimum size of the dams to around 450 meters. Using available resolution of 3” the dam cost would improve [97]. It would also be interesting to estimate the maximum altitude for SPHS to avoid water freezing in the tunnels, and the reservoir sedimentation rate and add to the model. Several other limitations that applied to this model are described in [28].

Appendix C: Additional results

The location of hydropower plants analyzed with the computed model in Indus and Jhelam river basins are represented with white dots shown in Figure C.11, hydropower plants in Chenab and Satluj river basins are presented in Figure C.12, and the hydropower plants analyzed in Kabul and Kunar river basins are presented in Figure C.13.

Figure C.14a presents the tunnels for the proposed SPHS plants by the computer module in white, connecting the river (lower reservoir) and the SPHS reservoir (upper reservoir). Similarly, Figure C.14b presents the SPHS proposed plants, not in white, but with an increase in topography of 500 meters for each SPHS tunnel. This is with the intention to show the locations with the highest concentration on proposed SPHS projects.

Figure C.11. Hydropower projects investigated on the Indus and Jhelam river basins. The white dots are the locations where the dams were proposed.

Figure C.12. Hydropower projects investigated on the Chenab and Satluj river basins. The white dots are the locations where the dams were proposed.
References

[1] U. Schwarz, Hydropower Pressure on European Rivers, Report of Fluvius, RiverWatch, EcoNatur, Geota. Vienna (2019).

[2] C. Zarfl, A.E. Lumsdon, J. Berlekamp, L. Tydecks, K. Tockner, A global boom in hydropower dam construction, Aquat. Sci. 77 (2015) 161–170, https://doi.org/10.1007/s00027-014-0377-0.

[3] A. Laghari, D. Vanham, W. Rauch, The Indus basin in the framework of current and future water resources management, Hydrol. Earth Syst. Sci. 16 (2012) 1063–1083.

[4] W. Yu, Y.-C. Yang, A. Savitsky, D. Alford, C. Brown, J. Wescott, D. Debowicz, S. Robinson, The Indus Basin of Pakistan: The Impacts of Climate Risks on Water and Agriculture, World Bank, Washington, 2013.

[5] N. Grigg, T. Foran, T. Darbas, M. Kirby, M. Colloff, M. Ahmad, G. Podger, The water-food-energy nexus in Pakistan: a biophysical and socio-economic challenge, Proc. Int. Assoc. Hydrol. Sci. 376 (2018) 9–13.

[6] M.U. Rashid, A. Latif, M. Yaoming, M. Yaseen, Spatial analysis of precipitation time series over the Upper Indus Basin, Theor. Appl. Climatol. 131 (2018) 761–775, https://doi.org/10.1007/s00704-017-2081-7.

[7] S. Charles, Q. Wang, M. Ahmad, D. Hashmi, A. Schepen, G. Podger, D. Robertson, Seasonal streamflow forecasting in the Upper Indus Basin of Pakistan: an assessment of methods, Water Resour. Manag. 32 (2018) 1675–1687, https://doi.org/10.1007/s11269-017-1897-x.

[8] J.D. Hunt et al. J.E. Storage 41 (2021) 02916

Figure C.13. Hydropower projects investigated on the Kabul and Kunar river basins. The white dots are the locations where the dams were proposed.

Figure C.14. Seasonal pumped hydropower storage plants developed by the model in the Indus basin, where the tunnels are represented in white.

hydrologic-ecohydraulic approach, Energy Convers. Manag. 223 (2020), 113267 https://doi.org/10.1016/j.enconman.2020.113267.

[9] Y. Zheng, M. Sahraei-Ardakani, Leveraging existing water and wastewater infrastructure to develop distributed pumped storage hydropower in California, J. Energy Storage. 34 (2021), 102204 https://doi.org/10.1016/j.est.2020.102204.

[10] M.U. Rashid, A.S. Shakir, N.M. Khan, Evaluation of Sediment Management Options and Minimum Operation Levels for Tarbela Reservoir, Pakistan, Arab. J. Sci. Eng. 39 (2014) 2655–2668. https://doi.org/10.1007/s13369-013-0936-z.

[11] M. Schleser, M.J. Franco, C. Juez, G. Be Geare, Reservoir sedimentation, J. Hydraul. Res. 54 (2016) 595–614, https://doi.org/10.1080/00221686.2016.1225320.

[12] A.J. Schleiss, M.J. Franca, C. Juez, G. Be Geare, Reservoir sedimentation, J. Hydraul. Res. 54 (2016) 595–614, https://doi.org/10.1080/00221686.2016.1225320.

[13] S. Ali, I. Bano, R. Kayastha, A. Shrestha, Comparative assessment of runoff and its components in two catchments of upper indus basin by using a semi distributed glacio-hydrological model, in: Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 18–22 Sept, 2017. Wuxian, China.
