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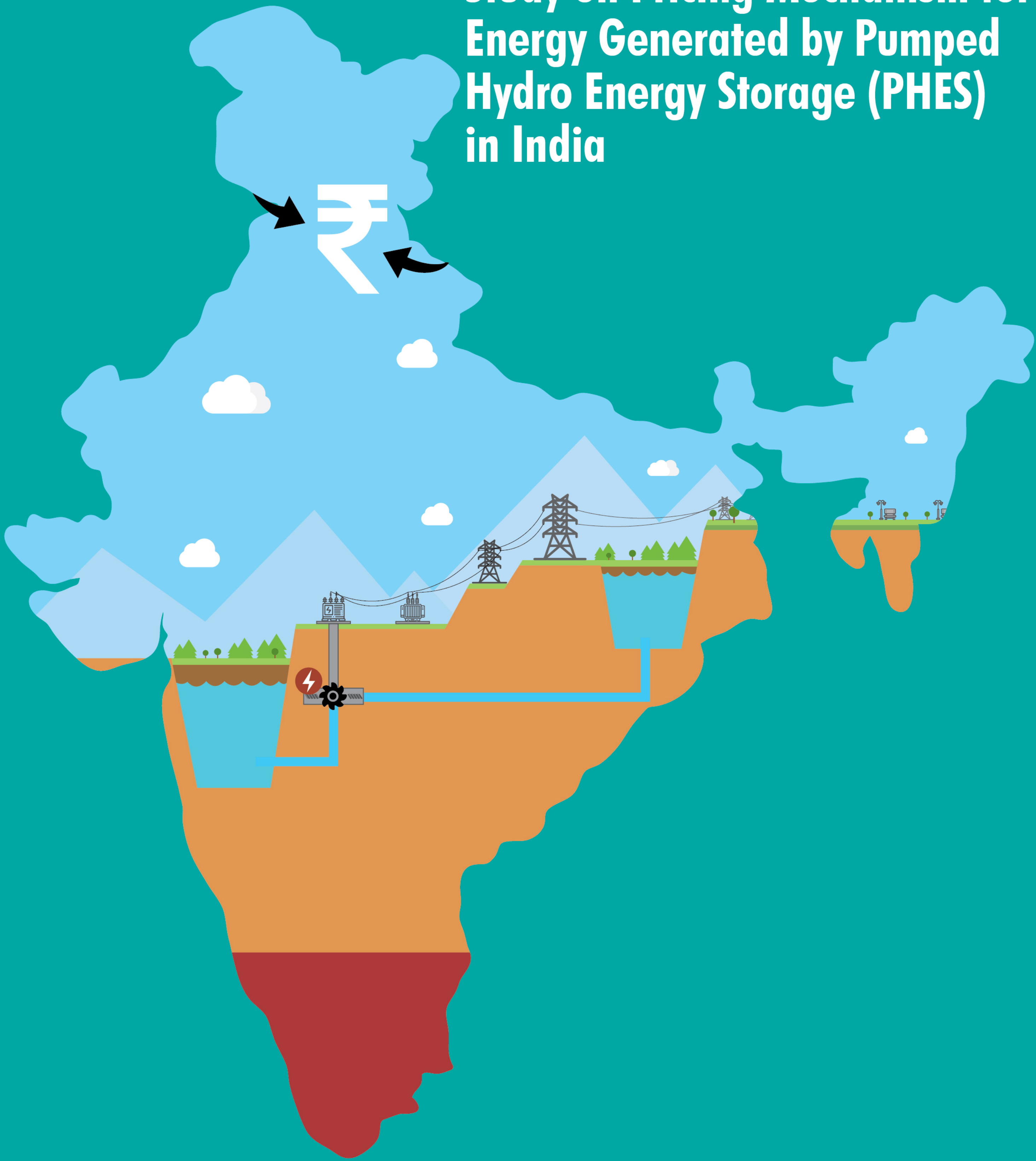
Study on Pricing Mechanism for Energy Generated by Pumped Hydro Energy Storage (PHES) in India



Study on Pricing Mechanism for Energy Generated by Pumped Hydro Energy Storage (PHES) in India

Center for Study of Science, Technology and Policy

November 2021

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Designed and edited by CSTEP

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This report should be cited as: CSTEP. (2021). Study on pricing mechanism for energy generated by pumped hydro energy storage (PHES) in India. (CSTEP-RR-2021-06).

November 2021

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Acknowledgements

The authors deeply appreciate the support provided by Dr Jai Asundi, Executive Director, CSTEP, during the course of this work. We also thank Mr Abhishek Nath, Sector Head, Energy and Power, and Mr Suresh N. S., Research Scientist, CSTEP, for their valuable feedback and insights.

We express our gratitude to Mr Sumanth Shankar Rao (Advisor, CSTEP, and Former MD, Mangalore Electricity Supply Company Limited), Mr Raghuramu N. V. (Retd. Superintending Engineer, Karnataka Power Corporation Limited), and Mr M. R. Sreenivasa Murthy (Former Chairman, Karnataka Electricity Regulatory Commission), for providing vital inputs to the report and for overall guidance.

We gratefully acknowledge the editorial support extended by Ms Sreerekha Pillai and Ms Garima Singh, and the design support provided by Ms Bhawna Welturkar and Mr Alok Kumar Saha.

Last but not least, we express our gratitude to Shakti Sustainable Energy Foundation (SSEF) for financially supporting the study. The findings and analysis presented in this publication are informed by their support.

Executive Summary

India plans to install 450 gigawatt (GW) of renewable energy (RE) generation capacity by 2030. However, RE is highly intermittent in nature and cannot be dispatched on the basis of real-time demand. Utility-scale energy storage technologies such as battery and pumped-hydro could be the answer to this problem. Pumped-hydro energy storage (PHES) is the oldest and most mature large-scale storage technology and accounts for 96% of global installed energy storage capacity. PHES offers superior features, such as continuous generation for 6 to 10 hours (depending on the storage capacity of its reservoir), high ramping capability (around 1% of its capacity/second), efficiency in the range of 70% to 80%, and long lifespan of 40 to 60 years. It remains the most cost-effective long-term storage option available today, despite the recent reductions in battery costs.

However, in spite of these advantages, the growth of PHES in India has been tepid so far. The Central Electricity Authority of India has estimated a PHES potential of 96 GW, of which only 3.3 GW is currently operational in India. This slow pace can be attributed to the high cost associated with the commissioning of PHES plants, the long gestation period (due to delays in obtaining environmental clearances), and the poor recovery from the existing pricing mechanism of PHES.

To resolve the issue of low recovery from the existing pricing mechanism, and to fully recover the cost that has been incurred by a PHES plant during pumping, this study report recommends a differential pricing mechanism for PHES during its pumping and generating mode (or peak and off-peak operation). The profit generation from the differential pricing mechanism should be used for fixed-cost recovery. Additionally, it is recommended that the pricing mechanism be developed for specific use cases, such as peak-load shaving and RE smoothing. The report illustrates the pricing mechanism for Tehri PHES in Uttarakhand and Pinnapuram PHES in Andhra Pradesh.

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1. Introduction

India plans to install 450 gigawatts (GW) of renewable energy (RE) generation capacity by 2030. A major share of RE comes from solar and wind energy sources. These are highly intermittent sources of energy, where generation cannot be accurately predicted. Moreover, the power generated from these RE sources cannot be dispatched on the basis of real-time demand.

Utility-scale energy storages have the capability to manage such grid-balancing issues. Of these energy storages, pumped-hydro energy storage (PHES) is a mature technology that can be utilised well in India, which has a PHES potential of over 96 GW. PHES not only generates electricity for supply but also stores it in the form of potential energy of water. It is operated with two water reservoirs at different altitudes, both of which are connected through a penstock (water-supply pipeline) and a reversible turbine in the middle. When PHES is operated in power-generation mode, the upper reservoir supplies water to the lower one and the turbine system generates electricity. To store energy, water is pumped to the upper reservoir again—using the excess energy available in the grid—and is stored in the form of potential energy. A PHES system is shown in Figure 1.

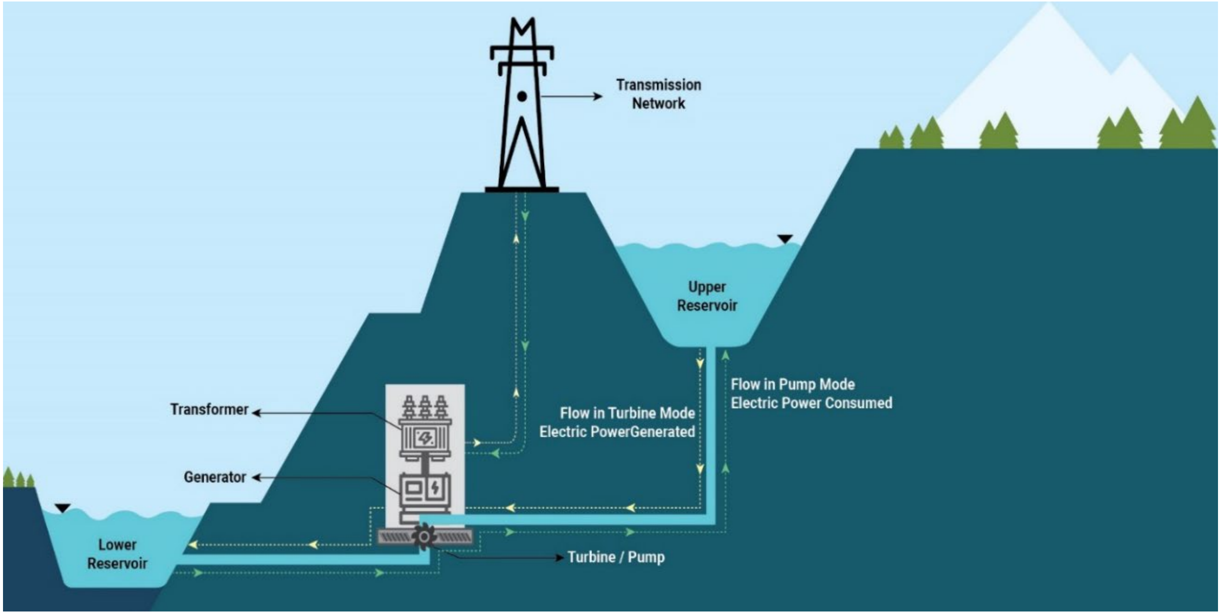


Figure 1: A pumped-hydro energy storage (PHES) system

PHES involves the use of reservoirs, either natural or artificial. Most of the proposed pumped storage projects worldwide are classified as either "open-loop" or "closed-loop" systems, based on the type of connectivity they have with rivers or other water bodies. While open-loop PHES are continuously connected to a naturally flowing water source, closed-loop PHES are off-stream plants that do not have a continuous connection to a naturally flowing water source. The powerhouses are designed underground and given the required connectivity through tunnels.

PHES plants are usually designed with a head range of 30–750 metres (Breeze, 2018), and a power range of 20–2000 megawatt (MW). The penstocks—which act as a conduit between the reservoirs, as well as manage the water flow to the pump/generator—are typically designed with a diameter of 5-10 metres.

Various configurations are used in pumped storage, a common one being a combination of fixed-speed and variable-speed reversible pump turbines. (More details of the different configurations are given in Annexure 1.) The variable-speed machine provides flexibility and faster response time, delivering its rated output in less than 30 seconds. The overall efficiency of PHES is in the range of 65%–80%, with a ramp rate of 1% of its capacity per second (International Renewable Energy Agency [IRENA], 2020; Kaldellis, Zafirakis, & Kavadias, 2009). These technical advantages of PHES make it the most suitable option to deal with grid-balancing challenges posed by the intermittent and variable nature of RE.

1.1 Use cases of PHES

PHES is able to efficiently support grid operation by providing services such as peak-load shaving, energy arbitrage, load following, round-the-clock support, RE smoothing, and other ancillary services.

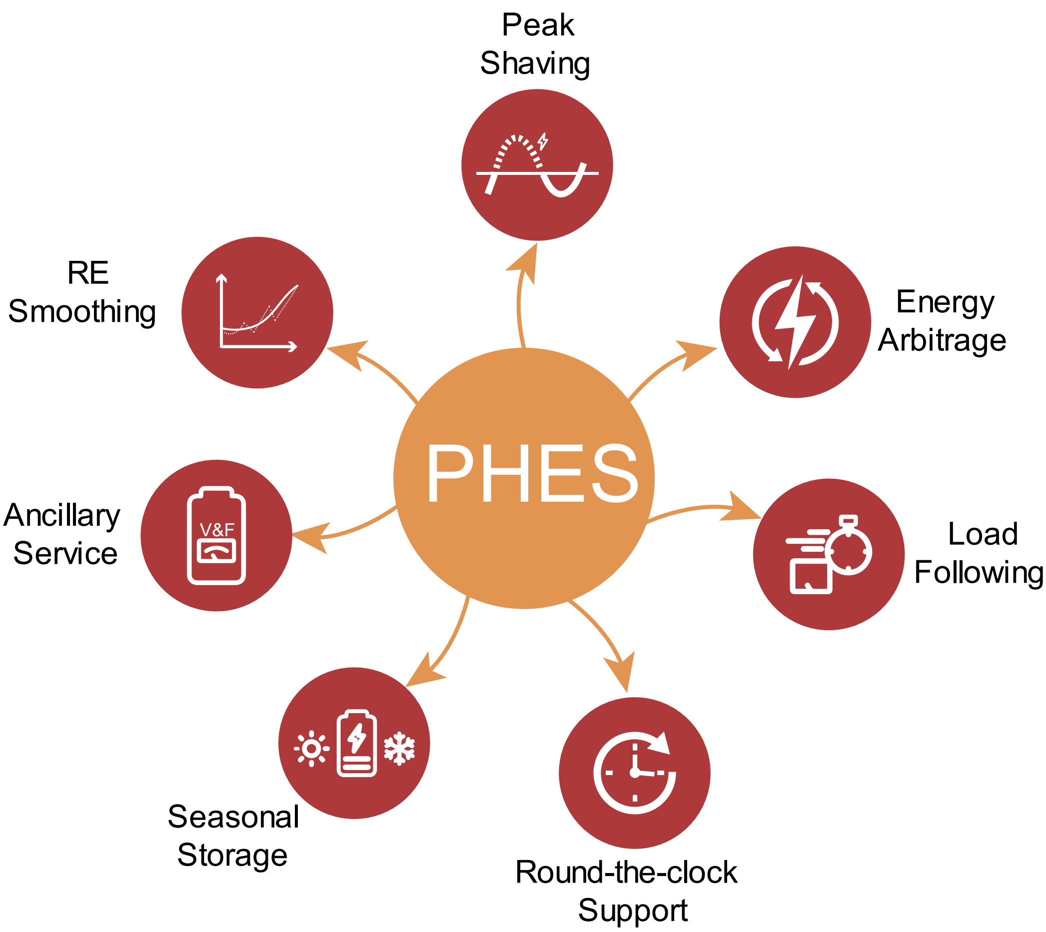


Figure 2: Use cases of PHES

- ***Peak-load shaving:*** PHES manages the peak load of the grid effectively, by storing energy in the off-peak hours and supplying it when the demand is high. Since PHES plants have high ramp up/ramp down rates of 200 MW/min, they can meet extremely high demands in very short periods of time.
- ***Energy arbitrage:*** PHES may prove economical in the daily energy arbitrage business as it buys bulk energy from power generators when the price is less (during off-peak hours) and sells it to power distribution companies when the price is high (during the peak hours).
- ***Load following:*** PHES, with its fast ramping-up/ramping-down capability, also maintains grid stability by taking care of the sudden changes in load.

- ***RE smoothing:*** In the case of large-scale integration of intermittent RE sources into the grid, PHES helps smooth out the variability by storing energy in the form of hydro potential (which can then be used when the grid needs it), thereby stabilising RE integration into the grid.
- ***Ancillary services:*** PHES:
    - Provides voltage support to the grid by generating/absorbing ***reactive power*** and hence mitigates voltage fluctuations across the system, which is caused due to imbalance in supply and demand of reactive power.
    - Maintains grid frequency within the desired range, acts as a ***spinning reserve,*** and also as a backup reserve during generation failure or power shortage.
    - Energises part of the grid or generation station during unplanned events or blackouts.
    - Renders good ***frequency regulation*** by maintaining frequency in the desired band of the grid. When the frequency is higher than 50 Hz, PHES operates in pumping mode, bringing down the frequency to below 50 Hz in the grid. On the other hand, when the frequency is below 50 Hz, PHES operates in generating mode and pushes up the frequency of the grid.
- ***Seasonal storage:*** The profiles of intermittent RE generation and demand vary seasonally. PHES has the ability to cater to these seasonal mismatches of RE generation, as well as those of the load.

1.2 PHES around the world

A total of 169 GW of PHES capacity is installed worldwide (Integrated Research and Action for Development, 2020). Out of this, China has the largest PHES capacity share of 18.9%, followed by Japan, USA, and Spain with 16.7%, 13.4%, and 4.7% share, respectively (International Renewable Energy Agency, 2017). With 4% of the global PHES capacity, India has the fifth-largest capacity share.

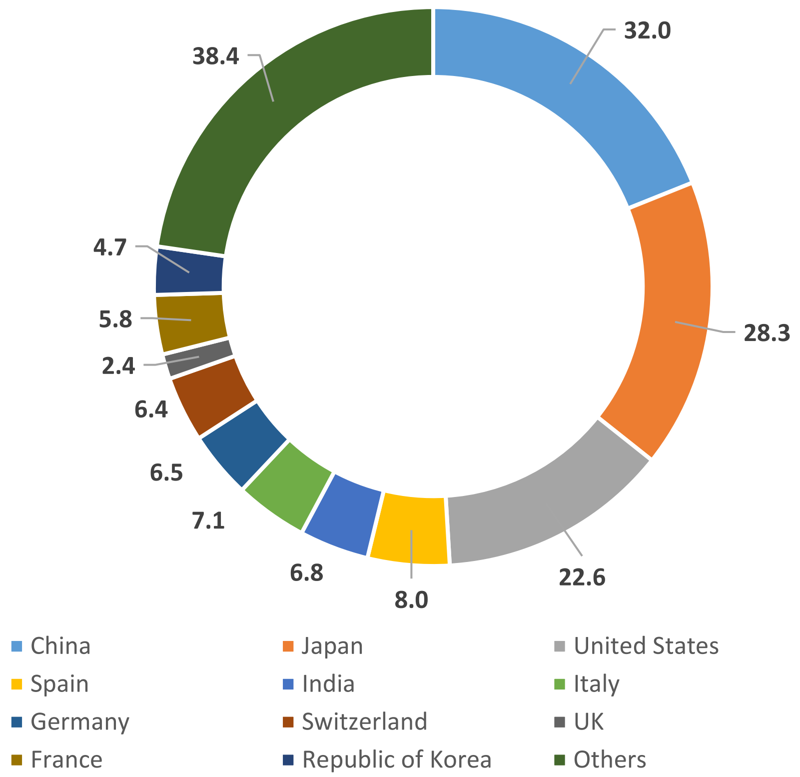
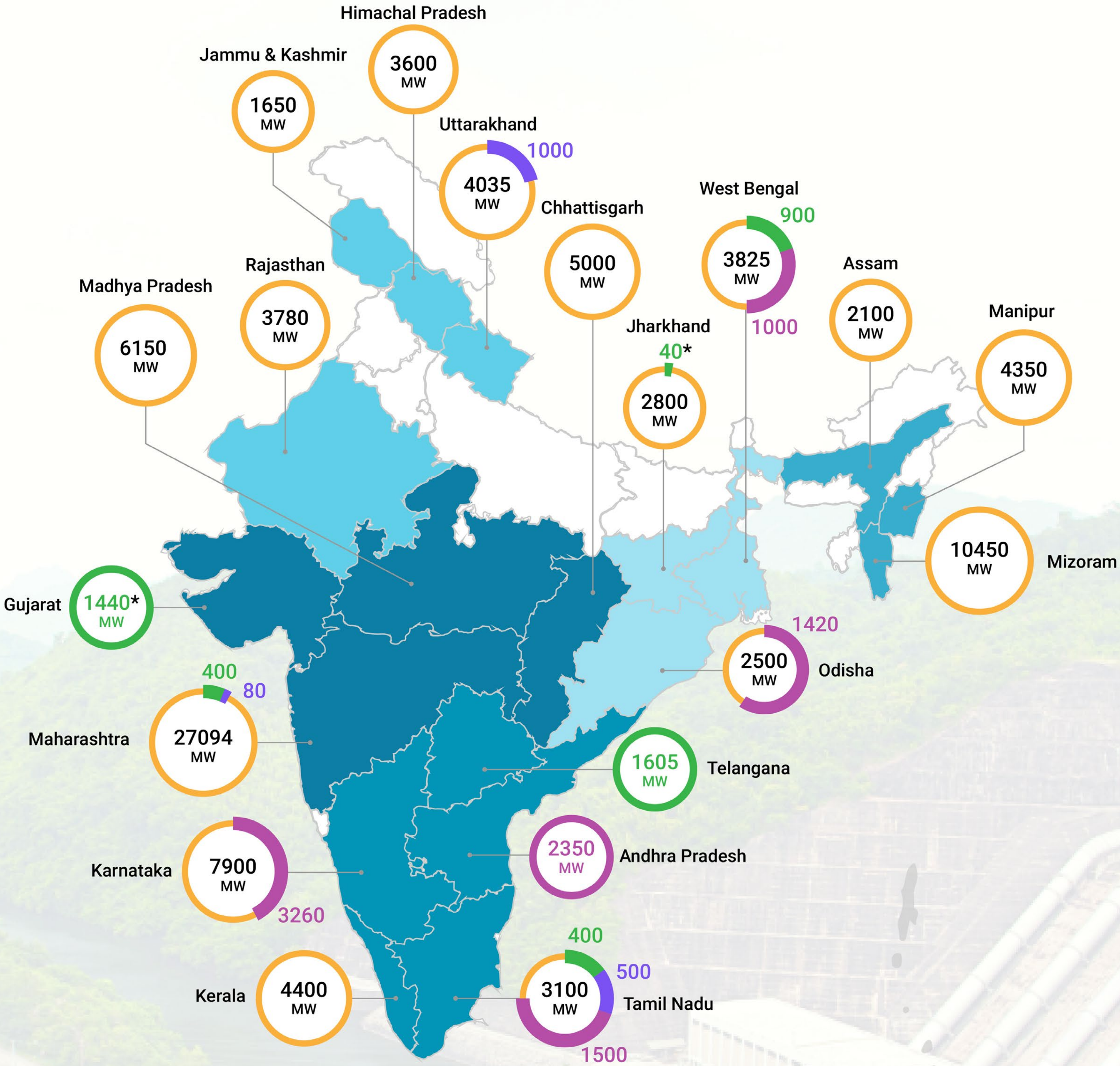


Figure 3: Country-wise PHES installation in GW

STATUS OF PUMPED-HYDRO ENERGY STORAGE IN INDIA

Status is for above 25 MW



Probable Installed Capacity (MW)

Capacity Developed (MW)

Capacity under Construction (MW)

Proposed Capacity (under DPR/survey investigation)

* Non-operational

Data Source: Pumped-storage in India, CEA: https://cea.nic.in/wp-content/uploads/hepr/2021/05/pump_storage_5-2.pdf *(Accessed on 22/7/2021)*

2. Status of PHES in India

To explore the hydroelectric potential of the country, the Central Electricity Authority (CEA) conducted studies and found 63 sites to be economically viable for prospective PHES projects. A total potential capacity of 96,529.6 MW (Central Electricity Authority, 2020) was estimated across all regions of the country. Of this, the western region has the highest potential (of 41%) owing to favourable topography, followed by the southern and north-eastern regions (both with around 18% potential), and then by the northern region (14%) and the eastern region (9%) (please refer to Table 1) (Central Electricity Authority, 2017; Japan International Cooperation Agency, 2018). Subsequently, detailed surveys and investigations were carried out by the PHES developers to understand the potential environmental impacts, and land-acquisition and resettlement issues related to these sites.

Table 1: Status of PHES projects in India

Operational capacity (MW)	Non-operational capacity (MW)	Under construction (MW)	Proposal development (MW)
3305	1480	1580	9780

State-wise pumped-storage development in India

Despite India's enormous potential for PHES, only six plants with a total capacity of 3,305 MW are currently operational in four states (Central Electricity Authority, 2021), as listed below:

- **Telangana** state accounts for two PHES plants, namely Nagarjuna Sagar (commissioned during 1980-1985 with an installed capacity of 705 MW), and Srisailam Left Bank Power House (commissioned during 2001-2003 with an installed capacity of 900 MW).
- **Maharashtra** state has two PHES plants with a cumulative installed capacity of 400 MW — Ghatghar (250 MW) and Bhira (150 MW). In addition to these, there is 12 MW PHES capacity each in Paithan and Ujjani within the state (Sivakumar, Das, & Padhy, 2014). (These are not included in the CEA documents as their capacity is less than 25 MW.)
- **Tamil Nadu** commissioned the Kadamparai project during 1987-88 with an installed capacity of 400 MW (comprising 4 units of 100 MW each).
- **West Bengal** initiated its first PHES project in Purulia with an installed capacity of 900 MW in May 2002 and was able to complete the project by 2007.

Though there are three PHES plants (with a cumulative capacity of 1,480 MW) (Central Electricity Authority, 2021) in the states of Gujarat and Jharkhand also, currently they are not operational in pumping mode due to the following issues:

- The Kadana project in Gujarat, which has an installed capacity of 240 MW, is presently not operational in pumping mode due to vibration in the machines. Testing has been going on, but the anticipated commissioning dates have not yet been disclosed.
- Another project in Gujarat, Sardar Sarovar, which has an installed capacity of 1,200 MW, has also been delayed since 1961. Its recent status shows that the construction of the tail-pool dam is complete. Discussions are on for operationalising the plant in pumping mode.
- Similarly, operations at the Panchet Hill plant in Jharkhand, which has an installed capacity of 40 MW, have been delayed due to issues related to land acquisition for construction of the tail-pool dam.

Besides these, three other plants with around 1,590 MW installed capacity are under construction. These include Tehri (1,000 MW) in Uttarakhand, Kundah (500 MW) in Tamil Nadu, and Koyna Left Bank (80 MW) in Maharashtra. All three projects are expected to be commissioned during 2022–2026.

Further, many other states have initiated PHES surveys and investigations. Currently, 19 plants of a cumulative installed capacity of 9,780 MW across five states are in different stages of development (such as pre-feasibility studies, survey and investigation, preparation of detailed project report, and examination of proposed projects under CEA).

2.1 Dispatch strategy of the existing PHES plants in India

PHES plants are operated in both pumping and generation modes. In the pumping mode, they act as a load i.e., consume excess power available in the grid to pump the water to the upper reservoir during the off-peak hours (mostly during night); while in the generation mode, they act as a power source in order to meet the peak demand of the grid by discharging water to the lower reservoir through turbines. The dispatch strategy of some of the operational PHES plants in India is discussed ahead (Central Electricity Authority, 2017).

1. Purulia PHES (West Bengal)

The Purulia PHES plant, commissioned in the year 2007-08, is located in Ajodhya hills in Purulia district, West Bengal. The installed capacity of the plant is 900 (4 X 225) MW and it is operated by West Bengal State Electricity Distribution Company Ltd. (WBSEDCL). This plant is operated as a closed-loop PHES.

The dispatch strategy followed by Purulia PHES for a typical day in the year 2016 is shown in Figure 4. The PHES operates in pumping mode when the state demand is low or for the off-peak duration (i.e. from hour 1 to hour 10.5). Here, it consumes power from the grid. The plant operates in generation mode during the peak hours of state demand by discharging water from the upper reservoir to the lower reservoir through turbines. The power generated is injected into the grid to meet the state demand between hour 18 and hour 24.

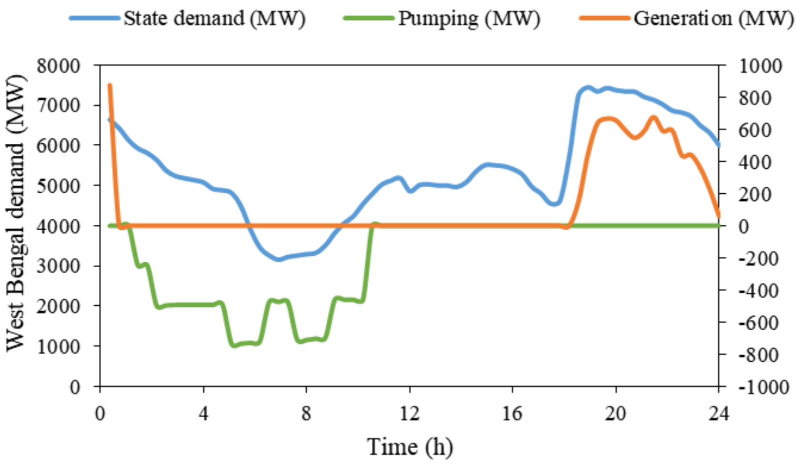


Figure 4: Purulia PHES dispatch strategy

2. Ghatghar PHES (Maharashtra)

The Ghatghar PHES, which was commissioned in the year 2008, is located in the Sahyadri range in Ahmednagar district of Maharashtra. The installed capacity of this PHES is 250 (2 X 125) MW and it is operated by Maharashtra State Electricity Transmission Company Ltd. (MAHATRANSCO). The upper reservoir of this plant is fed by Pravara river, and the lower reservoir by Shahi Nalla river. This PHES consists of two units and is operated in an open-loop mode. The pumping-mode and generating-mode operations of the Ghatghar PHES plant are shown in Figure 5. As can be seen in the figure, the plant operates in pumping mode when the state demand is low (i.e. from 1.00 a.m. to 5.30 a.m.). On the other hand, when the state demand is high (i.e. from 5.30 p.m. to 8.30 p.m. for unit 1 and from 5.30 p.m. to 11.00 p.m. for unit 2), the same hydro potential is converted into electrical energy by releasing water from the upper reservoir to the lower reservoir in generation mode.

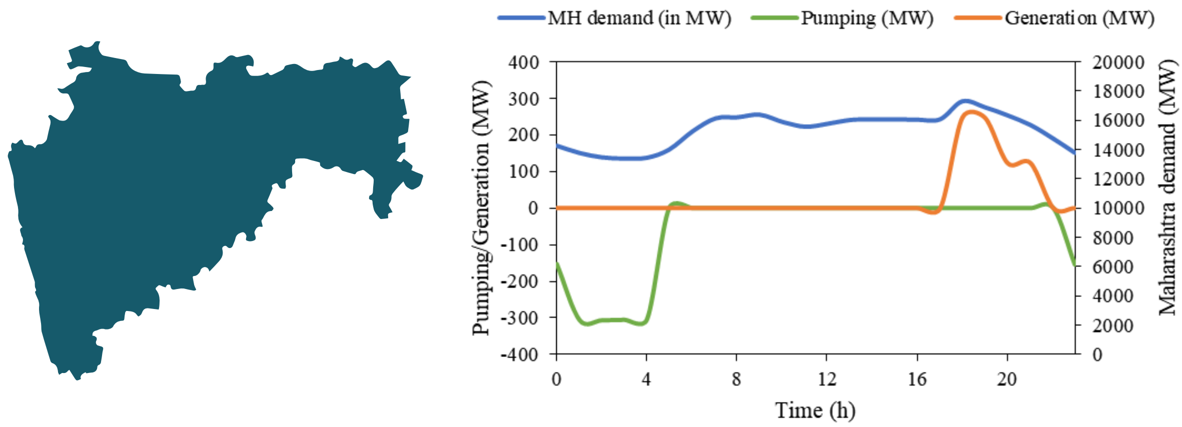


Figure 5: Ghatghar PHES dispatch strategy

3. Kadamparai PHES (Tamil Nadu)

The Kadamparai PHES plant is located in the Anamalai hills in Coimbatore district of Tamil Nadu. The installed capacity of the plant is 400 (4 X100) MW and it was commissioned during 1987-88. This PHES has Kadamparai dam as the upper reservoir (fed by Kadamparai river), and the upper Aliyar dam as the lower reservoir. It is operated by Tamil Nadu Generation and Distribution Corporation Ltd. (TANGEDCO).

The dispatch strategy of Kadamparai PHES in Tamil Nadu is linked to the RE generation (wind source) in the state, along with the peaking operation. The PHES operation for a typical day is as shown in Figure 6. The PHES plant operates in pumping mode during high-wind generation i.e. from 1.00 a.m. to 5.30 a.m., and in generation mode (for a short duration of 1 hour) during low-wind generation in the state i.e. from 6.30 a.m. to 7.30 a.m. During peak load i.e. from 8.00 p.m. to 10.30 p.m., it operates in generation mode (for a long duration of 2.3 hours).

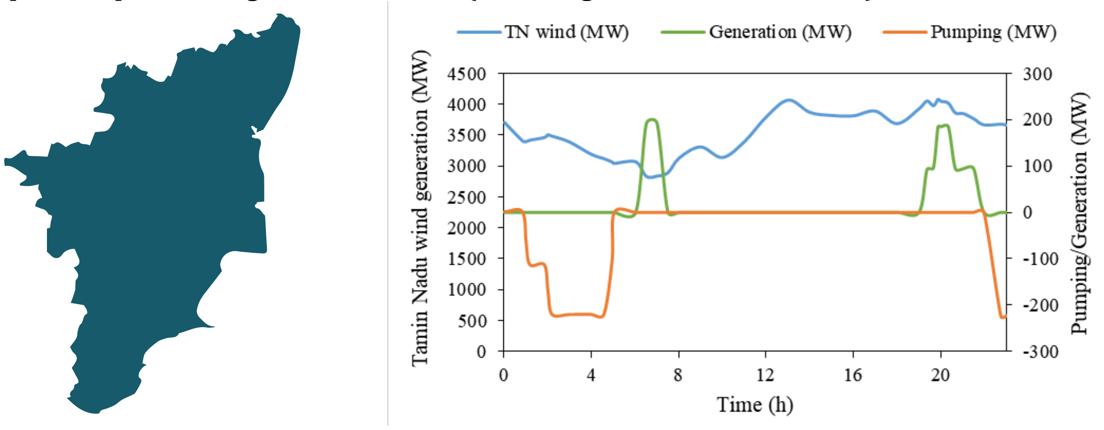


Figure 6: Kadamparai PHES dispatch strategy

2.2 Existing pricing mechanism of PHES in India

As per the Central Electricity Regulatory Commission (CERC) Tariff Determination Regulations 2019-2024 (Central Electricity Regulatory Commission, n.d.), a PHES project has a two-part tariff consisting of fixed-cost and variable-cost components. The fixed-cost component (also known as capacity charge) is used for recovering the capital cost incurred by the plant on an annual basis, such as the cost of plant and machinery, manpower, and administration cost, etc.

The capacity charge is calculated as follows:

If actual generation is >= 75% of the pumping energy consumed by the station during the month, then:

$$\boldsymbol{Capacity\ charge\ =\ (AFC\ x\ NDM\ /\ NDY)} \qquad \textbf{(1)}$$

If actual generation is < 75% of the pumping energy consumed by the station during the month, then:

Capacity charge = [(AFC x NDM / NDY) x (Actual Generation / 75% of Pumping Energy)] (2)

Where,

AFC = Annual fixed cost specified for the year (in rupees).

NDM = Number of days in the month

NDY = Number of days in the year

The variable-cost component (or the energy charge) is used to recover the cost incurred in operating the plant. It is calculated at a **flat rate of 20 paise/kWh** of total energy scheduled (in excess of design energy) plus 75% of the energy consumed in pumping from the lower reservoir to the upper reservoir.

Energy charge= 0.2 x [SEm – (DEm+ 75% of energy utilised in pumping water from lower to upper reservoir)] x (100 – FEHS) / 100 (3)

Where,

SEm = Monthly scheduled energy

DEm = Design energy for the month specified for the hydro-generating station, in MWh.

FEHS = Free energy for home state (as a percentage).

If the scheduled energy in a month is less than the design energy for the month plus 75% of the energy utilised in the month for pumping the water from the lower reservoir to the upper reservoir, the energy charges payable by the beneficiaries shall be zero.

Table 2 provides the details of the existing, under-construction, and proposed PHES plants in India, along with their approved tariffs. (The table is colour-coded such that the existing ones are shown in green, the under-construction ones in yellow, and the proposed ones are shown in blue.)

Table 2: Tariff and other details of PHES in India

Name	Generation Energy (MU)	Pumping Energy (MU)	Efficiency	Generating Hours	Pumping Hours	Levelised tariff (INR/kWh)
Srisailam (TS, 900 MW)	788	-	89	-	6	7.66
Ghatghar (MH, 250 MW)	470	645	-	6	7	7
Kadamparai (TN, 400 MW)	797	797	-	4	5	6.22
Purulia (WB, 900 MW)	1897	1700	75.5	6	8	6.89
Tehri (UK, 1000 MW)	1321.82	1651.66	80.2	4	7	7
Turga (WB, 960 MW)	1825	2503.5	74	5	6.75	5.85
Malshej Ghat (MH, 700 MW)	1680	2237	75	7	8	2.89*
Pinnapuram (AP, 1200 MW)	2774	3645	76.1	8	9.22	4.04*
Saundatti (KA, 1200 MW)	3329	4338	76.74	8	9.2	-
Sharavathy (KA, 2000MW)	4380	5412.9	80.9	6	7.5	5.33
Upper Kobal (Od) (320 MW)	506.0	675.04	75.05	5	6.5	2.70*
Kundah (TN, 500 MW)	1005	1052	77.5	6	6.25	5.64
Yerravaram (AP, 1000MW)	2183.9	2694.9	81.04	5.9	7.3	8.18
Balimele (Od, 500 MW)	1095	1303.5	84	6	7.13	8.58
Sillahalla (TN, 1000 MW)	2130	2485	85.7	6	7.16	6.11

* excluding pumping costs

Existing **Under-construction** **Proposed**

2.2.1 Need for a differential pricing mechanism for PHES

Under the current PHES pricing mechanism, yields from the energy charge are zero, as the monthly scheduled energy will always be less than the design energy and the 75% pumping energy combined. This is because the current pricing mechanism considers PHES only as a generator that needs to recover its cost by selling power at a specific tariff (determined by the regulatory authorities) from the beneficiary/consumer. But PHES operates in such a way that it acts as both a generator and a consumer. When water is being pumped from the lower reservoir to the upper reservoir, PHES draws power from the grid and acts as a consumer. On the other hand, when it releases water and generates energy, it acts as a generator.

In addition, PHES plays a multifunctional role, and as such, is able to support stable grid operations by offering various services, such as peak-load shaving, energy arbitrage, load following, round-the-clock support, RE smoothing, and other ancillary services. However, the current pricing mechanism provides a generic tariff, ignoring the various services offered by PHES to the grid. Because of the generic tariff, PHES is not able to fully leverage its usability. It is, therefore, important that a pricing mechanism is developed to account for each specific service that PHES offers.

To fully recover the cost that has been incurred by a PHES system during pumping, a differential pricing mechanism needs to be employed during the pumping mode and the generating mode (or during peak and off-peak operations).

Furthermore, as seen in Table 2, many PHES plants have a tariff that is above INR 6/kWh. Considering that the average power procurement cost is declining, it would be difficult for a PHES plant to earn profits at the determined tariff by operating as a standalone generator in the market or by signing long-term bilateral agreements with distribution companies.

Although PHES has a huge technical advantage, its growth in India has been sluggish. There is a need to attract more investment into this sector for better growth. This can be achieved only if developers see some profit being generated from the operations. While the current tariff mechanism ensures the recovery of the full cost of the PHES plant over the years, it does not ensure any profit from the operations. This has also hampered private investment in the sector. There is, thus, an urgent need for a pricing mechanism that can ensure profit generation for the developers over and above their fixed-cost and variable-cost components. The mechanism should be based on the specific services being offered by the PHES plant to the grid. The following section discusses the pricing mechanism for two specific use cases of PHES.

3. Differential Tariff Computation for Different Use Cases

This section discusses the proposed tariff computation methods for the use case of peak-load shaving and renewable-energy smoothing.

3.1. Tariff computation for energy arbitrage/peak-load shaving/load following

PHES systems are used as merchant power plants in the market i.e. as independent power plants competing to sell power. They are operated in the power markets of India, such as Indian Energy Exchange (IEX) and Power Exchange India Limited (PXIL). The methodology proposed here can be employed for energy-arbitrage, peak-load-shaving, and load-following use cases.

The primary input requirements for the tariff-computation method are day-ahead real-time market prices, market buying and selling volume, and the load profile of the state. The dispatch strategy of PHES in the market can be either of the following:

- Pumping during low prices and generating during high prices
- Pumping during low prices and discharging/generating during peak load

Therefore, the pumping cost of PHES is the weighted sum of the off-peak prices in the market (depending on pumping requirements). The generation cost is the weighted sum of peak prices in the market (depending on generation requirements). The revenue earned by the PHES developer will be the price differential between peak and off-peak prices. The above methodology can be summarised as shown in Figure 7.

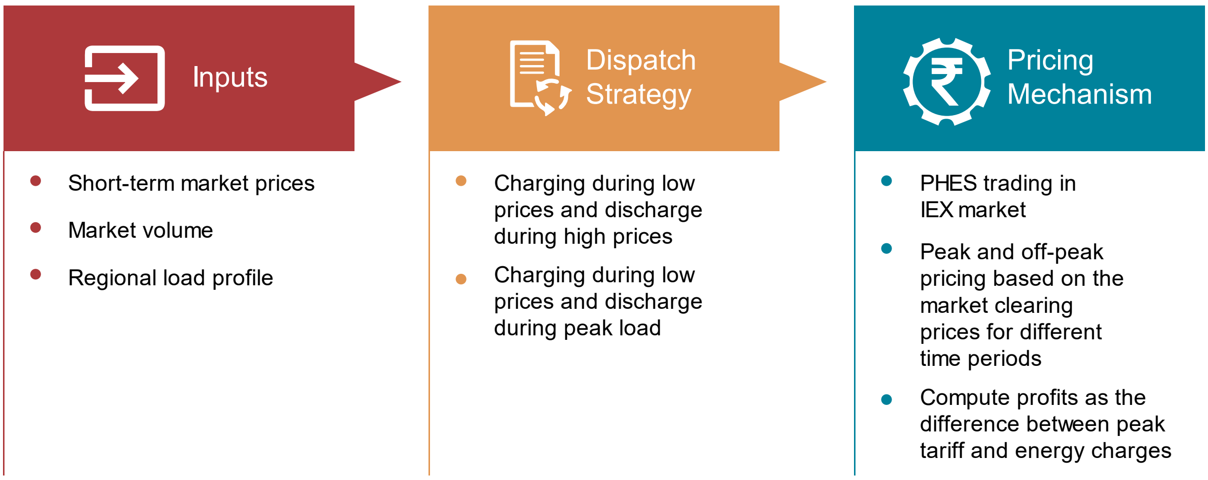


Figure 7: Tariff computation method for energy arbitrage/peak-load shaving/load following

3.1.1 Inputs: IEX market-data insights

For the study, data inputs from IEX market were collected. These include the market-clearing prices (MCPs), and the market selling and buying volume of the different regions across India for two years (2019 and 2020) (Indian Energy Exchange, n.d.). A snapshot of the IEX price-minute curves is shown in Figure 8(a) for the different regions for a period of 20 days in 2019. The regions are A1 (Mizoram, Tripura, Manipur, Nagaland); E1 (West Bengal, Sikkim, Bihar, Jharkhand); E2 (Orissa); N2 (Uttar Pradesh, Uttaranchal, Rajasthan, Delhi); S1 (Andhra Pradesh, Telangana, Karnataka, Pondicherry [Yanam], South Goa); S2 (Tamil Nadu, Pondicherry [Puducherry, Karaikal, Mahe]); W2 (Maharashtra, Gujarat, Daman and Diu, Dadra and Nagar Haveli, North Goa).

From the graph, it is clear that during most of the periods, the price minute across the regions matches. A comparison was done with the 2020 price minute as well and it was seen that the price trends match. However, the average MCP decreases year on year, as shown in Figure 8(b).

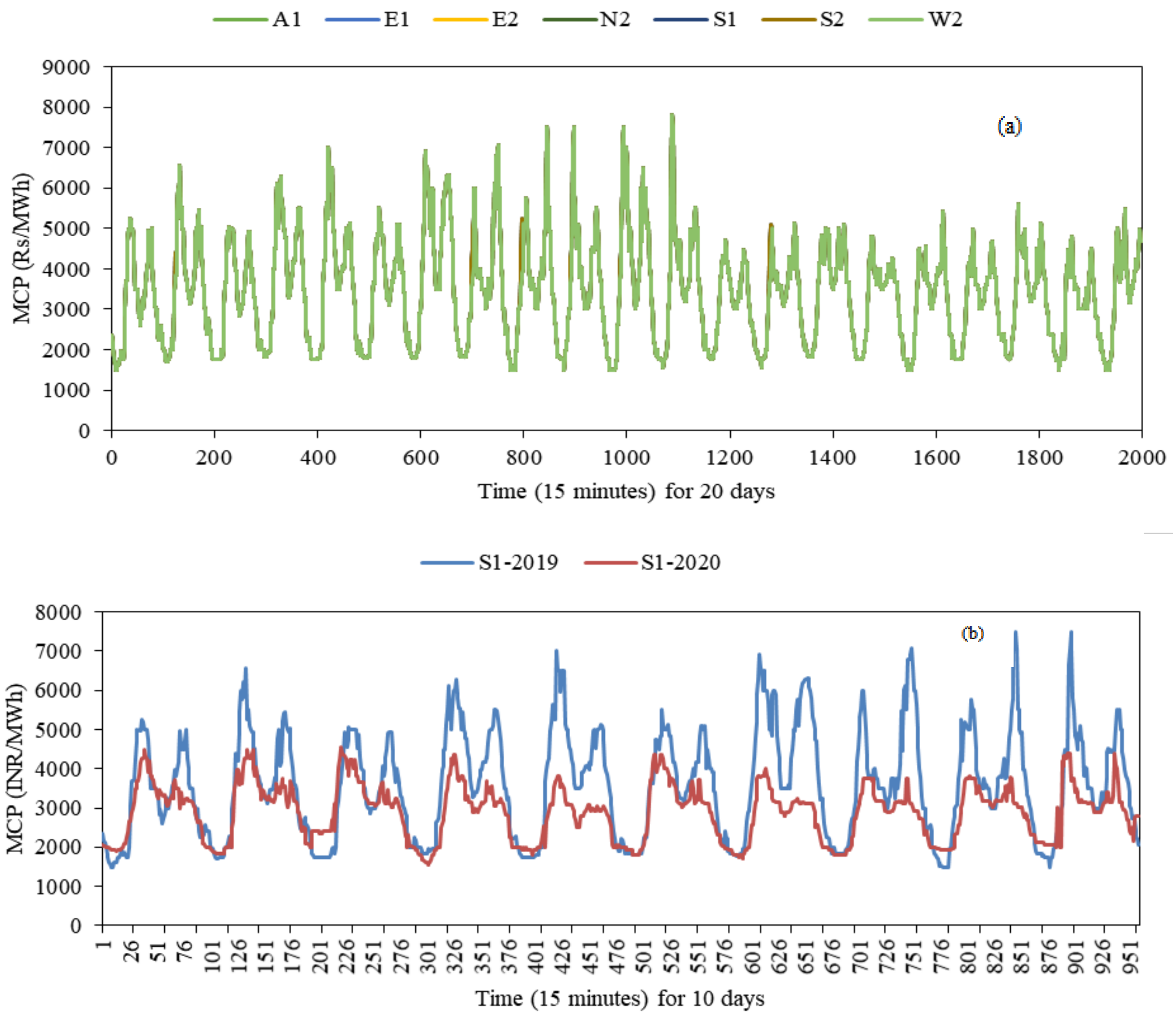


Figure 8: IEX market data – (a) Price minute across regions; (b) Comparison of 2019 and 2020 MCP for S1 region

3.1.2. Case study of Uttarakhand

The tariff computation method for peak-load shaving is further illustrated through the Uttarakhand case study, with the example of Tehri PHES. In the state of Uttarakhand, the Tehri PHES plant is to be commissioned by the year 2022. The beneficiary states for this PHES include Delhi, Haryana, Uttarakhand, and Rajasthan. Since the PHES plant will provide power to more than one state, it has to follow the CERC tariff regulations. Uttarakhand comes under the N2 region of in the IEX market. The price-minute curve, the load curve, the buying volume, and the selling volume for it are shown in Figure 9.

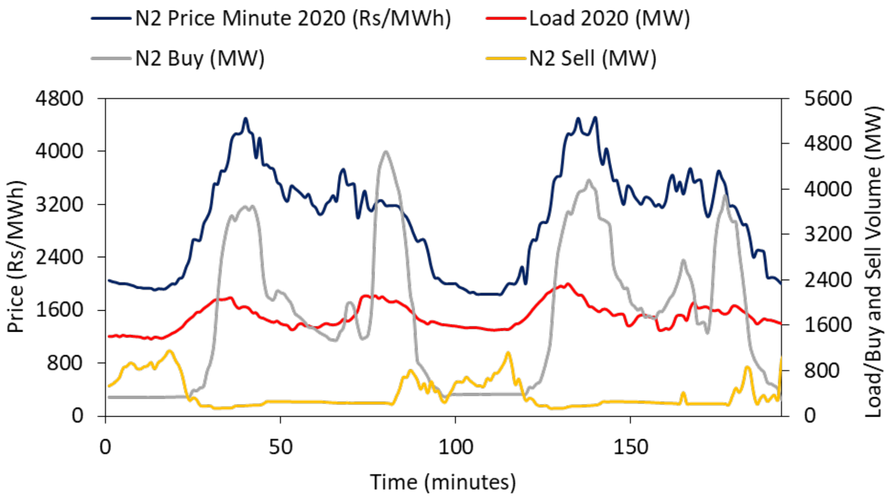


Figure 9: Price-minute curve, load curve, the buying volume and the selling volume for N2 region for a day

The Tehri PHES has a capacity of 1000 MW with a round-trip efficiency of 80%. The annual generation and consumption of the plant will be 1321.8 gigawatt hours (GWh) and 1651.6 GWh, respectively.

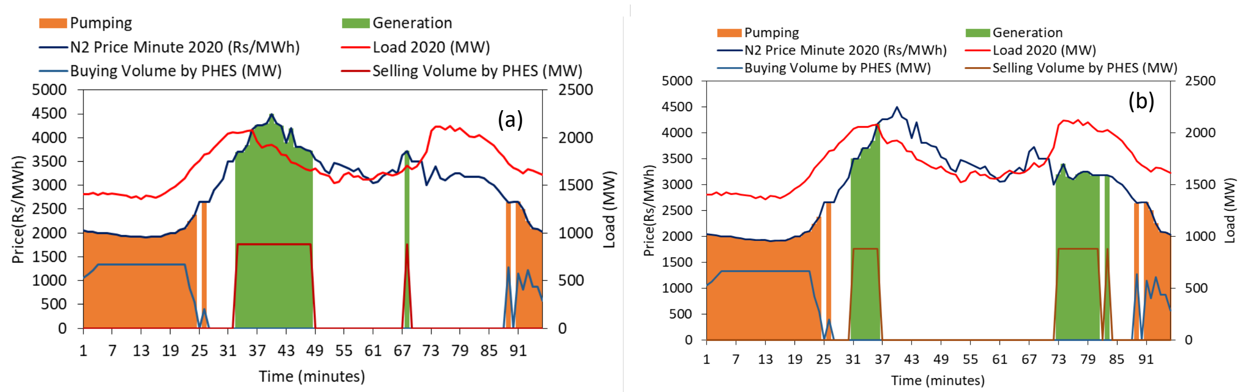


Figure 10: Dispatch plot of Tehri PHES – (a) Profit maximising; and (b) Peak-load shaving

Figure 10 shows the dispatch plot of Tehri PHES for a day, wherein Figure 10(a) shows the profit-maximising scenario where the low-priced price minute is used for pumping and the high-priced instances are used for generation; and Figure 10(b) shows the peak-load-shaving scenario where low-priced price minute is still used for pumping, while the PHES plant generates power during high peak-load periods. The profit earned while operating the plant for the profit-maximising scenario, as shown in Figure 10(a), is INR 38,25,323, with an average peak tariff of 3.94 INR/kWh and an off-peak tariff of 2.15 INR/kWh. Similarly, the profit earned while operating PHES as a peak-load-shaving asset, as shown in Figure 10(b), is INR 16,34,214, with an average peak tariff of 3.32 INR/kWh and an off-peak tariff of 2.15 INR/kWh. There is a clear reduction in profit when the PHES plant is operated in the market as a peak-load-shaving asset. In both cases, the point of connection (POC) charges, transmission losses, and IEX fees are considered.

Further, on some days the price-minute curves tend to remain constant, which results in a loss to the PHES developer. To tackle the price variability, the profit-maximising scenario was repeated for the whole year and the revenue for the different days was plotted, as shown in Figure 11. It is seen that the PHES plant should not be operated on some days as doing so will incur losses. The results are summarised in Table 3.

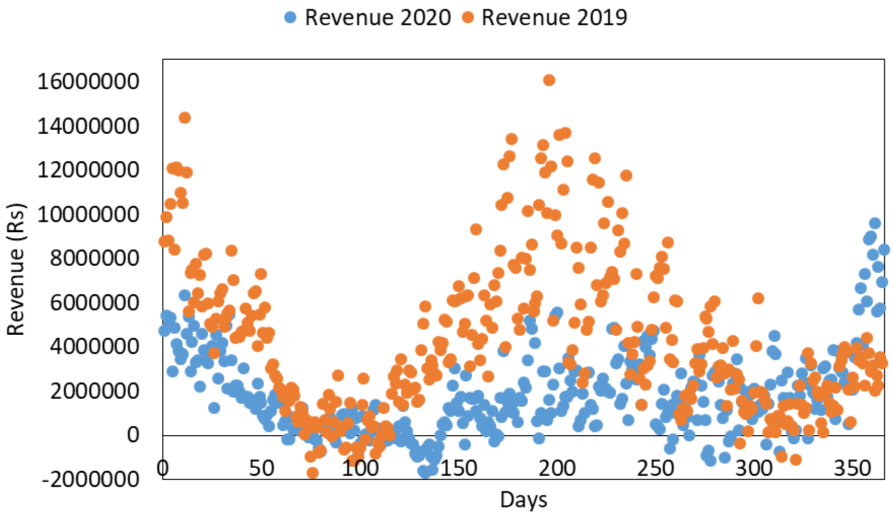


Figure 11: Revenue for different days in 2019 and 2020

When tariffs are calculated through a differential pricing mechanism in the market, the Tehri PHES plant earns a net profit of INR 157 crore and INR 70 crore, based on the 2019 and 2020 MCPs, respectively. The revenue generated through such differential pricing can be used for recovering the capacity charges (annual fixed cost or AFC). The capacity charges are computed on the basis of AFC (as shown in equation 1) according to the CERC tariff regulations of 2019-23 (Central Electricity Regulatory Commission, n.d.). The AFC is based on the total project cost, return on equity, depreciation, interest on loan capital, and operation and maintenance (O&M) expenses, etc., which works out to be around INR 1017.2 crore. The profit earned will provide a fixed-cost recovery of 16% and 7% in 2019 and 2020, respectively, as shown in Table 3.

Table 3: Comparison of tariff-computation results for 2019 and 2020

Results	2019	2020
Number of no-positive-revenue-generation days	21	53
Ratio of average peak price to off-peak price required to generate revenue	1.35	1.33
Maximum revenue generated for a day (INR) Average peak price (INR/kWh) Off-peak price (INR/kWh)	1,60,82,247 (15-Jul) 7.5 2.25	96,14,821 (26-Dec) 5.3 1.95
Net profit for the year (INR crore)	157	70
Percentage fixed-cost recovery	16%	7%

3.2. Tariff computation for RE smoothing

This tariff-computation method can be used by grid-connected plants which utilise RE for their pumping requirements, as well as by co-located PHES plants with RE. Integrating PHES plants with RE enables a round-the-clock support for these plants. The input requirements for computing the tariff are the RE profile (solar and wind profile), and the load profile as seen by the PHES plant. The PHES utilises the excess RE available, to charge, and discharges during low-RE instances and high load, thereby helping the RE plant to provide dispatchable power. This will also avoid the cost of RE curtailments and help the electricity distribution companies (DISCOMs) to meet their renewable-purchase-obligation (RPO) targets. Here the PHES plants can enter into long-term contracts or bilateral trade with DISCOMs.

The tariff-computation methodology can be shown as follows (Figure 12).

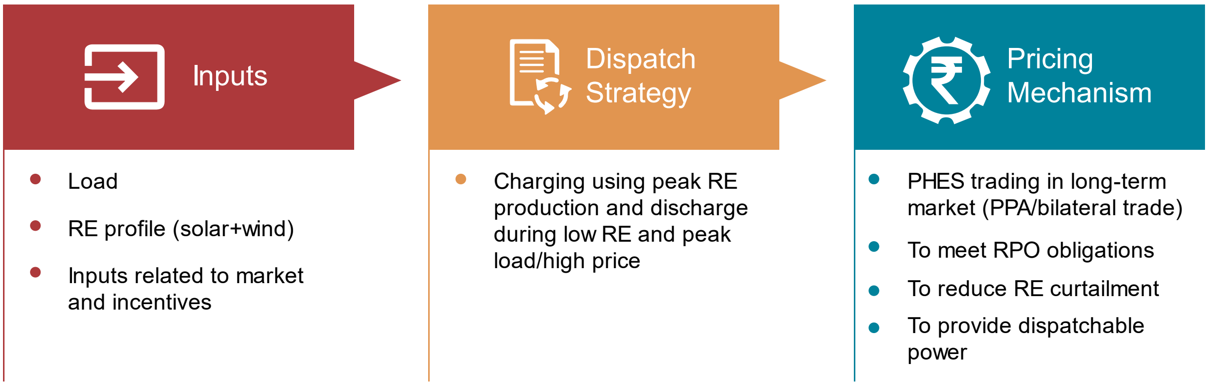


Figure 12: Tariff computation for RE smoothing

The pumping cost of the PHES will include the RE cost, along with the interconnection charges. The generation cost will include the pumping price and certain incentives for providing grid flexibility. Such incentives may include the following:

i. **Compensation for avoiding RE curtailment:** In case of a transmission constraint, low system demand, or grid security issue, the supply of RE is curtailed from the grid. As RE has been given a "must-run" status, any curtailment has to be appropriately compensated for. Since PHES would help in reducing RE curtailment by using excess RE for pumping, the same compensation has been considered as the incentive for PHES. The different levels of compensation are shown below in Table 4.

Table 4: Compensation for avoiding RE curtailment

RE-curtailment penalty scenarios	Compensation
Grid security reasons	0
Transmission constraints (up to 7% curtailment)	Up to 50% of curtailed energy at contracted price
Transmission constraints (beyond 7% curtailment)	50% of curtailed energy at contracted price
Low system demand	50 paise/kWh

ii. **Avoided cost from high-priced purchase of thermal or gas plants:** A PHES integrated with an RE plant would be able to supply firm, reliable, and round-the-clock power supply. This would help DISCOMs to avoid the cost of power purchase from high-priced thermal power plants. This avoided cost can be used to incentivise PHES.

iii. **Grid-flexibility compensation:** PHES is capable of dealing with the challenges associated with the intermittent and variable nature of RE, thus providing grid flexibility. This service provided by PHES needs to be accounted for through grid-flexibility incentives. A 50 paise/unit incentive is provided for ancillary services towards grid flexibility. A similar compensation has been considered for PHES.

Table 5: Grid flexibility compensation

Grid flexibility scenarios	Compensation
Minimum scenario	0
Reserve regulation ancillary services (RRAS) markup price	50 paise/kWh
Maximum scenario	1 Rs/kWh

iv. **Generation-based Incentive (GBI):** This can attract more investment to the sector. Here, a minimum and maximum value of 0 and 1 INR/unit, respectively, has been considered.

The profit or loss earned by a PHES developer will be determined on the basis of the above incentives.

3.2.1 Case study of Pinnapuram PHES in Andhra Pradesh

This tariff-computation method is illustrated through the case study of the Pinnapuram integrated-RE storage project in Andhra Pradesh. It has been planned to install a solar plant with a capacity of 2,000 MW, a wind plant of 400 MW capacity, and a PHES plant of 1,000 MW capacity at the site. The annual power generation and consumption of the plant will be 2,774 GWh and 3,645 GWh, respectively, with a round-trip efficiency of 76%.

The RE profile (both solar and wind) for the location is simulated using renewables.ninja webtool (Imperial College London & ETH Zürich, n.d.) for the year. The load profile of Andhra Pradesh is obtained from Power System Operation Corporation Limited (POSOCO)[1]. The load seen by the PHES is normalised (from the state load) by keeping the shape of the load profile intact. The RE and the load profiles are shown in Figure 13.

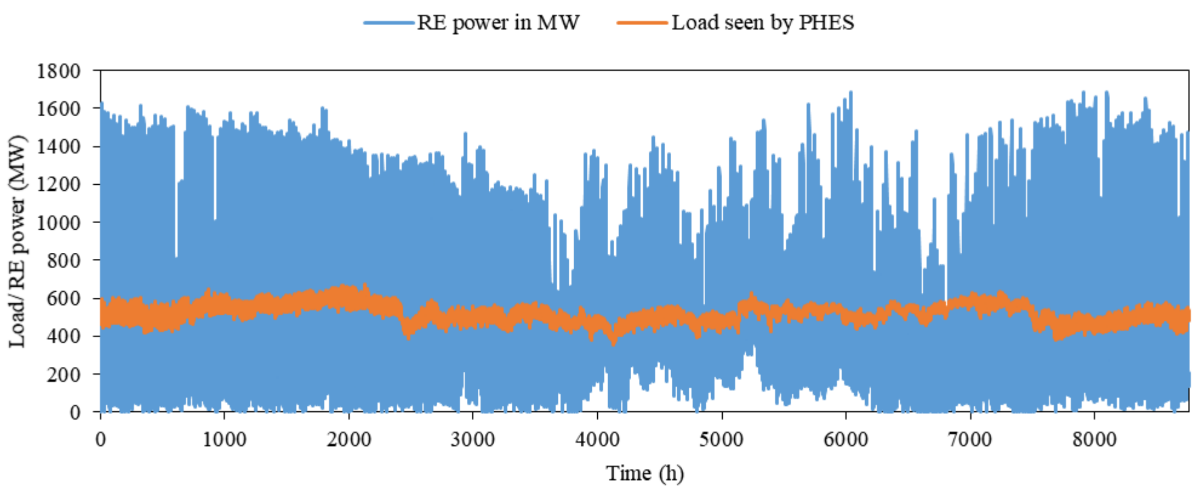


Figure 13: RE profile (both solar and wind) at the Pinnapuram RE plant and normalised load as seen by the PHES for a year

The dispatch strategy of this plant is shown in Figure 14. The excess RE is used for pumping, while during low-RE periods and high demand, the PHES plant generates energy.

For computing the compensation under “avoided cost from high-priced purchase of thermal or gas plants”, the study analysed the specific case of Pinnapuram project from the Andhra Pradesh tariff order. Table 6 depicts the cost that DISCOMs would avoid by not purchasing power from

[1] Personal communication

thermal plants. For the case study, the maximum and the minimum deviation from non-conventional energy sources (NCE) in the tariff order ranged between 0.37-0.91 INR/unit.

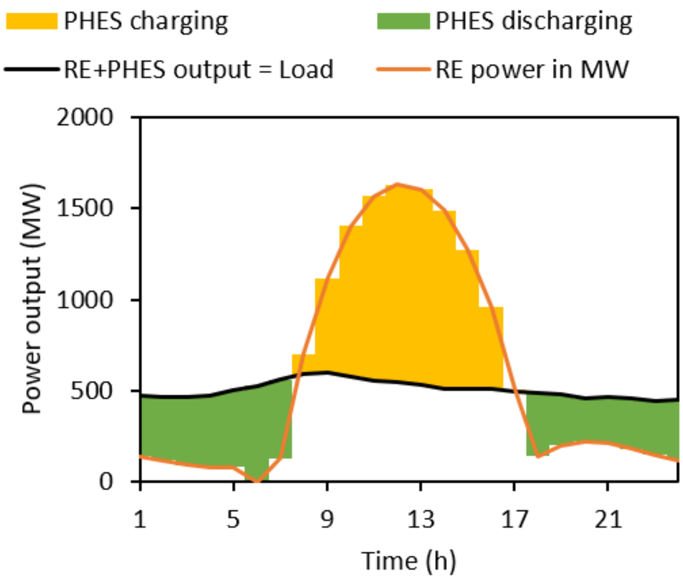


Figure 14: Dispatch strategy for a day for the PHES plant at Pinnapuram

Table 6: Avoided cost from high-priced purchase of thermal or gas plants

Power Source	Energy (GWh)	Fixed Cost (INR/unit)	Variable Cost (INR/unit)	Total Cost (INR/unit)	Deviation from NCE (INR/unit)
APGENCO thermal	7,104	1.54	3.39	4.93	0.37
RTPP stage IV	1,018	1.80	3.66	5.46	0.91
NTTPS V Stage	1,467	1.80	3.14	4.94	0.39
SDSTPP-I	6,565	2.00	3.14	5.14	0.59
SDSTPP-II	1,621	1.80	3.14	4.94	0.39
Non-Conventional Energy (NCE)	14,097	0.00	4.55	4.55	0.00

The tariff computation for the Pinnapuram project is shown in Table 7. It shows the minimum and maximum scenarios, as well as the three intermediate scenarios that could be applicable for the project. The minimum and maximum RE cost considered for the scenarios is INR 2 and 3 per unit, respectively. Similarly, an interconnection charge of INR 1 per unit is also assumed and added to the pumping cost. Hence, the profit earned by the Pinnapuram project will be in the range of INR 0.37 to INR 4.41 per unit with a capacity charge recovery of 10% to 122%.

Table 7: Tariff computation for the Pinnapuram project

		Minimum scenario	Intermediate scenario 1	Intermediate scenario 2	Intermediate scenario 3	Maximum scenario
Pumping cost (INR/kWh)	RE cost	2	2	2.5	2	3
	Interconnection charges	1	1	1	1	1
Compensation (INR/kWh)	Compensation for avoiding RE-curtailment penalty	0	0.5	0.875	1	1.5
	Avoided cost from high-priced gas / thermal plants (from AP tariff order)	0.37	0.37	0.37	0.91	0.91
	Grid-flexibility incentive	0	0	0.5	0.5	1
	Generation-based incentive (GBI)	0	0.5	0.5	0.5	1
Generation cost (INR/kWh)		3.37	4.37	5.745	5.91	8.41
Profit/loss (INR/kWh)		0.37	0.87	2.245	2.91	4.41

4. Financing mechanism of PHES around the world

The PHES system is highly capital intensive in nature. As such, substantial investment is required to make it commercially viable. To attract investors for PHES development, appropriate financing mechanisms are required. This section, therefore, discusses the financing mechanism of PHES around the world, detailing the specific mechanisms in the United States of America (USA), Australia, and China. The relevance of these funding schemes to the Indian context is also discussed.

4.1. United States of America (USA)

USA has one of the largest share of PHES, with an installed capacity of 22.6 GW (International Renewable Energy Agency, 2017). It is promoting the development of PHES further to increase its flexible energy storage capacity. For this purpose, the Loan Program Office (LPO) under the Department of Energy (DoE) provides loans to the developers for increasing the PHES capacity. A funding of USD 30 billion(US Department of Energy, 2021) has been released over the last 10 years for all RE projects under three major funding schemes of debt capital at low interest, with partnerships and flexible financing options such as viability gap funding (VGF) (Hadjerioua et al., 2020). Additionally, the Water Power Technologies Office (WPTO) under DoE is funding research projects associated with PHES, with the aim of enhancing the commercial viability of PHES in the power sector.

The Iowa Hill PHES project is one of the flagship PHES projects in USA. Funded through the VGF mechanism, the 400 MW PHES is built over the 688 MW Upper American River Hydroelectric Project (UARP) in Sierra Nevada, California. The initial estimated project cost was USD 1,210 million, but overruns in the direct cost and other overhead costs that were not accounted for during construction, led to an increase of USD 240 million in the overall cost by 2015. Due to this, a VGF support in the range of USD 162 to USD 243 million had to be provided in the middle of the construction process. This helped in making the project viable, while keeping the PHES tariff competitive.

4.2 Australia

In Australia, the expense distribution model is a prevalent funding mechanism adopted for PHES project development in the country. The model is based on collaborative ownership and funding. Here, the required investment, resources, and assets can be owned by multiple partners, including private and government stakeholders. Based on the value of the contribution, the benefits from PHES are shared. These kinds of PHES projects are bundled with RE power generation in the same region.

The K2-Hydro PHES project ("Construction to begin on Kidston Pumped Hydro," 2021) in Australia is a standard project for demonstrating the expense distribution model. It is a 250 MW PHES, where one reservoir has been developed as a dam on a closed Kidston gold-mining site. The project developer is Genex Power Company, while the operator is another stakeholder named EnergyAustralia. The developer has taken the whole dam on long-term rent from the state government to operate the plant. For the fixed-cost recovery, the stakeholders have guaranteed the government rent for the dam, thereby decreasing the land-purchase cost. The project receives its power for pumping from an adjacent commissioned 320 MW solar-power project. The electricity is purchased without any extra utility charges and with almost zero technical losses.

Similarly, to overcome the viability challenge of another pumped-hydropower project, Cultana PHES, the expense distribution model is being considered. Cultana PHES is a seawater-based project in Port Augusta, South Australia (Australian Renewable Energy Agency, 2020). The purpose of this project is to meet the regional power demand of the Australian Defense Force.

This 225 MW PHES is being developed by a consortium of EnergyAustralia, Arup Group, and Melbourne Energy Institute, to distribute the capital investment in development. The initial estimated total cost of engineering, procurement, and commissioning (EPC) (lump-sum turnkey), including contingency, was about USD 790 million. The pre-feasibility study (ARENA, 2020) of the project showed that the net installed generating capacity requires an investment of USD 3.5 million/MW, whereas the benchmark range for PHES projects globally is approximately USD 2 million/MW. This capital investment gap is keeping the project below the viability mark. Presently, asset distribution is considered as an opportunity in such conditions. Therefore, it has been requested that the land (120 hectares) owned by the Department of Defense (DoD) be provided for the project for curtailment of EPC cost to make the project viable.

4.3 China

In China, PHES developers usually consider the conventional funding of 70:30 debt-equity ratio for developing their projects. With 32 GW, China has the world's largest share of PHES capacity (International Renewable Energy Agency, 2017). Owing to this huge storage capacity, China is promoting competition between the existing PHES projects through generation-based incentives (GBI). This tariff mechanism provides an additional subsidy on a per-unit generation basis, with respect to the national average utilisation hours of the PHES plants in the country. If a PHES plant generates more energy, its per-unit price of subsidy also increases. This reduces the generation tariff, and increases competition, resulting in high PHES utilisation.

The Pushihe PHES power plant is one of the largest pumped-hydro storages in China, with a generation capacity of 1,200 MW. It generates an average annual revenue of 663.3 million yuans, and the total annual pumping cost is 589.7 million yuans. Thus, it earns 73.6 million yuans annually (approximately 20% capital recovery rate) from electricity sales. Generally, PHES projects in China do not participate in the competitive power markets due to their high tariffs.

Thus here, GBI plays a crucial role by providing additional subsidy (as shown in Table 8) (Zhang et al., 2018), when the plant generates additional electricity. This additional subsidy is provided on the basis of generation ranges with respect to national average utilisation hours as specified in Table 8. This mechanism motivates the PHES plants to gain higher subsidies by generating more electricity, while making the tariffs competitive.

Table 8: GBI-based additional subsidy provided to Chinese PHES plants

Range	**Subsidy Price**
0～100%	0.01￥/kWh
100～200%	0.02￥/kWh
Above 200%	0.03￥/kWh

Table 9 summarises the funding mechanism for the different countries discussed above.

Table 9: Summary of funding mechanism for different countries

Country	Funding Mechanisms
USA	Budgetary subsidy on fixed-cost part •Debt capital at low interest •Partnership •Viability gap funding (VGF)
Australia	Expense distribution business model with multiple collaborators
China	Standard investment with 70:30 debt-equity ratio (generation-based incentive on tariff to promote competition between different PHES)
India	Standard investment with 70:30 debt-equity ratio

4.4 Relevance to Indian context

Most of the installed PHES projects in India (4.78 GW) adopted the conventional funding method of 70:30 debt-equity ratio, where debt comprises a long-term loan taken from banks or other funding organisations on a fixed interest rate. Generally, this funding method works well for other conventional and RE plants. However, PHES has high capital costs as well as high operational costs. International funding from the International Cooperation Agency (JICA) (Japan International Cooperation Agency, 2018) and Overseas Economic Cooperation Fund (OECF) ("Ghatagar Dams Project, Maharashtra", n.d.) of Japan was secured for the 900 MW Purulia project (INR 1503.35 Cr.) in West Bengal and the 250 MW Ghatghar PHES plant in Maharashtra, respectively.

Keeping in view the international best practices, India can adopt the suitable PHES funding mechanisms. The country has considerable experience with viability-gap-funding mechanism for large-scale RE projects. This can be utilised for increasing PHES viability as well. Based on the geographical distribution of the potential PHES sites across the country, the expense distribution model (resources, assets, and investment distribution) can be explored through collaboration between local governments and developers. A public-private-partnership (PPP) model can also be integrated with a similar concept. In the Indian context, utilisation of unused assets and infrastructure will help in reducing the risks associated with energy pricing and energy volume, and provide stable cash flow.

Foreign direct investment (FDI) was encouraged to boost RE development in India. FDI limits were raised to 100% of the project cost and automatic funding routes were provided for RE. However, despite huge potential, no significant FDIs have materialised for PHES development so far. Recently, the Solar Energy Corporation of India (SECI) concluded the auctioning process for a 1.2 GW renewable-plus-storage-capacity tender, which was won by Greenko group (900 MW with PHES) and ReNew power (300 MW with battery storage)("Greenko, ReNew Power win SECI's 1.2 GW Hybrid Plus Storage Tender," 2020). The response of investors and other stakeholders was positive towards the tender, indicating a conducive atmosphere for future RE-integrated storage tenders in the country. This ensures better opportunities for FDIs in the Indian PHES sector.

5. Recommendations

With the high penetration of RE in India, we require utility-scale storages such as the PHES system to balance the grid. However, the growth of PHES has been tepid because of the high cost associated with its commissioning, the long gestation period (caused by delays in obtaining environmental clearances), and the poor recovery resulting from the existing pricing mechanism.

The issues of high cost and environmental clearance can be resolved by employing a closed-loop and smaller capacity PHES system that uses less water. Such system will mitigate delays, and avoid cost overruns, legal hurdles, and protests regarding environmental clearances.

To resolve the issue of low recovery from the existing pricing mechanism, it is important to explore a new pricing mechanism, as well as, consider alternative funding mechanisms.

Based on our analysis, we make the following recommendations:

- A differential pricing mechanism should be employed to calculate different pumping and generation prices (instead of one that considers only generation-based energy charges).
- The profit generated from the differential pricing mechanism should be used for fixed-cost recovery.
- The pricing mechanism for a PHES plant should be based on its specific use cases.

The recommendations for specific use cases of the PHES system emerge from the results of the tariff-computation carried out for these cases in this study. The results of the tariff computation method applied for energy-arbitrage, peak-load-shaving, and load-following use cases are given in Table 10, and those of RE-smoothing, and round-the-clock-support use cases are given in Table 11.

Table 10: Results of tariff-computation method for energy-arbitrage/ peak-load-shaving/ load-following use cases

<table>
<tr><th colspan="4">For Energy-arbitrage/ Peak-load-shaving/ Load-following use cases</th></tr>
<tr><td colspan="3">PHES operation</td><td>In market as merchant power plants. Profit reduction happens if PHES is used to provide grid flexibility in the market.</td></tr>
<tr><td rowspan="5">For the Uttarakhand Tehri PHES case study</td><td colspan="2">Peak: Off-peak price ratio</td><td>1.33-1.35 (for profit generation)</td></tr>
<tr><td rowspan="2">Net profit (INR crores) for the year</td><td>2019</td><td>157</td></tr>
<tr><td>2020</td><td>70</td></tr>
<tr><td rowspan="2">% Fixed-cost recovery for the year</td><td>2019</td><td>16%</td></tr>
<tr><td>2020</td><td>7%</td></tr>
</table>

Table 11: Results of tariff computation method for RE-smoothing/round-the-clock support use cases

For round-the-clock-support and RE-smoothing use cases of PHES		
PHES utilisation		**As a grid asset**
One, or a combination of the incentives mentioned alongside should be provided		• Compensation for avoiding RE curtailment • Avoided cost from high-priced purchase of thermal or gas plants • Grid flexibility incentive similar to ancillary unit plants • Generation-based incentive in the range of INR 0–1 per unit to attract more investment in the sector
For the Andhra Pradesh **Pinnapuram PHES** case study	Profit generation range (INR/kWh)	0.37-4.41
	% Fixed-cost recovery	10% to 122%
	100% Fixed-cost recovery happens when	Price differential between pumping and generation price is 3.62 (INR/kWh)

This study analysed the different use cases of PHES, including energy arbitrage, peak-load shaving, load following, round-the-clock support, and RE smoothing. The analysis could be extended to ancillary-services and seasonal-storage use cases as well.

In addition to the above pricing mechanisms, we also recommend the following financing mechanisms for total project cost funding:

- **Budgetary subsidy on viability gap funding (VGF):** India has considerable experience with the VGF mechanism for large-scale RE projects. This should be extended to PHES projects as well.
- **Expense distribution model** (resources, assets, and investment distribution) can be made feasible through collaboration between local government and developers. A public–private partnership (PPP) model can also be integrated with a similar concept. The utilisation of unused assets and infrastructure (such as open-pit coal mines and beneficiary-owned lands) will help reduce the risks associated with energy pricing and energy volume, and provide stable cash flow.
- **Foreign direct investments (FDIs)**: Though the Government of India has approved 100% FDIs for the development of the RE sector, there has been no significant flow of funds for PHES. Government initiatives, such as the development of large-scale energy storage alongside RE, can open up new opportunities for FDIs in the PHES sector.

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5. Annexure I: Technical aspects of PHES in India

In India, PHES sites are identified primarily on the basis of favourable site-specific characteristics like steep slopes and high plateaus. Besides the site-specific aspects, there are some other factors which inform the design of PHES. These are detailed below:

Configuration of PHES

PHES mainly have the following three configurations:

- **Four units:** In this configuration, a separate pump is combined with a motor and a turbine and connected to a generator. This configuration would require significant space and hence is not being used currently.
- **Three units:** In this configuration, a single reversible motor/generator is combined with a pump and turbine. It can improve the efficiency of both pump and turbine.
- **Two units:** The two-unit configuration comprises of a reversible pump/turbine which is connected to a reversible motor/generator. This configuration requires a smaller area as compared to other configurations. However, this configuration poses the problem of reduced efficiency, as compared to other configurations.

Reversible units can be categorised into fixed-speed and variable-speed units. In the fixed-speed reversible units, the units under pumping mode draw constant power and cannot be optimised for grid flexibility. On the other hand, the variable-speed reversible units can be optimised for uptake of power during operation, which provides greater flexibility, thereby supporting grid stability.

Type of turbines

Turbines are used for converting hydraulic energy into mechanical energy. The hydraulic turbines are classified into impulse and reaction turbines.

The different types of turbines used in PHES are given below:

- **Francis turbine:** Francis turbine is well suited for medium-head and medium-discharge applications. It is used at head ranges of 20 to 750 meters and a power rating that ranges from 0.25 to 800 MW per unit.
- **Pelton turbine:** Pelton turnbine is generally used for a high-head application. It is classified as an impulse turbine since the buckets have no pressure drop. The direction of flow is axial, where the water delivery is from the high head through a conduit (which is called a penstock).
- **Kaplan turbine:** Kaplan turbine is classified as a reaction turbine that is suitable for a lower head range. Since the guide vanes and runner blades in the Kaplan turbine are load adjustable, it offers higher efficiency.

Selection of turbines

Turbines are selected on the basis of the head range available on the site. Pumped storage projects have been constructed with a head range of about 100 feet to 2500 feet (50-1000 m), and a power range of 20 to 500 MW. The table shows the comparison of the head range and the type of turbines with specific speed:

Table 12: Turbine types and its characteristics

Turbine	Head	Specific speed
Pelton wheel	>300 m	8.5-30(Single jet) or 3051 (2 or more)
Francis Turbine	50-450 m	51-255
Kaplan Turbine	Up to 60 m	255860

Source: Nagpurwala Q. H. Hydraulic Turbines

The table below gives the technical details and cost of various operational, under-construction, and proposed PHES plants in India.

Table 13: Technical details of various PHES (under different stages of development) in India

Sl. No.	PHES	Installed capacity (MW)	No. of units	Rated unit capacity	Rotational speed (rpm)	Type of machine	Type of power house	Upper reservoir	Lower reservoir	Cost (INR Cr)
1	**Srisailam LBPH (Andhra Pradesh)**[2]	900	6	Turbine (MW): 6x150; Pump (MW): 6x153	136.4	Vertical Shaft, Francis Reversing	-	Srisailam Dam	Nagarjunsagar Dam	2620
2	**Ghatghar (Maharashtra)**[3]	250	2	Turbine (MW): 2x125	-	Vertical shaft, Francis type	Underground, Ferroconcrete	Ahemadnagar	Thane	41452 million yen
3	**Kadamparai (Tamil Nadu)**[4]	400	4	Turbine (MW): 4x100	500	Reversible Vertical Francis	Underground	Kadamapari Reservoir	Upper Aliyar Dam	225
4	**Purulia (West Bengal)**[5]	900	4	Turbine (MW): 4x225, Pump (MW): 4x230	250	Reversible pump turbines (vertical Francis, rated head 177m, maximum power discharge : 150 cum/sec) of 225 MW each	Underground	Upper dam	Lower dam	2638
5	**Nagarjunsagar (Telangana)**[5]	700	7	Turbine (MW): 7x100	157.8	Francis type Reversible	-	Nagarjunasagar Dam	Tail pond not yet constructed	-
6	**Tehri (Uttrakhand)**[6]	1000	4	Turbine (MW): 4x250	250 & 214.3	Variable speed vertical Francis type reversible Turbine	Underground	Tehri Dam Reservoir	Koteshwar Dam Reservoir	4835.6
7	**Turga (West Bengal)**[7]	1000	4	Turbine (MW): 4x250	-	Francis type, vertical shaft reversible pump	Underground Bullet shape	Valley of Turga nala	downstream end of the valley	6921.9

[2] https://www.jica.go.jp/english/our_work/evaluation/oda_loan/post/2006/pdf/project35_full.pdf
[3] https://www.keralaenergy.gov.in/files/pdf2018/presentations08_02_2018.pdf
[4] http://164.100.47.193/lsscommittee/Energy/16_Energy_43.pdf
[5] https://cea.nic.in/wp-content/uploads/2020/03/annexures_mom-psp.pdf
[6] https://www.thdc.co.in/content/tehri-pumped-storage-plant
[7] https://openjicareport.jica.go.jp/pdf/12343943.pdf

8	**Malshej ghat (Maharashtra)**[8]	700	2	Turbine (MW): 2x350	333	Reversible Francis Pump turbines	Underground	Junnar, Khubi, Pune	Murbad, Thitabi, Thane	2825.9
9	**Pinnapuram (Andhra Pradesh)**[9]	1000	6	Turbine (MW): 4x200 + 2x100; Pump (MW): 4x220+2x130	200 MW turbine: 166.7; 100 MW turbine: 214.28	Francis type (vertical shaft), Reversible turbine, 3 variable speed and 3 fixed speed pump-turbine sets	Underground 'D' Shape	Pinnapuram reservior (Proposed)	Gorakallu Reservoir (Exisiting)	4829.2
10	**Saundatti (Karnataka)**[10]	1200	7	Turbine (MW): 5x200 + 2x100; Pump (MW): 4x230+2x105	200 MW turbine: 166.7; 100 MW turbine: 250	Francis type (vertical shaft), Reversible turbine, 3 variable speed and 4 fixed speed pump-turbine sets	Surface Powerhouse	Saundatti Reservoir (Proposed)	Renuka Sagar Reservoir (Exisiting)	4985.9
11	**Sharavathy (Karnataka)**[11]	2000	8	Turbine (MW): 8x250; Pump (MW): 8x229.66	375	vertical shaft Francis type	Underground	Talakalale Lake	Gerosoppa Reservoir	5014.4
12	**Upper Kolab (OD) (320 MW)**[12]	320	2	Turbine (MW): 2x160; Pump (MW): N/A	428.6	Vertical axis Francis Reversible Turbine	Underground	Upper Kolab Reservoir	Satiguda Reservoir	1600
13	**Upper Sileru (AP, 1350 MW)**[13]	1350	9	Turbine (MW): 9x150; Pump (MW): 9x171	190	Vertical shaft Reversible	Underground	Balimela Dam	Yeleru reservoir	11054.1
14	**Kundah (TN, 500 MW)**[14]	500	4	Turbine (MW): 4 X 125, Pump (MW): 4 X 131.25	375	Vertical shaft, single runner, and reversible pump, Francis type, directly coupled	Underground	Porthimund Reservoir	Avalanche-Emerald reservoir	1831.2

[8] https://www.thdc.co.in/content/malshej-ghat-pss
[9] http://environmentclearance.nic.in/writereaddata/Online/TOR/16_Apr_2018_131828533910820IHRPinnapuramPFRFinalToR.pdf
[10] http://environmentclearance.nic.in/writereaddata/Online/TOR/16_Apr_2018_123630363PJWJ2GJTSaundattiIRESPPFRfinalToR.pdf
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[13] http://www.environmentclearance.nic.in/writereaddata/Online/TOR/01_Apr_2019_194332577H0QAC5XWAnnexure-PFR.pdf
[14] http://environmentclearance.nic.in/writereaddata/Online/TOR/21_Oct_2019_124949257IJ0QBZKYkundahdpr.pdf

15	**Upper Indravathi (OD, 600 MW)**	600	4	Turbine (MW): 4x150; Pump (MW): N/A	375	Vertical Shaft, reversible pump	Underground	Upper Indravati Reservoir	Lower Indravati Reservoir	1600.5
16	**Yerravaram (Andhra Pradesh)**[15]	1000	4	Turbine (MW): 4x250; Pump (MW): 4x275	214.29	Reversible Francis Turbine	Underground	Nallah near Yerravaram village	Nallah downstream of Yerravaram village	3869.7
17	**Balimela (Odisha)**[16]	500	2	Turbine (MW): 2x255.12; Pump (MW): 2x285.326	200	Francis type, vertical shaft reversible pump-turbine	Underground Cavern	Balimela Reservoir	TBD	Option-1: 1999.1, Option-2: 2045.3
18	**Humbarali (Maharashtra)**[17]	400	2	Turbine (MW): 2x200; Pump (MW): 2x200	428.6	Vertical shaft reversible Francis	Underground	Vazarde Nallah	Koyna reservoir	838.9 Cr
19	**Sillahalla (Tamil Nadu)**	1000	4	Turbine (MW): 4x250;	N/A	Francis reversible	N/A	Udhagamandalam (planned)	Kundah (planned)	4205.6

Existing **Under-construction** **Proposed**

[15] https://nredcap.in/PDFs/2020_Tenders/7_Yerravaram_Preliminary_Report.pdf
[16] http://environmentclearance.nic.in/writereaddata/Online/TOR/09_Oct_2019_121414120LEMK1QX7pfr.pdf
[17] https://www.thdc.co.in/content/humbarli-pss

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