**Pumped Storage Hydropower Projects: A Comprehensive Analysis**


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# Pumped Storage Hydropower Projects: A Comprehensive Analysis

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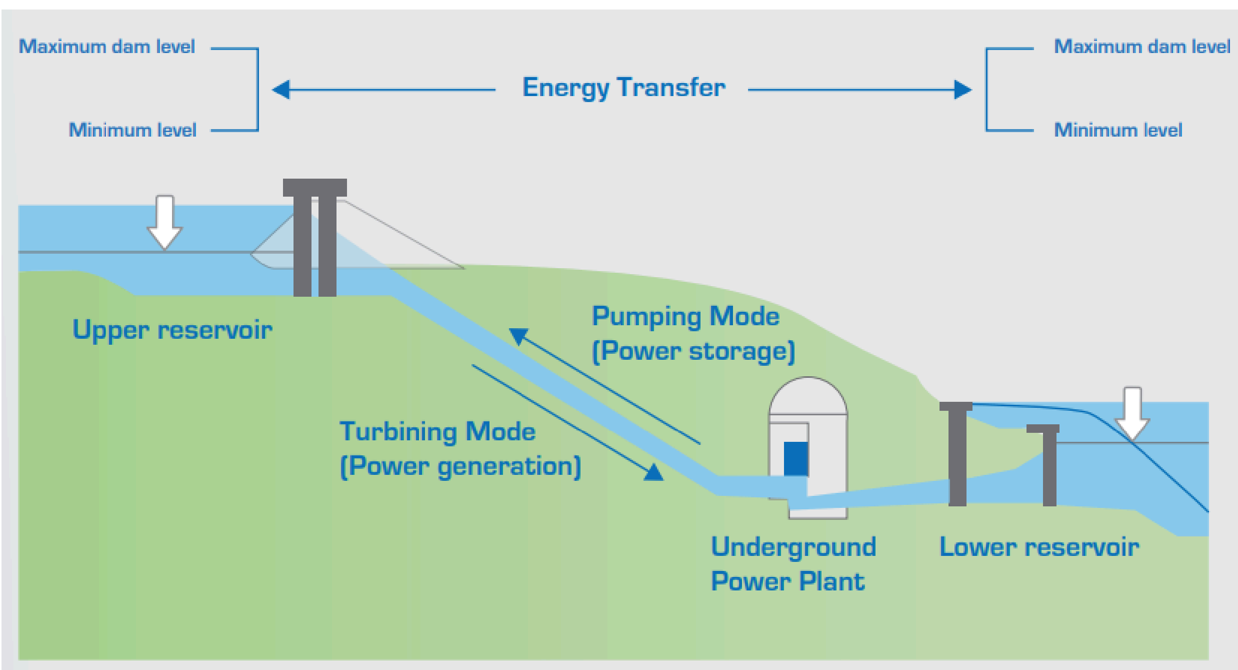
## Introduction to Pumped Hydro Storage

Pumped Storage Hydropower (PSH) represents one of the most established and efficient large-scale energy storage technologies available today, accounting for approximately 96% of utility-scale energy storage capacity in the United States and 99% of bulk energy storage capacity worldwide. This technology has reliably served electricity grids for over half a century, providing crucial stability and flexibility to power systems.

## How Pumped Hydro Storage Works

The system requires two fundamental components:

1. Two water reservoirs positioned at different elevations (typically with a significant height difference).
2. Reversible turbine-generator units that can function both as turbines for electricity generation and as pumps for water elevation



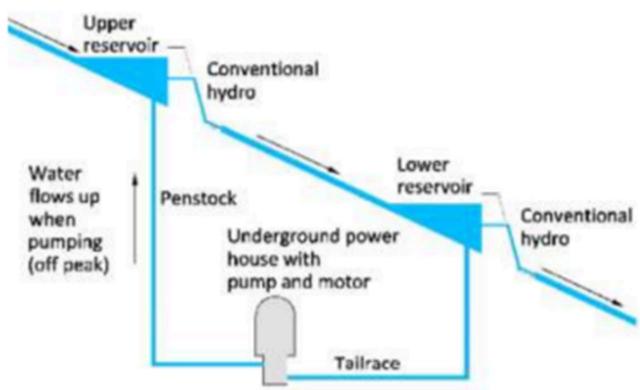
The operational cycle consists of two primary phases:

1. **Energy Storage Phase (PUMP mode)**
   During periods of low electricity demand or excess generation (often during off-peak hours):
   - Excess electricity from the grid powers the reversible turbines in pump mode
   - Water is pumped from the lower reservoir to the upper reservoir
   - The potential energy of the water is effectively stored at the higher elevation

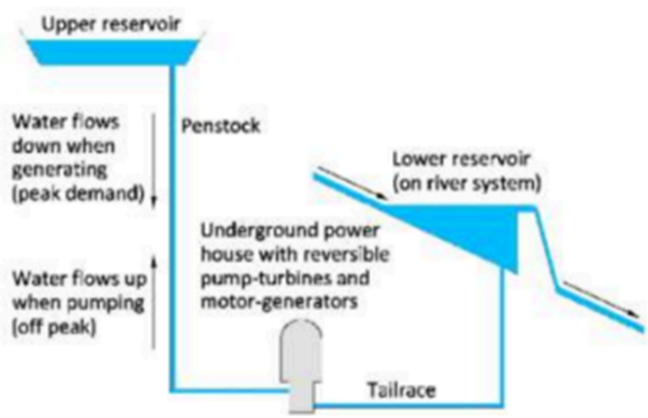
2. **Energy Generation Phase (GENERATE mode)**
   During periods of high electricity demand or insufficient generation:
   - Water from the upper reservoir is released through penstocks (large pipes or channels)
   - The flowing water drives the turbines, which rotate generators to produce electricity
   - The generated electricity is fed into the power grid
   - The water collects in the lower reservoir, ready for the next pumping cycle

# Types of Pumped Hydro Storage

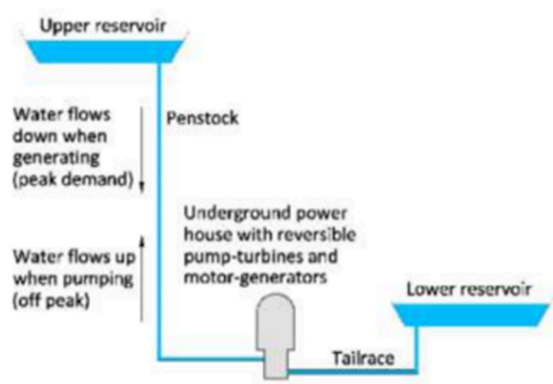
1. **On Stream loop PSH**
   - Both upper and lower reservoirs are directly located on a natural waterway (e.g., a river or stream).
   - Relies on the flow of the natural water body for operation.
   - Can impact river ecology, sediment transport, and aquatic life.
   - Limited flexibility in site selection due to dependence on river location.




2. **Off-stream Open Loop PSH**
   - One or both reservoirs have a hydrologic connection to a natural water body.
   - Water can be drawn from or returned to a river, stream, or canal.
   - Allows greater flexibility in site location than on-stream systems.
   - Still involves environmental considerations due to interaction with natural water bodies.




3. **Off Stream Closed-Loop PSH**
    - Completely isolated from natural water bodies.
    - Water is recycled continuously between two reservoirs.
    - Typically uses artificially constructed reservoirs.
    - Minimal environmental impact on local ecosystems.




## Key Benefits of Pumped Hydro Storage

1. **Grid Stability and Reliability**
    - Provides essential balancing services by absorbing excess electricity during low demand and supplying power during peak demand
    - Offers ancillary services such as inertia from spinning turbines, helping maintain proper grid frequency and reducing the risk of power outages
    - Serves as backup power during grid failures, as PSH systems can operate independently of the traditional power grid
2. **Renewable Energy Integration**
    - Complements intermittent renewable energy sources like wind and solar by storing excess generation during favorable weather conditions

    - Releases stored energy during periods of low renewable generation, creating a more consistent and reliable clean energy supply
    - Enables higher penetration of renewable energy sources in the overall energy mix
3. **Environmental Benefits**
    - It uses water as the storage medium rather than chemicals or metals, reducing environmental impact compared to battery technologies
    - Minimal water consumption as the same water is reused repeatedly (evaporation losses are typically offset by rainfall in most locations)
    - It can be powered by renewable energy sources for pumping operations, creating a circular green energy system
4. **Economic Advantages**
    - Low operational costs once constructed
    - Long service life provides decades of return on investment
    - Cost-effective long-duration storage compared to alternative technologies
    - Can generate revenue through energy arbitrage (buying/storing cheap electricity and selling during high-price periods)

## Reservoir Capacity Calculation

| Block | Demand | Generation | Mode of Operation | Surplus/ Deficit (MWh) | Unit Rate (Rs./MWh) | Amount(Rs.) | Water pumped/flown (in m3) | Water pumped/flown (in l) |
|---|---|---|---|---|---|---|---|---|
| 00:00-01:00 | 21000 | 20000 | Generate | 1000 | 5000 | 5000000 | 4591836.735 | 4591836735 |
| 01:00-02:00 | 20000 | 18000 | Generate | 2000 | 5000 | 10000000 | 9183673.469 | 9183673469 |
| 02:00-03:00 | 19000 | 17000 | Generate | 2000 | 5000 | 10000000 | 9183673.469 | 9183673469 |
| 03:00-04:00 | 19000 | 15000 | Generate | 4000 | 5000 | 20000000 | 18367346.94 | 18367346939 |
| 04:00-05:00 | 20000 | 18000 | Generate | 2000 | 5000 | 10000000 | 9183673.469 | 9183673469 |
| 05:00-06:00 | 21000 | 20000 | Generate | 1000 | 5000 | 5000000 | 4591836.735 | 4591836735 |
| 06:00-07:00 | 23000 | 24000 | Pump | -1000 | 2000 | -2000000 | -4591836.735 | -4591836735 |
| 07:00-08:00 | 23000 | 24000 | Pump | -1000 | 2000 | -2000000 | -4591836.735 | -4591836735 |
| 08:00-0 | 22000 | 23000 | Pump | -1000 | 2000 | -2000000 | -4591836.735 | -4591836735 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 9:00 | | | | | | | | |
| 09:00-10:00 | 21500 | 22000 | Pump | -500 | 2000 | -1000000 | -2295918.367 | -2295918367 |
| 10:00-11:00 | 21500 | 22000 | Pump | -500 | 2000 | -1000000 | -2295918.367 | -2295918367 |
| 11:00-12:00 | 21000 | 25000 | Pump | -4000 | 2000 | -8000000 | -18367346.94 | -18367346939 |
| 12:00-13:00 | 21000 | 20000 | Generate | 1000 | 5000 | 5000000 | 4591836.735 | 4591836735 |
| 13:00-14:00 | 20000 | 18000 | Generate | 2000 | 5000 | 10000000 | 9183673.469 | 9183673469 |
| 14:00-15:00 | 23000 | 22000 | Generate | 1000 | 5000 | 5000000 | 4591836.735 | 4591836735 |
| 15:00-16:00 | 22000 | 23000 | Pump | -1000 | 2000 | -2000000 | -4591836.735 | -4591836735 |
| 16:00-17:00 | 22000 | 23000 | Pump | -1000 | 2000 | -2000000 | -4591836.735 | -4591836735 |
| 17:00-18:00 | 22411 | 22000 | Generate | 411 | 5000 | 2055000 | 1887244.898 | 1887244898 |
| 18:00-19:00 | 23000 | 23500 | Pump | -500 | 2000 | -1000000 | -2295918.367 | -2295918367 |
| 19:00-20:00 | 24000 | 23500 | Generate | 500 | 5000 | 2500000 | 2295918.367 | 2295918367 |
| 20:00-21:00 | 24500 | 25000 | Pump | -500 | 2000 | -1000000 | -2295918.367 | -2295918367 |
| 21:00-22:00 | 24800 | 25000 | Pump | -200 | 2000 | -400000 | -918367.3469 | -918367346.9 |
| 22:00-23:00 | 24500 | 25000 | Pump | -500 | 2000 | -1000000 | -2295918.367 | -2295918367 |
| 23:00-00:00 | 24000 | 22000 | Generate | 2000 | 5000 | 10000000 | 9183673.469 | 9183673469 |

This is a 24-hour operational log for a pumped storage system. Each row shows the activity during a 1-hour time block. Based on whether the demand is higher or lower than generation, the plant either generates electricity (releasing water) or pumps water uphill (storing energy).

The total electricity required by consumers in that hour is measured in megawatt-hours (MWh). This is what the grid needs to supply. High-demand periods usually occur in the morning and evening peaks.

The electricity is produced from various sources, including the pumped storage plant and other grid generators. When generation is less than demand, the plant may need to generate more power. When there is more, the surplus may be stored.

### Modes of Operation

This shows whether the pumped storage system is operating in "Pump" or "Generate" mode.

- Pump = storing excess energy by pumping water uphill.
- Generate = releasing stored water to produce electricity

### Surplus/Deficit (MWh)

This is the difference between generation and demand:
Surplus/Deficit=Generation−Demand

- Positive value = deficit → need to generate power.
- Negative value = surplus → energy can be stored

### Amount (Rs.)

The total monetary value of electricity stored or generated in that hour. Calculated as:
Amount=Surplus or Deficit×Unit Rate

- Positive amount = income from selling generated power.
- Negative amount = cost of pumping (buying cheap energy to store)

### Water pumped/flown

The volume of water either pumped (in Pump mode) or released (in Generate mode) is measured in cubic meters and liters. It is calculated based on the energy required to move water over a height (head), factoring in system efficiency.
This was calculated using the formula given below:

$$E = \eta \cdot \rho \cdot g \cdot h \cdot V$$

which can be rearranged as,

$$V = \frac{E}{\eta \cdot \rho \cdot g \cdot h}$$

where E denotes energy in Joules, V denotes the volume of water in m3, η denotes the efficiency (approximately 0.8), ρ denotes the density of water (1000 kg/m3), g denotes the gravitational acceleration (9.8 m/s), h denotes the height difference between the reservoirs (approximately 100 m).

# Global Analysis of Pumped Storage

- As per 2023, PSH has a total capacity of 180 GW and there has been a rise of 6.2 GW since the previous year.
- PSH accounts for 90% of the world's energy storage capacity which makes it the dominant form of large scale energy storage.
- The leading countries in PSH capacity are China, Japan, USA and some European countries like Germany and Italy.

| Country | Installed PSH Capacity (approx.) | % of Total Capacity |
|---|---|---|
| China | 56,000 MW+ | ~5% |
| Japan | 27,000 MW | ~10% |
| United States | 22,000 MW | ~3% |
| Europe (Total) | 50,000+ MW | Varies |
| India | ~4,750 MW (Operational) | <2% |

## China:

- As of 2023, China has more than 26 PSP projects totaling about 54 GW.
- There has been support of policies for pricing structures of electricity which improved the two-part tariff mechanism for PSP.
- Introduction to financial incentives like Government subsidies, tax breaks and low-interest loans which encourages the investment in PSP projects.
  China's multi-layered support—policy, pricing reform, regional planning, and business innovation—has made it a global leader in pumped storage hydropower.

## Japan:

- The government of Japan has set a target to develop 10GW of additional PSP capacity.
- The Ministry of Economy, Trade and Industry (METI)of Japan supports the development of advanced PSP technologies. It does partnerships with private firms and international investors and identifies new PSP sites according to the grid needs.

- Japan has planned to launch the Ancillary services markets (day-ahead and week-ahead) for frequency regulation, voltage control, and reserves.
- PSP plants will earn revenue by offering grid services beyond just selling electricity.

## **<u>USA:</u>**

- The U.S. The Department of Energy(DOE) aimed to modernize aging hydro plants and boost PSH potential. This is expected to attract $468 million in public private investment.
- As of end-2022, 96 PSP projects were in the U.S. pipeline, totaling 91 GW, but none under construction. This was a unique situation globally.
- Acts like New clean Energy credits was designed for zero/negative - emissions technologies and it included bonus incentives for projects using domestic materials or located in energy-transition region
- Federal Power Act (FERC License Required):PSP projects using federal land or waters must obtain a license from FERC (Federal Energy Regulatory Commission).Over 16,500 MW of PSP already approved—mostly licensed over 30 years ago.

# Analysis of Pumped Storage in India

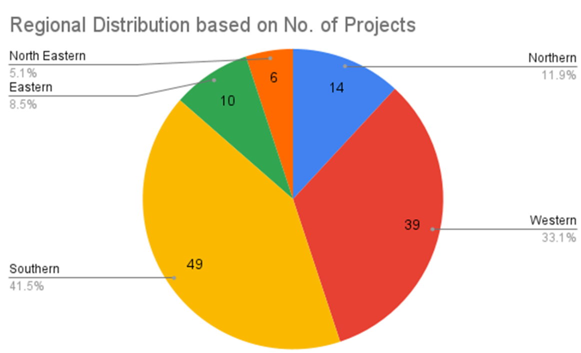
- India has a PSH potential of over 1,00,000 MW as per the Central Electricity Authority (CEA), but as of 2024, only 4,800 MW is operational. This gap presents an immense opportunity for investment, especially considering rising energy storage demand due to renewable energy expansion and increasing private sector interest in closed-loop PSH projects (where reservoirs are isolated from rivers).

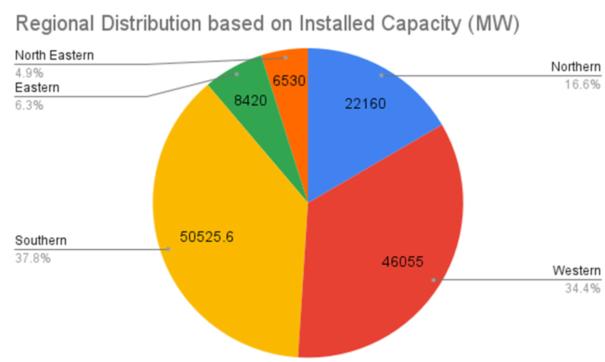
- India aims to achieve 500GW of non-fossil fuel energy capacity by 2030 which is heavily dependent on solar and wind power. PSH addresses this by absorbing surplus renewable energy during periods of low demand and releasing it during high demand.

- The "buy low, sell high" model of pumped storage ensures a positive cash flow and improved return on investment (ROI) for utilities.

- PSH plays a strategic role in reducing peak demand charges and offsetting the use of costlier peaking thermal power plants.

## Regional Analysis of Pumped Storage in India




- The Southern region takes lead in both no. of projects and the installed capacity, followed by the Western region.
- The top three states leading the PSHs in India are Maharashtra (36,755 MW), Andhra Pradesh (26,420 MW) and Tamil Nadu (14,400 MW).

## Major PSH Projects in India

| Name of project | State | No of unit x Unit size (MW) | Installed Capacity | Condition |
|---|---|---|---|---|
| Nagarjuna Sagar | Telangana | 7 x 100.6 | 700.6 | Operational |

| | | | | |
|---|---|---|---|---|
| Kadamparai | Tamil Nadu | 4 x 100 | 400 | Operational |
| Bhira | Maharashtra | 1 x150 | 150 | Operational |
| Kadana | Gujarat | 4 x 60 | 240 | Not operational in pumping |
| Srisailam | Telangana | 6 x 150 | 900 | Operational |
| Sardar Sarovar | Gujarat | 6 x 200 | 1200 | Not operational in pumping |
| Ghatghar | Maharashtra | 2 x 125 | 250 | Operational |
| Purulia | West Bengal | 4 x 225 | 900 | Operational |

| Status | No. of Projects | Installed Capacity |
|---|---|---|
| In operation | 8 | 4745.6 |
| Under construction | 4 | 2780 |
| DPR concurred by CEA | 1 | 1000 |
| Under examination | 1 | 1350 |
| Under S&I | 33 | 42150 |
| Under S&I held up | 5 | 5320 |

The Central Electricity Authority (CEA) has identified a potential of approximately 103 GW for on-river pumped storage projects in India. Efforts are underway to expedite the development of these projects to meet the country's growing energy storage needs and renewable integration goals.

## Existing Policy Framework for PSH in India

1. Legal Status of PSP
    - PSPs are now officially part of the power system.
    - Can operate standalone or along with generation, transmission, and distribution.
    - Granted connectivity under Electricity (Transmission) System Planning, Development & ISTS Charges framework.
2. Energy Storage Obligation (ESO)
    - Ensures long-term availability of storage capacity.
    - Distribution licensees must procure a minimum % of power from RE through storage systems.
    - Starts at 1% (2023–24) → 4% (2029–30)
3. Waiver of ISTS Charges

- Full waiver on inter-state transmission charges for PSP projects commissioned up to 30.06.2025.
- For projects beyond this date, gradual levy of transmission charges will apply.

4. Replacement of Diesel Generators (DG)
    - Under Electricity (Rights of Consumers) Amendment Rules, 2022, DG set users (especially commercial/industrial) are encouraged to shift to cleaner technologies like RE + battery storage.
5. Guidelines for Battery Energy Storage Systems (BESS)
    - Covers procurement & integration of BESS with generation, transmission, distribution, and ancillary services.
    - Promotes standardized procurement, risk-sharing among stakeholders, competitive and bankable projects
6. Guidelines for Development of PSP Projects
    - Released on 10.04.2023 to fast-track PSP rollout.
    - Focuses on cost-effective and time-efficient development, strengthening energy security through flexible storage capacity

7. Regulatory Framework & Tariff Mechanisms

    Two-Part Tariff Structure:
    - Fixed Cost: Includes return on equity (ROE) at 16.5% for reservoir-based PSH (vs. 15.5% for run-of-river projects) to incentivize long-term investments.
    - Variable Cost: Covers energy charges at ₹0.20/kWh for excess generation and 75% reimbursement of pumping costs.

    Competitive Bidding (TBCB Guidelines, 2025):
    - Mandates tariff-based bidding for off-stream PSH projects to ensure transparency.
    - Two modes:
    - Mode 1: Procurer identifies sites; developers build on a BOOT basis (25–40 years).
    - Mode 2: Developers self-identify sites, reducing delays.

    Levelized Tariff:
    - Estimated at ₹4.98/kWh (capital cost: ₹6.5 crore/MW) with a landed tariff (including pumping) at ₹8.92/kWh.
8. Financial Incentives & Subsidies
    - Budgetary Support:
      ₹10–15 million/MW for enabling infrastructure (roads, bridges) for CEA-approved projects.
      Central Financial Assistance (CFA): Up to 24% equity support for NE states in joint ventures with CPSUs.
    - Tax Concessions:
      GST Reimbursement: Full reimbursement of state GST during construction.
      Stamp Duty Waivers: States like Tamil Nadu offer 50% concession for land acquisition.
    - Debt Relief:
      Extended debt repayment period to 18 years and project lifespan to 40 years to improve viability.
9. Grid Integration & Market Reforms
    - Energy Storage Obligations (ESOs):
      Mandates DISCOMs to procure 4% of energy from storage by 2023–24, rising to 10% by 2029–30.
    - Ancillary Services Monetization:

PSH developers can earn revenue through frequency regulation and voltage support, valued at ₹4–6/kWh.
- ISTS Charge Waivers:
  Exemption from inter-state transmission charges for renewable energy stored via PSH.

10. Challenges & Policy Gaps
    - Interstate Water Disputes:
      Sardar Sarovar stalled the pumping mode due to unresolved water-sharing agreements between Gujarat, Maharashtra, and MP.
    - High Capital Costs:
      Retrofit costs for Kadana PSH (₹450 crores) highlight the need for better risk-sharing models.
    - Regulatory Ambiguity:
      Lack of clarity on peak/off-peak pricing differentials affects revenue predictability.

# Comprehensive Analysis of Pump Storage Hydropower Projects in Gujarat

## Summary

India is rapidly advancing its pumped storage hydropower (PSH) sector to support its ambitious target of 500 GW of non-fossil fuel capacity by 2030. With the intermittent nature of renewable energy sources like solar and wind, PSH has emerged as a critical solution for grid stability and energy storage

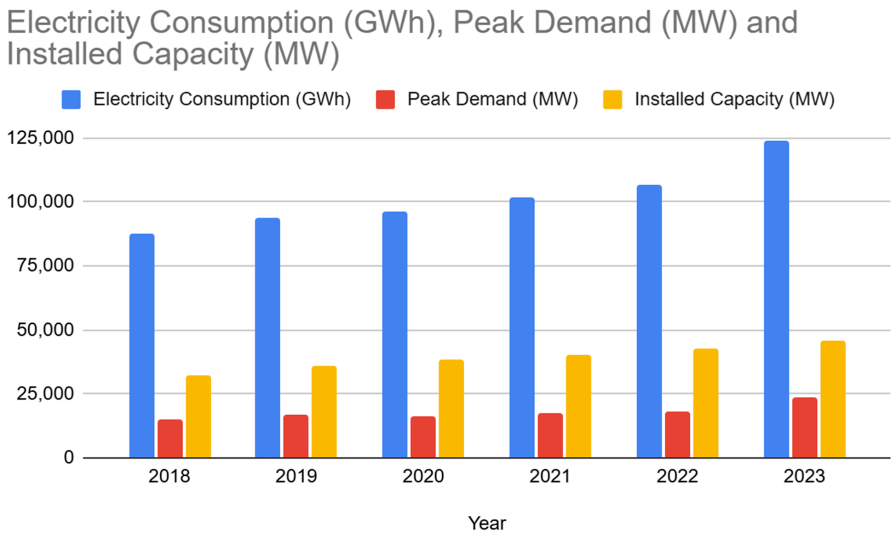
As of 2025, India has committed to developing 60 GW of pumped storage capacity by 2032, requiring an estimated investment of ₹4,200 billion. The Central Electricity Authority (CEA) initially projected a need for 26.7 GW of PSH capacity by 2032. However, current development plans have far exceeded this estimate, with 38 projects totaling 50,670 MW already lined up for commissioning by 2032.

The Ministry of Environment, Forend Climate Change is currently processing Terms of Reference proposals for 87 projects with a combined capacity of 104,690 MW, demonstrating a significant interest in PSH development. India's estimated total PSP potential stands at an impressive 181,350.6 MW across both on-river and off-river sites.

## Gujarat Electricity Profile (2018-2025)

- 16 Sites Reserved by GUVNL for PSH with total potential of 14,210 MW
- Major sites: Moti Palsan (2,400 MW), Anjan Kund (2,210 MW), Kaprada (1,300 MW), etc.
- 750 MW Kuppa Project in Chhota Udaipur with ₹4,000 crore investment; work to begin in FY26
- 100+ Potential PSH Locations identified with estimated capacity over 32 GW across Gujarat

| Year | Electricity Consumption (GWh) | Peak Demand (MW) | Installed Capacity (MW) | Capacity Utilization (%) | T and D losses (%) | Per capita Consumption (kWh) |
|---|---|---|---|---|---|---|
| 2018 | 87,680 | 15,340 | 32,429 | 58.2 | 17.2 | 1,480 |
| 2019 | 93,542 | 16,752 | 35,890 | 57.6 | 16.8 | 1,565 |
| 2020 | 96,235 | 16,098 | 38,446 | 52.4 | 16.5 | 1,590 |
| 2021 | 101,873 | 17,289 | 40,318 | 54.7 | 15.9 | 1,676 |
| 2022 | 106,469 | 17,865 | 42,719 | 56.2 | 15.7 | 1,735 |
| 2023 | 124,101 | 23,916 | 45,912 | 61.5 | 15.2 | 2,010 |
| 2024 | 132,540* | 24,540 | 51,869 | 58.3* | 14.8* | 2,125* |




## Gujarat's Strategic PSH Initiative

Gujarat has positioned itself at the forefront of India's PSH development with ambitious plans aligned with its renewable energy target of 100 GW by 2030. The state has:

- Reserved 16 sites for pumped hydro storage projects with a combined capacity of 14,210 MW
- Set a target of achieving 10 GW of PSH capacity by 2032

## Key Projects in Gujarat

Gujarat currently has two key pumped storage hydropower projects: Kadana and Sardar Sarovar. As of December 2024, India's total installed PSHP capacity was 4745.6 MW, with Gujarat contributing a notable share to this figure.

| Project | Installed Capacity (MW) | Daily Pumping Hours | Daily Generation Hours | Efficiency | Daily Storage Capacity (MWh) | Daily Generation Potential (MWh) |
|---|---|---|---|---|---|---|
| Sardar sarovar | 1200 | 8 | 6 | 75% | 9600 | 7200 |
| Kadana | 240 | 8 | 6 | 75% | 1920 | 1440 |

# Kadana Pumped Storage Project

- The Kadana Pumped Storage Project is located in Mahisagar district of Gujarat and utilizes the waters of the Mahi River. With an installed capacity of 240 MW, it was one of the early pumped storage projects in India.
- The Kadana Pumped Storage Project was commissioned in 1990, with two units commissioned in 1990 and two more added in 1998. The project is executed by Gujarat State Electricity Corporation Ltd (GSECL).
- The machines operated in generation mode until 2004, and trial pumping mode operation was conducted during 2004-05. However, operation in pumping mode was not continued subsequently due to vibration problems in the machines. According to the Central Electricity Authority, rectification of these issues would require approximately Rs. 108 Crores per unit, with a total expenditure of about Rs. 450 Crores needed to make all four units operational in pumping mode.

- Current efforts to revive the project include:
    1. A trial of Unit No. 3 under pump mode, with plans to replicate successful corrections in other units
    2. Exploration of revival options through the Original Equipment Manufacturer (OEM)
    3. A study by IIT Roorkee to explore the feasibility and timeline for the revival of pump mode operation

**Technical Specifications:**

- Installed Capacity: 4 units of 60 MW each, totaling 240 MW
- Upper Reservoir: Kadana Dam with a height of 35.98 m
- Lower Reservoir: Dolatpura Weir with a height of 10.2 m
- Gross Head: 48.20 m
- Upper Reservoir FRL: 127.70 m, MDDL: 114 m
- Lower Reservoir FRL: 85.4 m, MDDL: 79.54 m
- Live Storage (Upper): 42500 Mcft (approximately 1203 Mcum)
- Turbine Type: Deriaz Kaplan
- Annual Energy Generation: 337.03 MU
- Design Energy: 131.33 MU

## Sardar Sarovar Pumped Storage Project

- The Sardar Sarovar Pumped Storage Project represents one of India's largest PSH installations, with a total capacity of 1200 MW. Located near Navagam in Nandod district of Gujarat, this project utilizes the waters of the Narmada River.

- The Sardar Sarovar Project was commissioned between 2004 and 2006. It is a multipurpose river valley project designed not only for power generation but also for irrigation, flood control, and drinking water supply. The dam provides irrigation benefits to vast agricultural areas in Gujarat, Madhya Pradesh, and Rajasthan and supplies drinking water to urban centers in Gujarat.

- The River Bed Power House (RBPH) of the project has 6 units of reversible motor/generator and pump/turbine, each with 200 MW installed capacity. However, despite the installation of reversible turbines, the project has not been operating in pumping mode for several reasons:
    1. The lower reservoir at Garudeshwar weir was not operational for many years (though now completed)
    2. Some equipment required for pumping mode operation was not installed.
    3. Interstate disputes over the operation of the project in pumping mode

- The generation benefits of the Sardar Sarovar Project are shared between three states: Gujarat (16%), Maharashtra (27%), and Madhya Pradesh (57%), as per the Narmada Water Disputes Tribunal (NWDT) Award. However, the NWDT award did not specifically mention the operation of the project in pumping mode, leading to disagreements among the states.

- The Government of Madhya Pradesh has raised concerns regarding water sharing if the project is operated in pumping mode, as this was not envisaged in the NWDT award. While Gujarat and

Maharashtra have agreed to incur additional expenditure to operationalize the project in pumping mode, Madhya Pradesh remains reluctant.

- Recent developments include the formation of a committee under the Chairmanship of the Chairperson, CEA, with representatives from various stakeholders to suggest possible measures to operationalize the Sardar Sarovar Pumped Storage Project. Two meetings of this committee were held in January and March 2023, and an action plan is being prepared.

**Technical Specifications:**
- Installed Capacity: 6 units of 200 MW each, totaling 1200 MW
- Upper Reservoir: Sardar Sarovar Dam with a height of 120.68 m
- Lower Reservoir: Garudeshwar Weir with a height of 19.75 m
- Gross Head: 116.60 m (maximum)
- Upper Reservoir FRL: 138.68 m, MDDL: 110.64 m
- Lower Reservoir FRL: 31.57 m, MDDL: 26.71 m
- Live Storage (Upper): 5760 Mcum
- Water Conductor System: 6 penstocks of 7.61 m diameter
- Turbine Type: Francis vertical reversible

## Potential Pumped Storage Hydropower Sites in Gujarat (GUVNL):

| Sr. No. | Site Location (Village, District) | Project Potential (MW) |
|---|---|---|
| 1 | Moti Palsan, Valsad | 2400 |
| 2 | Anjan Kund, Dang | 2210 |

| | | |
|---|---|---|
| 3 | Kaprada, Valsad | 1300 |
| 4 | Wilshon Ghat, Valsad | 1000 |
| 5 | Ganiyabar, Chhota Udepur | 830 |
| 6 | Dharsimel, Chhota Udepur | 730 |
| 7 | Umedpura, Banaskantha | 660 |
| 8 | Turkheda, Chhotaudepur | 480 |
| 9 | Dobachapura, Chhota udepur | 500 |
| 10 | Sagbara, Narmada | 240 |
| 11 | Junaraj, Narmada | 340 |
| 12 | Khajuri, Dahod | 280 |
| 13 | Panam, Dahod | 290 |
| 14 | Abhapur Khervada, Sabarkantha | 200 |
| 15 | Limkhetar, Narmada (NWDT) | 1500 |
| 16 | Vanazi, Narmada (NWDT) | 1250 |

## Challenges and Issues of PSHs in Gujarat

### Technical Challenges

1. Equipment Issues: The Kadana PSP faces vibration problems in its machines, requiring significant investment (approximately ₹450 crores) for rectification3. The complexity of retrofitting existing installations presents a technical challenge.
2. Infrastructure Gaps: The Sardar Sarovar project required additional infrastructure, including the completion of the lower reservoir at Garudeshwar weir and the installation of equipment necessary for pumping mode operation.
3. Operational Expertise: Operating PSH plants in pumping mode requires specialized expertise and operational protocols that may need to be developed or enhanced.

### Interstate and Policy Challenges

1. Water Sharing Disputes: The Sardar Sarovar project faces challenges related to interstate agreements on water sharing. The NWDT award did not specifically address pumping mode operation, leading to disagreements among the beneficiary states.

2. Cost Sharing: There are disputes regarding the sharing of costs for additional infrastructure and equipment required for pumping mode operation. While Gujarat and Maharashtra have agreed to bear these costs, Madhya Pradesh has expressed reluctance.
3. Regulatory Framework: The lack of a comprehensive regulatory framework specifically addressing PSH operation and remuneration models has hindered the development and operation of these projects.

**Economic Challenges**

1. Investment Requirements: Substantial investment is required to make these projects operational in pumping mode. For Kadana, approximately ₹450 crores are needed for the rectification of all four units.
2. Economic Viability: The economic viability of PSH projects depends on the price differential between peak and off-peak electricity, which may not always be sufficient to justify the investment.
3. Long Gestation Period: PSH projects typically have long gestation periods (5-15 years) compared to other storage technologies, making them less attractive for immediate investment.

## Economic Aspects of Pumped Storage Hydropower Plants

**Positive Aspects*:***

- Stores energy during low-demand, reducing reliance on expensive plants.
- Stores surplus solar and wind energy, reducing wastage and stabilizing the grid.
- Responds in seconds to grid fluctuations, avoiding expensive grid imbalances.
- Typically lasts over 50 years with minimal operating costs.
- Creates jobs, supports infrastructure, and boosts local businesses.

**Negative Aspects:**

- High Initial Costs
- Long payback period, delayed returns due to high capital expenditure.
- Continuous costs for upkeep and upgrades..
- Compensation for displacement and restoration.
- Geographical Limitation

## Environmental Aspects of Pump Storage Hydropower Plants

**Positive Aspects*:***

- PSH stores the energy without burning fossil fuels and emits **zero greenhouse gases** during operation. It also supports the transition to low-carbon energy systems.
- PSH can store the surplus power of solar and wind energies thus it reduces the wastage of solar and wind power
- Unlike batteries, PSH  doesn’t rely on rare earth minerals and doesn't produce toxic wastes. It also has a life span of more than 50 years thus it is a much better alternative for batteries.

- PSH once constructed has a low water usage and low environmental noise and thermal pollution. Thus it offers minimal day-to-day ecosystem disturbance.

**Negative Aspects:**

- Construction of upper and lower reservoirs can lead to submerging of forests, agricultural lands or habitats. This can lead to loss of biodiversity and displacement of flora/fauna.
- It can also lead to displacement of communities that may have to be relocated or evacuated and this cultural displacement can lead to loss of livelihood.
- In regions with limited water availability, usage of large volumes for storage might compete with agriculture and drinking water and can cause seasonal water shortages.

## Areas where India is lagging

- India has over 96 GW of PSH potential (CEA), but less than 5 GW is operational. In contrast, China and Japan have tapped a larger percentage of their geographical potential.
- Environmental clearance, land acquisition delays, and lack of single-window approvals slow down project execution.
- The absence of time-of-day pricing and underdeveloped ancillary service markets limit the financial viability of PSH.
- Most Indian plants use fixed-speed turbines, while countries like Japan and Germany employ variable-speed technology for greater efficiency.

## Where is India catching up?

- India now classifies large hydropower as renewable, opening up financing and incentive pathways for PSH.
- Large conglomerates like Tata Power, Greenko, and JSW Energy are actively investing in closed-loop pumped storage, which has a lower environmental impact.
- India has significant mountainous terrain and reservoir systems that are ideal for PSH, especially in Southern and Central India.
- Labor and construction costs are lower in India compared to developed nations, potentially making PSH more economical in the long term.

## Recommendations for PSH Development

- There must be a centralized and transparent framework for allotting PSH sites across the region. As currently there is not a cohesive coordination among the stakeholders, there must be coordination to ensure planning and overlapping investments.

- PSP should be officially recognized as: Independent energy storage systems or grid/network assets. Such classification affects tariff design, grid access, incentives, and cost recovery.

- Given the high upfront costs and long gestation periods of PSPs, access to finance is crucial. Measures like: Viability Gap Funding (VGF),Higher Return on Equity (ROE) of up to 18%,Green bonds and blended finance, Public-Private Partnerships (PPPs)can make PSP projects more attractive to investors and lenders. Early financial closure also prevents delays due to cost escalation.

## Some Guidelines to promote pumped storage by the government:

- Project allotment and development models:
  PSPs can be allotted through Nomination basis to Central/State PSUs, competitive bidding for private sector participation,self-identified sites by developers. Developers must commence construction within 2 years of allotment.
- Regulatory and Statutory Clearances:Projects without forest/wildlife impact can be cleared ,enabling faster environmental clearance.States are advised to prepare a standardized bid document and model concession agreement to ensure transparency and consistency.
- Incentives and Fiscal Benefits:
  PSPs exempted from:Electricity Duty (ED), Cross Subsidy Surcharge (CSS),Water CessFree, Power Obligations
  These measures reduce the cost burden and improve financial viability.
- Private Sector Participation
  Private developers encouraged via:Long-term Power Purchase Agreements (PPAs) participation in RE hybrid tenders with storage, competitive tariffs through open access markets
- Use of Existing Infrastructure
  Preference for PSPs that:
  Reuse existing reservoirs or dams and avoid new land acquisition or water diversionE and encouragement for off-river or closed-loop projects to minimize environmental and social impacts.
- Energy Storage and Grid Integration Policies
  PSPs recognized as non-consumptive use of water with no requirement for water royalty or usage fees. Recognized under the Energy Storage Obligation framework alongside battery storage.

## Salient Features of Pumped Storage Hydropower (PSH) in India:

- PSH is a mature, globally accepted technology that uses surplus electricity to pump water and store energy.It is clean and safe, producing no harmful byproducts or disposal challenges.
- PSH provides large-scale, long-duration storage needed to handle intermittent solar and wind power.
- PSH systems have a lifespan of 40–50+ years, much longer than battery storage (typically 10–15 years). The levelized cost of storage is lower due to longer asset life and scale.
- Projects can be built on existing reservoirs or as off-river closed-loop systems, minimizing ecological and displacement issues
- India has over 103 GW of on-river PSH potential identified by the Central Electricity Authority (CEA).Off-river potential is also being assessed and promoted.

## Conclusion:

Pumped Storage Hydropower (PSH) is a key enabler of India's renewable energy goals, offering grid stability and energy storage at scale. Despite challenges such as environmental concerns, land acquisition, and high costs, supportive policies and incentives are driving progress. Economically, PSH provides long-term value through grid balancing and peak shaving while also offering a cleaner alternative to fossil fuels.

Although India currently trails global PSH leaders in installed capacity, it is quickly advancing with several large-scale projects underway. Gujarat's proactive efforts highlight how regional action can contribute to national energy security and a sustainable future.

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