Working paper

Pumped Storage Plants in India: Assessing Policies and Progress

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Abstract

The paper presents the evolution of policy on pumped storage plants (PSPs) and their performance in India. It builds a dataset of PSP projects from the information published by the Central Electricity Authority (CEA) and the CapEx dataset maintained by the Centre for Monitoring Indian Economy (CMIE). Participation of the private sector in the development of PSPs has increased considerably since 2018. Out of the 130 GW capacity that is under stages of planning, 102 GW is being developed by the private sector. However, the ratio of projects which receive concurrence and are eventually completed remains low. Of the 91 projects in the dataset, 17 are under implementation and six have been completed. The completed projects account for 3.3 GW of storage capacity. The low ratio of PSPs that are completed, combined with the experience of delay in executing hydropower projects, implies that the requirements of storage capacity addition from PSPs by 2026-27 and 2031-32 will be met only if the capacity under planning is realised and the projects are completed within six years.

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1 Introduction

Governments across the world have committed to tripling renewable power capacity, doubling energy efficiency improvements, substantially reducing methane emissions, and accelerating the just, orderly and equitable transition away from fossil fuels by 2030 as a consequence of the Paris Agreement.[1] The shift to renewable sources faces the problem of intermittency and variability of available energy. Energy storage systems (ESS), which store excess renewable energy (RE) during low demand and release during peak hours, are crucial for scaling renewable energy systems globally. ESS can thus reduce reliance on fossil fuels and support the integration of renewable energy sources. Globally, installed storage capacity is predicted to expand by 56% to reach more than 270 GW by 2026.[2]

Various technologies can be used to convert electricity to other forms of energy, which can eventually be stored.[3] An older but significant and one of the most widely relied upon technologies is that of pumped storage plants (PSPs). These are adaptations of conventional hydropower plants, where there are two reservoirs at different heights, and water is cycled between the two reservoirs for the generation of power or energy storage, depending on the need. PSPs lend stability to the power grid, including when the variable nature of renewable energy poses risks of grid collapse. The largest aggregate capacities for pumped storage are in China, Japan and the United States. The International Energy Agency forecasts that PSPs should make up almost 30% (65 GW) of global hydropower capacity expansion during 2021-2030 – the highest decadal growth in the history of pumped storage development.[4] The forecast expects an additional 3300 GWh of storage capability to come from projects using existing infrastructure, with India accounting for almost 80% of such growth.[5]

India has set a target to achieve 50% cumulative installed capacity from non-fossil fuel-based

[1] International Energy Agency, COP28 Tripling Renewable Capacity Pledge (2024) ⟨https://tinyurl.com/2xxata49⟩.

[2] International Energy Agency, How rapidly will the global electricity storage market grow by 2026? (1 December 2021) ⟨https://www.iea.org/articles/how-rapidly-will-the-global-electricity-storage-market-grow-by-2026#⟩.

[3] These technologies are regarded as electrical energy storage (ESS) technologies and are grouped as follows: mechanical energy storage, chemical energy storage, electrochemical supercapacitor energy storage, battery energy storage), superconducting magnetic energy storage and thermal energy storage. (Mathew Aneke and Meihong Wang, Energy storage technologies and real life applications – A state of the art review. (2016) ⟨https://eprints.whiterose.ac.uk/154479/1/2016_05_05_MA_Modified_Manuscript_NotMarked.pdf⟩)

[4] International Energy Agency, Hydropower Special Market Report Analysis and forecast to 2030 (2021) ⟨https://iea.blob.core.windows.net/assets/83ff8935-62dd-4150-80a8-c5001b740e21/HydropowerSpecialMarketReport.pdf⟩.

[5] ibid.

energy resources and to reduce the emissions intensity of its GDP by 45% by 2030.[6] India has also seen policy changes in ESS over the last few years. Legal recognition to ESS was granted in 2022, and new policy guidelines for PSPs were notified in 2023. The Central Electricity Authority (CEA) has estimated the storage capacity requirements, which will enable greater integration of renewable sources of energy. These include 26.69 GW of pumped storage capacity and 47 GW of battery energy storage system (BESS) capacity by 2031-32.[7] The National Framework for Promoting Energy Storage Systems introduced in 2023 indicated that the Government of India (GoI) wants to promote a range of ESS technologies and may introduce technology-agnostic bidding guidelines for the procurement of ESS.[8] However, so far, the government has promoted BESS and PSPs as storage resources. There is also an increased interest in green hydrogen, which is yet to attain commercial deployment.[9]

Given the importance of storage and PSPs in India's storage policy strategy, this paper looks at the development of PSPs in the country. The paper addresses the following questions:

1. Where do PSPs feature in the overall storage policy?
2. How many PSPs are under various stages of development? How many are eventually being completed?
3. Are the policy measures encouraging the private sector to participate in the development of PSPs?
4. Is the stated requirement of adding 26.69 GW of PSPs storage capacity by 2032 likely to be completed in the current context?
5. What lessons from our experience of executing hydropower projects are relevant for the development of PSPs?

Our analysis shows that the policy environment has become conducive to the development of energy storage systems in general and PSPs in particular. In recent times, the private sector has shown significant interest in developing PSPs. Given that distribution companies often arbitrarily issue backing down instructions to RE generators,[10] the increased adoption by the private sector could be driven by the need to ensure that investments in RE projects

[6] Government of India, India's Updated First Nationally Determined Contribution Under Paris Agreement (2021-2030) (2022) ⟨https://unfccc.int/sites/default/files/NDC/2022-08/India%20Updated%20First%20Nationally%20Determined%20Contrib.pdf⟩.

[7] Please refer to Table 13 in Section 2 for more details.

[8] Ministry of Power, National Framework for Promoting Energy Storage Systems (2023) ⟨https://tinyurl.com/2s42fxxj⟩.

[9] Ministry of New and Renewable Energy, National Green Hydrogen Mission (2023) ⟨https://nghm.mnre.gov.in/admin/uploads/resources/167465243440278NationalGreenH2Mission.pdf⟩.

[10] *Judgment in appeal no 197/2019* (APTEL, 2 August 2021).

become dependable at large.

Based on our examination of PSPs in the list published by the CEA and the projects listed in the CMIE CapEx dataset, we see that of the 91 projects identified since 1970, 17 have begun implementation, and only six have been completed. If the more recent projects, which have been identified after 2019, take only six years to complete (matching the time taken by the most recently completed PSP), then it is possible that the 26.69 GW storage capacity requirement will be fulfilled. However, if projects take 12 to 24 years (in line with the completion times of past PSPs), then this capacity is unlikely to be created. Furthermore, hydro projects have often suffered from time and cost overruns relative to other renewable energy projects. Although it is beyond the scope of this paper, it would be useful to examine the reasons that explain the gap between the number of projects that get identified and the projects that are eventually commissioned. The reasons behind the time and cost overruns of completed projects would also provide clues for improving the policies on energy storage.

We acknowledge that between the two commercially viable technologies, BESS and PSPs, the latter present several advantages. Batteries are restricted by their storage capacity and their lifespan, and will have to be replaced frequently. PSPs, on the other hand, have the longest service life of 50–150 years and are capable of storing and generating energy on a much larger scale. Arguably, a cost-benefit analysis which internalises externalities such as environmental costs, employment and other policy priorities may tilt the balance in favour of PSPs.[11] Despite these advantages, the poor track record of completing PSPs, coupled with the delay in completing hydropower projects, suggest that the government should accommodate the construction risks with PSPs sufficiently while formulating storage policy.

The structure of the paper is as follows. Section 2 looks at the developments in the storage policy landscape. Section 3 clarifies how we prepared the dataset and the methods relied upon in the paper. Section 4 documents the rise in the identification of potential sites and commensurate willingness of developers to invest in PSPs, changes in the ownership patterns of the developers and their geographical distribution. Section 5 examines the status of development of the PSPs, if they are advancing in the development stages, and the time it takes them to do so. It also questions whether the estimates prepared by the CEA are likely to be realised at the current rate of completion. Section 6 assesses whether the experience

[11]Rakesh Kacker, Sushil Soonee, and Gaurav Bhatiani, "Pumped Storage Key to Energy Transition" [2022] Financial Express ⟨https://www.financialexpress.com/opinion/pumped-storage-key-to-energy-transition/3058794/⟩.

with hydropower projects in the country will inform the reality of storage capacity addition from PSPs. Section 7 concludes.

2 The policy landscape of storage

India relies on an institutional framework that is distributed across different ministries including Power, Coal, Petroleum and Natural Gas, New and Renewable Energy and the Department of Atomic Energy to tackle its energy policy challenges. In addition to the Ministries, public authorities like the Central Electricity Authority of India (CEA), a technical advisory body to the government and a regulatory regime which includes State Electricity Regulatory Commissions, also make policy in the electricity sector.

At the Union level, the Ministry of Power (MoP), the Central Electricity Regulatory Commission (CERC) and the CEA have been introducing new guidelines and regulations to accommodate storage technologies. Table 1 provides an overview of measures taken by the Union government to encourage the growth of energy storage. The overview draws attention to the rapid pace at which policies are being introduced or changed to increase the deployment of energy storage. The policies aim to incentivise and assist the deployment of energy storage - a relatively new sector in the Indian energy landscape. ESS is a delicensed activity; the policies and bidding guidelines aim to promote private investment into energy storage. In August 2023, MoP also released a National Framework for Promoting ESS.[12] The document synthesises the government's ambition for energy storage, compiling the disparate policies in one place, and outlining the long term plans of the government for the sector's growth. Consequently, the policy environment has become more conducive to the growth of energy storage technologies. We now turn to describing key elements of the policy developments in energy storage.

[12]National Framework for Promoting Energy Storage Systems (n 8).

Table 1 Timeline of policy development in energy storage

Year	Policy Change/Introduction
January 2017	CERC issues staff paper on introduction of electricity storage system
February 2018	GoI constitutes expert committee to draft National Energy Storage Mission
March 2019	Cabinet approves National Mission on Transformative Mobility and Battery Storage
March 2019	MoP recognises PSPs with capacity more than 25 MW as part of RE
September 2019	NITI Aayog releases roadmap for ESS, 2019-2032
October 2021	MoP notifies rules giving must run status to RE power plants
November 2021	MoP orders waiver of ISTS charges for BESS and PSPs commissioned up to 30.06.2025
January 2022	Ancillary Services Regulations apply to energy storage
March 2022	MoP notifies Guidelines for Procurement and Utilisation of BESS
July 2022	MoP notifies Energy Storage Obligation Trajectory till 2032
December 2022	Electricity (Amendment) Rules, mandate that ESS be considered a part of the power system, clarify status as delicensed activity
January 2023	National Green Hydrogen Mission contemplates pilot projects in energy storage sector
March 2023	Ministry of New and Renewable Energy notifies bidding trajectory for RE projects
May 2023	CEA prepares National Electricity Plan outlining storage requirements from PSPs and BESS till 2032
April 2023	MoP notifies Guidelines for Development of PSPs
June 2023	Resource Adequacy Guidelines allow consideration of storage capacity in resource adequacy plan, allow distribution licensees to contract storage capacity
August 2023	MoP releases National Framework for Promoting ESS to achieve twin objectives of energy transition and energy security
January 2024	Electricity (Amendment) Rules eliminate need to license transmission lines for independent ESS projects
March 2024	MoP notifies scheme for Viability Gap Funding for development of BESS
August 2024	MoP releases Draft Guidelines for Procurement of Storage Capacity or Stored Energy from PSPs

2.1 Storage as part of renewables procurement

India has established annual Renewable Purchase Obligation (RPO) targets for power procurers, including distribution utilities, open access consumers and captive power producers.[13] States devise RPO targets for purchase of renewable energy by obligated entities and MoP has also prescribed a national trajectory for RPOs.[14] Despite the State Electricity Regulatory Commissions having the authority to enforce RPOs, compliance remains weak.[15]

Initially, the RPOs included two categories— solar and non-solar. In 2022, this categorisation was revised to include energy storage.[16] MoP notified a year-wise trajectory for Energy Storage Obligation (ESO) to ensure that obligated entities have sufficient storage capacity to enable RE integration and achieve the energy transition targets being set by the government. The ESO specifies that the percentage of total energy consumed from solar and/or wind, with or through energy storage should be set at 1% in 2023-2024 and gradually rise to 4% by 2029-2030. The year-wise details are presented in Table 2.

Table 2 Energy storage obligations

The table presents the long-term trajectory for ESOs as notified by the Ministry of Power to ensure that obligated entities have sufficient storage capacity. As per the trajectory, the ESO shall gradually increase from 1% in FY 2023-24 to 4% by FY 2029-30, with an annual increase of 0.5%.

Year	Storage on Energy Basis
2023-24	1%
2024-25	1.5%
2025-26	2%
2026-27	2.5%
2027-28	3%
2028-29	3.5%
2029-30	4%

Prompted by the MoP notification, a few states like Bihar, Haryana, Madhya Pradesh, Maharashtra, Manipur, Mizoram and Rajasthan have added storage as a category in their

[13] This is done through Section 86(1)(e) of Electricity Act, 2003 which mandates State Electricity Regulatory Commissions (SERCs) to specify a minimum share of total consumption from renewable sources of energy for their state.

[14] Sneha Mannur, Saumendra Aggrawal, and Ashwin Gambhir, "A comprehensive review of State RPO framework and regulations: Learnings for effective implementation" [2024] Prayas Energy Group ⟨https://tinyurl.com/e3y76hcc⟩.

[15] Ibid.

[16] Ministry of Power, Renewable Purchase Obligation and Energy Storage Obligation Trakectory, till 2029-2030 (22 July 2022) ⟨https://shorturl.at/0mmdJ⟩.

respective RPO frameworks.[17] Notably, the latest MoP trajectory for RPOs also does not include storage as a separate category.[18]

Power from renewable energy sources is typically procured through long term contracts entered into with state utilities. In March 2023, the Union government notified the bidding trajectory for renewable energy to encourage procurement from renewable energy sources.[19] The trajectory would require tendering agencies to invite bids of 50 GW of renewable energy annually till 2027-2028. Procurers of renewable energy prefer stable and less intermittent profile of renewable energy. As a result, hybrid renewable energy tenders (with or without storage) have become popular.[20] MoP has also introduced bidding guidelines for standalone ESS and storage-linked tenders,[21] resulting in 9 GW of RE and 15 GWh of storage contracted through storage-linked tenders.[22]

2.2 Needs assessment

The CEA is obligated to prepare a National Electricity Plan every five years.[23] In the latest edition of the Plan, notified in 2023, the CEA has prepared estimates for both PSP and BESS storage models by 2027 and by 2032.[24] The plan suggests that non-fossil fuel based capacity is likely to increase to 616 GW in 2031-32, which includes 486 GW of renewable energy based installed capacity. With a high amount of renewable energy integration contemplated in the National Electricity Plan, estimates for storage capacity addition have been set accordingly.[25]

Table 3 indicates that the CEA expects 16.13 GW of storage capacity to exist by 2026-27, of which a little over 50% is to be met by BESS and the rest by PSPs. By 2031-32, it expects the capacity to grow five-fold to about 74 GW. 27% of this is expected to come from PSPs, and the remainder from BESS.

[17] Mannur, Aggrawal, and Gambhir (n 14).

[18] Ministry of Power, Renewable Purchase Obligation and Energy Storage Obligation Trakectory, till 2029-2030 (23 October 2023) ⟨https://powermin.gov.in/sites/default/files/Notification_Regarding_Renewable_Purchase_Obligation_RPO.pdf⟩.

[19] Ministry of New and Renewable Energy, Office Memorandum: Bidding Trajectory for Renewable Energy Power Projects (31 March 2023) ⟨https://shorturl.at/JsQKS⟩.

[20] Prabhakar Sharma, Ashita Srivastava, and others, "Utility-scale Renewable Energy Tendering Trends in India" [2024] IEEFA ⟨https://tinyurl.com/462nhvt8⟩.

[21] Jyoti Gulia, Prabhakar Sharma, and others, "Energy Storage: Connecting India to Clean Power on Demand" [2023] IEEFA ⟨https://ieefa.org/sites/default/files/2023-12/Energy%20Storage_Dec23.pdf⟩.

[22] Ann Josey, Shantanu Dixit, and others, "Governments should encourage more players in the power sector, not less" [2024] Indian Express ⟨https://tinyurl.com/333bp69c⟩.

[23] Section 3(4) of the Electricity Act, 2003

[24] Central Electricity Authority, National Electricity Plan (2023) ⟨https://shorturl.at/gSV6W⟩.

[25] Ibid.

Table 3 Storage capacity requirements which will accompany renewable capacity addition

This table presents the storage capacity requirements as calculated by the Central Electricity Authority.

Year	PSP (GW)	BESS (GW)	Total(GW)
2026-27	7.45	8.68	16.13
2031-32	26.69	47.24	73.93

Source: Central Electricity Authority, National Electricity Plan Vol I: Generation, 2023

While the National Electricity Plan in estimating storage requirements contemplates BESS and PSPs; the overarching framework for promoting ESS suggests that the government would like to encourage the development of emerging technologies alongside mature storage technologies.[26] Consequently, the National Framework outlines,

> In order to ensure optimum development of Energy Storage systems, it is necessary to promote a range of established ESS technologies alongside emerging technologies that demonstrate significant potential. The Central Government may notify technology agnostic bidding guidelines for Long Duration Energy Storage (LDES), Short Duration Energy Storage (SDES), and Ancillary Services to assist utilities, procurers, and developers in faster development of financially viable and environmentally sustainable ESS projects for the Indian power sector.

The guidelines for LDES and SDES will become more relevant as the share of renewable energy in India's generation capacity becomes more prominent. An assessment of the procurement policy and estimate of needs takes us to specific policy initiatives for PSPs.

2.3 Developing PSPs

In April 2023, the MoP notified the Guidelines to promote development of PSPs (Guidelines).[27] The Guidelines include the policy and fiscal incentives which aim to make the storage component of such projects financially viable. The Guidelines acknowledge that the demand for storage is likely to increase given that more renewable energy is likely to be integrated, and recognises that PSPs are best suited for addressing this demand. The Guidelines observe,

> Amongst the various technologies available for addressing this requirement of storage and ancillary services, Pumped Storage Projects (PSPs) are clean, MW scale, domestically available, time tested and internationally accepted... PSPs are clean, green and safe. They don't produce

[26] National Framework for Promoting Energy Storage Systems (n 8).

[27] Ministry of Power, Guidelines to promote development of Pumped Storage Projects (10 April 2023) ⟨https://shorturl.at/NKmQ3⟩.

any poisonous/ harmful by-products or pose problems of disposal. The advantages of promoting PSPs are not only based on their usefulness in maintaining grid stability and facilitating VRE integration but also their other positive attributes when compared to other available energy storage systems.

The Guidelines take the view that PSPs are ideally suited to address dynamic supply and demand. Additionally, they can help reduce RE curtailment. Cognisant of the role PSPs can play in enabling greater integration of RE, the Guidelines have four main components. First, they allow state governments to award projects to Central Public Sector Undertakings (CPSUs) and State Public Sector Undertakings (SPSUs), on a nomination basis as opposed to through a bidding process. Projects can continue to be allotted to private developers through competitive bidding. Second, there are significant incentives for development of PSPs, including the waiver of Inter-state Transmission System (ISTS) charges, exemption from free power obligations, and the removal of upfront premium for project allotment, amongst others. Third, they instruct the Electricity Regulatory Commissions to undertake market reforms for monetisation of ancillary services provided by PSPs. Finally, the guidelines attempt to rationalise environmental clearances for PSPs, allowing for treatment of PSPs constructed on existing reservoirs and on off-the-river sites as a separate category.

In parallel, the CEA has been working on measures that will expedite the commissioning of PSPs. According to the scheme under Section 8 of the Electricity Act, 2003, read with Union government notifications,[28] the law places certain limits on capital expenditure on hydro electric schemes. For expenditure above these limits, the CEA is required to approve the project. The project developer is required to submit a Detailed Project Report (DPR) to the CEA for approval. Since 2022, the CEA has been revising the guidelines for granting approval and preparation of DPRs in order to expedite the commissioning of PSPs.[29] The details of the changes have been documented in Table 4.

[28]Central Government vide Notification No. SO 550(E) dated 18.04.2006 modified vide Notification No. SO 490(E) dated 28.01.2014

[29]Central Electricity Authority, Guidelines for Formulation of Detailed Project Reports for Pumped Storage Schemes, (Version 1.0) (2022) ⟨https://tinyurl.com/4c7u3c3p⟩; Central Electricity Auhtority, Guidelines for Formulation of Detailed Project Reports for Pumped Storage Schemes, Version 2.0 (2023) ⟨https://tinyurl.com/5yhjb47f⟩; Central Electricity Authority, Guidelines for Acceptance, Examination and Concurrence of Detailed Project Reports for Pumped Storage Schemes (2023) ⟨https://tinyurl.com/5x9typww⟩; Central Electricity Authority, Guidelines for Acceptance, Examination and Concurrence of Detailed Project Reports for Pumped Storage Schemes, (Version 3.0) (2024) ⟨https://tinyurl.com/yuzjhyh6⟩; Central Electricity Authority, Guidelines for Formulation of Detailed Project Reports for Pumped Storage Schemes, (Version 3.0) (2024) ⟨https://tinyurl.com/yfaxypxe⟩.

Table 4 Measures expediting commissioning of PSPs

This table documents the measures taken by the CEA to expedite the commissioning of PSPs. By revising its guidelines the CEA has attempted to reduce the time taken for preparing DPRs and granting approval to PSPs.

Year	Effect of Guidelines
2022	CEA reduces timeline for preparation of DPR from 900 days to 720 days
2022	CEA reduces timeline for concurrence from 150 to 75 days for projects allotted through competitive bidding and to 125 days for other projects
2023	CEA further reduces the timeline for preparation of DPR to 690 days for projects in non-Himalayan regions
2023	CEA further reduces the timeline for concurrence from 75 days to 50 days for projects allotted through competitive bidding and to 90 days for all other projects
2024	CEA makes 50 days the timeline for concurrence for all projects
2024	CEA shortens the checklist of documents to be submitted by project developers

More recently, the Union government, in the budget speech for the year 2024-25, indicated that it will announce a policy to promote PSPs.[30] On August 22, 2024, the MoP published draft guidelines for tariff-based competitive bidding for procurement of stored capacity or stored energy from PSPs.[31] Pertinently, equivalent guidelines for the promotion of BESS are already in place.

For the development of hydropower projects including PSPs, the role of the state government assumes importance as water and land are state subjects. Many states have introduced policies for the development of PSPs.[32] These policies aim to channel public and private investment in PSPs and lay down criteria for allotment of sites, modes of project development, and their utilisation. As we discuss in the next section, there is great variance in the uptake

[30]Government of India, Budget 2024-2025 Speech of Nirmala Sitharaman Minister of Finance (23 July 2024) ⟨https://shorturl.at/yvLTg⟩.

[31]Draft Guidelines for Tariff Based Competitive Bidding for Procurement of Storage Capacity/Stored Energy from Pumped Storage Plants 2024.

[32]Government of Andhra Pradesh, Andhra Pradesh Integreated Clean Energy Policy (2024) ⟨https://shorturl.at/Kzbmt⟩; Government of Maharashtra, Policy for development of Pumped Storage Projects (PSPs) (20 December 2023) ⟨https://shorturl.at/gwLCx⟩; Government of Madhya Pradesh, Scheme for Implementation of Pumped Hydro Storage (28 April 2023) ⟨https://tinyurl.com/2u4hhzc2⟩; Government of Tamil Nadu, Tamil Nadu Pumped Storage Projects (PSP) Policy- 2024 (22 August 2024) ⟨https://www.tangedco.org/static/tangedco/assets/files/linkpdf/TNPSPPolicyGO8205092024.pdf⟩.

of PSPs across India with announced projects being concentrated in certain states more than others.

In summary, the Union government is rapidly developing policy on energy storage and attempting to attract investment to the sector. Policymakers have acknowledged the crucial role that will be played by energy storage in accomplishing the energy transition targets, and have estimated the storage capacity needed to fulfil those targets. However, when compared to renewable energy policies, energy storage is a relatively new sector. While the policy development is at a nascent stage to examine its overall effectiveness, we attempt to assess the influence it may have had in the growth of PSPs in the country in the next section.

3 Data and methods

The data for our analysis is taken from CapEx, a database of projects in India developed and maintained by the Centre for Monitoring Indian Economy (CMIE).[33] This database tracks projects from announcement to completion, providing detailed information on project location, products, capacities, key stakeholders, major events, completion details, and cost revisions. Project life-cycle stages are recorded based on publicly available sources and direct communication with executing entities. Our dataset thus includes event dates as well as a "Project Status" classification assigned by CapEx to each project (see Table 5)

[33] https://capex.cmie.com/

Table 5 Classification of projects by CMIE CapEx

Status	Basis for Classification
Announced	Promoters of the project have made an announcement of an intention to invest (but implementation has not begun)
Announced and Stalled	Project is stalled after the announcement and before implementation
Shelved	Company withdraws from a project it had announced, before implementation could begin
Under Implementation	Project makes some tangible progress like receipt of government permissions or significant clearances, acquisition of land, or commencement of negotiations for acquisition of land, finalisation of sources of funding, appointment of contractors, etc.
Implementation Stalled	Project is stalled after implementation has begun
Abandoned	Company withdraws from a project after implementation had begun
Completed	Project is completed
No Information but Live	No information is available from either public or direct sources, but efforts are ongoing to gather relevant details. Once the necessary information is obtained, the project is reclassified into the appropriate category
No Information	No information has been available for a project for over 18 months, and CMIE has discontinued further follow-ups on it

Under CMIE's classification, a project once announced can get stalled, shelved, or begin implementation. Once a project begins implementation it can further get stalled, abandoned, or completed. A project may be announced but may neither get stalled or shelved, nor begin implementation. Projects labelled as *Announced* fall into this category. Actions such as signing MoUs or seeking approvals and clearances do not count as implementation, so the project remains classified as Announced. Once milestones like securing approvals, acquiring land, or other key steps are achieved (as outlined in Table 5), the project is updated to *Under Implementation* and alternatively, if a project is stalled or shelved, it is moved out of the Announced category into the appropriate one. There are also a number of projects for which CapEx has not been able to source information for more than 18 months, known as *No Information* projects.

3.1 The PSP dataset

We extracted data on electricity generation projects from CMIE CapEx and conducted a keyword search for the term 'pumped storage' in both the project names and the types of products they are expected to generate. This approach identified 156 PSPs. To validate the data published by CMIE CapEx, we relied on information released by the CEA.[34]

We cross-referenced all the projects listed in the CMIE CapEx database with the information published by CEA (as of 31 December 2024) and found 89 matches. During the mapping, we found that while CapEx lists four PSPs as completed, the equivalent category in CEA suggests that there are six PSPs in operation[35]. Given that the completion rate is important for our study we sourced the data for the two projects from publicly available information and made it a part of our dataset, taking the final count to 91. For these 91 projects, we extracted variables like full project name and number, company name and code, unit type, project status, total cost and cost overrun, owner, capacity, location, product type, and key dates such as announcement date, environmental clearance date, loan sanction date, implementation date, and completion date. The summary of the final PSP dataset is presented in Table 6.

Table 6 PSP dataset

This table provides a summary of the PSP dataset, categorising projects by status, along with the total number of projects and their combined capacity.

Project Status	N	Capacity (GW)
Announced	59	93.26
Announced & Stalled	2	2.20
Under Implementation	17	26.17
Completed	6	3.31
No Information	7	5.99

3.1.1 Mapping the categories

The CEA publishes monthly information on PSPs classifying them into the following categories; i) Terms of Reference (ToR) granted by the Ministry of Forest, Environment and Climate Change (ii) under survey and investigation, iii) DPR concurred, iv) under construction, and v) in operation.

[34]Central Electricity Authority, Information on Pumped Storage Projects ⟨https://cea.nic.in/pumped-storage-plants/?lang=en⟩.

[35]CEA lists eight projects to be in operation, but two of these are dysfunctional

Table 7 maps the number of projects from each CEA category to their corresponding status in CMIE.

Table 7 Mapping CEA categories to CMIE classifications

This table presents the number of projects within each CEA category and their corresponding classification as done by CMIE. These categories also indicate the stages in the development of PSPs, with the grant of ToR by the MoEFCC situated at the start of the development process.

CEA Category	N	CMIE Project Status
ToR granted	30	24 Announced 2 Announced & Stalled 1 Under Implementation 3 No Information
Under Survey & Investigation	43	35 Announced 2 No Information 6 Under Implementation
DPR Concurred	5	4 Under Implementation 1 No Information
Under Construction	6	6 Under Implementation
In Operation	5	4 Completed 1 No Information

In the project life-cycle, a developer first seeks the grant of ToR from the MoFECC. After the grant of ToR, the developer undertakes the survey and investigation (S&I) of the project site. After preparing the S&I report, it submits the Detailed Project Report (DPR) to the CEA. These stages only display the potential of capacity that can be added, it is only after the concurrence of the CEA that the project has a real possibility of beginning construction.

Most projects where the ToR has been granted or are still under S&I are listed as Announced in CapEx. However seven projects in the CapEx database are listed as Under implementation, but according to the CEA are still in the early stages i.e. ToR granted and Under S&I. A closer examination of these projects revealed that they had reached stages like receiving a Letter of Intent, obtaining environmental clearance, having a foundation stone laid, or securing budgetary allocations—each of which qualifies a project for Under Implementation status in CapEx. Additionally, one project has begun construction (see Appendix A.1). We adhere to the CapEx classification because these stages indicate a clear commitment of resources and intent to proceed with the project.

3.2 The all-RE dataset

We extracted data on electricity generation projects, to compare how hydropower projects are faring against other types of RE. This resulted in a dataset of 8,721 projects. CapEx classifies projects as Renewable Electricity but does not specify the exact type of RE. Additionally, hydro projects greater than 25 MW in capacity are categorised as Conventional Electricity in the CapEx database. Therefore, we examined the types of products[36] these projects are expected to generate. While some projects only label their output as "electricity", most provide specific information about the type of RE used. We also searched for mentions of RE types in the project names. This process yielded a dataset of 6,329 projects, categorised into Solar, Wind, Hydro, and Others. The "Others" category encompasses all other RE projects like bio-gas, waste-based projects, and those where CapEx did not specify the RE type either in the project name or the product description. Table 8 presents the total number of projects in our all-RE dataset.

Table 8 Number of RE projects

This table presents the total number of RE projects in our dataset.

RE Type	N
Hydro	1414
Solar	2785
Wind	1149
Others	981

In our dataset, solar power projects make up the largest share, with 2,785 (44%) projects, followed by hydropower with 1,414 (22.3%) announced projects. Additionally, there are 1,149 (18.2%) wind power projects, while the 'Others' category constitutes the remaining 15.5%.

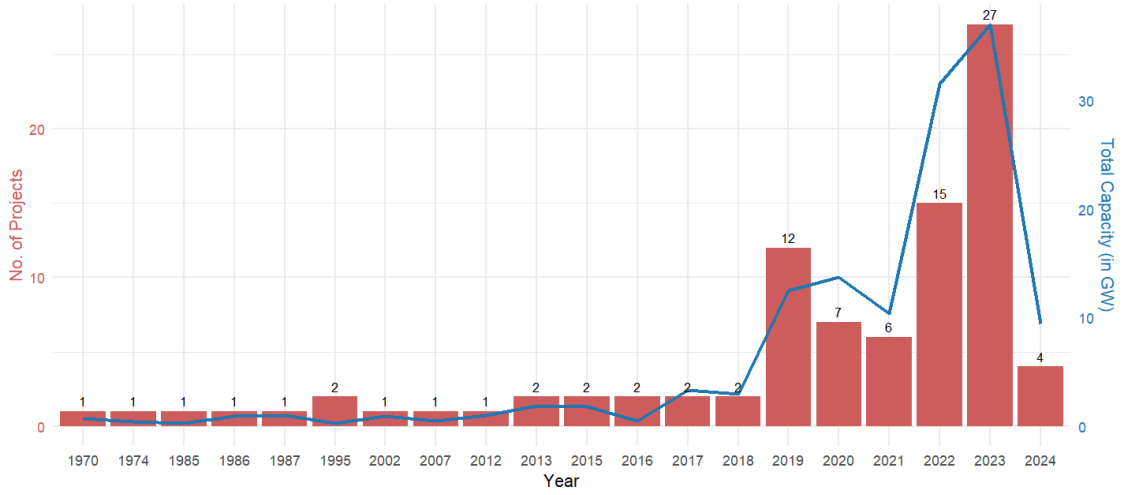
4 The status of PSP projects

The first PSP was identified in 1970 with a capacity of 705.6 MW, after which there have been some scattered attempts over the years. Private sector involvement in PSPs began rising significantly after 2019, though most projects remain in the early stages of development. As shown in Figure 1, 15 projects totalling 31.5 GW were identified in 2022, followed by 27 projects with a combined capacity of 37 GW in 2023.

[36] "Product" is a category listed by CapEx that mentions a project's output(s)

Figure 1 Number of PSPs and total capacity identified

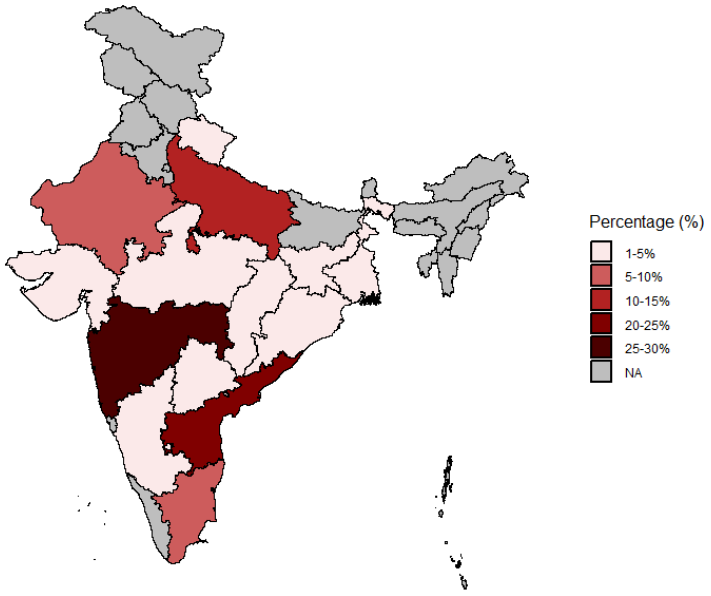
The figure displays the total number of PSPs identified over the years alongside the sum of their capacities. The red bars represent the total number of PSPs, indicated on the left-hand axis, while the blue line illustrates the total capacity, as shown on the right-hand axis.



PSPs are unevenly distributed across the regions of the country. As seen in Figure 2, Maharashtra, Andhra Pradesh, Uttar Pradesh, Rajasthan and Tamil Nadu account for 76.4% of PSP capacity.

Figure 2 Percentage of total PSP capacity by state

The figure illustrates PSP capacities identified in each state, with darker shades indicating a higher share of total capacity.



The National Electricity Plan also recognises that PSPs in the southern region are likely to yield benefits during the period 2027-32.[37] The plan suggests that the southern region will require less BESS and PSPs would emerge as the cost-effective technology for the region. As discussed in Section 2, Andhra Pradesh and Tamil Nadu have already introduced policies to encourage the deployment of PSPs.

Table 9 shows the ownership of the projects in different stages of development. Of the 91 projects in our dataset, 34% are being developed by state-owned entities. However, these projects account for only 20% of the total investment, indicating that public sector projects tend to have lower capacities. Notably, the 34% share of state-owned developers in PSPs is significantly higher than in other renewable energy sectors. For example, according to CapEx data, only 19.2% of solar projects and 6.9% of wind power projects have a state-owned developer.

[37]National Electricity Plan (n 24).

Table 9 Number of projects and amount invested by ownership

This table compares the total number of PSPs identified by public and private sector developers, along with the total investment in these projects announced by each sector. It is important to note that these figures represent the initial cost estimates calculated at the start of the projects and do not account for any cost overruns that may arise.

Owner	N	%	Investment (Rs. trillion)	Investment (%)
Public	31	34.07	1,251,450	20.10
Private	60	65.93	4,973,734	79.90

It was only in 1991 that private participation was allowed in hydropower generation.[38] This could partially explain the higher share of state-owned PSPs compared to projects in other renewable technologies. However, this ownership distribution is likely to shift in the coming years, as private sector investment in PSPs has gained momentum only recently. Notably, 55 of the 60 PSPs with private developers in our dataset were identified after 2018. The total estimated investment in these projects has reached approximately Rs. 6.2 trillion.

Next, we study the progress of the PSPs as they advance in the stages of development after being identified. As described earlier, a project gets listed as "Under Implementation" on CapEx if it manages to secure the necessary approvals and clearances after being identified as a potential site for PSP development.[39] Table 10 summarises the total number of projects identified within each time interval and gives information about the distribution of projects that have begun implementation or have been completed. The table categorises projects into those identified before 2000, between 2001 and 2010, between 2011 and 2020, and annually after 2020. This classification accounts for the sharp increase in project identification in recent years, as shown in Figure 1, which may influence implementation and completion trends differently compared to earlier projects.

[38] Akhilesh Sati and others, "Growth of Hydropower in India: Role of the Private Sector" [2022] Observers Research Foundation ⟨https://www.orfonline.org/expert-speak/growth-of-hydropower-in-india⟩.

[39] For details on classification of projects see Table 5

Table 10 Total number of projects implemented and completed (as on December 2024)

This table summarises the total number of projects identified in each interval, followed by the number of projects that began implementation. The final column shows the number of implemented projects that have been completed. The years following 2020 are presented individually.

Year of Identification	Projects	Implemented	Completed
Before 2000	7	7	5
2001-10	2	2	1
2011-2020	30	8	0
2021	6	2	0
2022	15	1	0
2023	27	3	0
2024	4	0	0

Out of the 91 projects, only 23 have entered the implementation phase which implies that they are in the advanced stages of planning and development. As shown in Table 10, only seven out of the 30 PSPs identified between 2011-2020 have begun implementation. Only two of the six projects identified in 2021, one of the 15 projects identified in 2022 and three of the 27 projects identified in 2023 have begun implementation. The low number of projects entering the implementation phase indicates that PSPs remain an economically risky investment for developers. Pertinently, of the 71 projects announced since 2019, 55 will be developed by the private sector.

The mean and median times to begin implementation are 1.1 and 1.8 years, respectively, as shown in Table 11. The median time is lower for public sector projects, but the mean of 2.7 years and the maximum of 9.2 years is higher than the private sector projects. These are based only on those projects that have begun implementation and are, therefore, a very small subset of the full dataset.

Table 11 Time between date of identification to starting implementation

This table presents the summary statistics for the time taken (in years) from a project's identification to the start of its implementation, with a comparison between public and private sector projects. The number of projects that have begun implementation is given in column N.

					(in years)
Owner	N	Min	Median	Mean	Max
Public	10[a]	0.08	0.29	2.67	9.17
Private	11	0.08	1.33	1.69	4.58
All	21	0.08	1.08	2.16	9.17

[a]Kadamparai PSP and Nagarjuna Sagar PSP have been excluded from this analysis as they do not have an implementation date, having not been sourced from CMIE CapEx.

The data on the PSPs that are under implementation or completed shows that the PSPs that advance to the implementation phase do so within three years of being identified. Additionally, given that there is no publicly available information on projects that have not begun implementation, it is not possible to ascertain the reasons for the low implementation rate of PSPs.

Table 12 summarises the six PSPs that have been completed. These projects are based in the states of Telangana, Tamil Nadu, Maharashtra, Andhra Pradesh and West Bengal. The fastest project was in Bhira in Maharashtra with a 0.15 GW capacity and took 2.42 years, while the Ghatghar project, also in Maharashtra, took almost 23 years to complete. The average time taken by the six projects was 13 years and the median time was 15 years.

Table 12 Completion time of completed projects

This table summarises the six PSPs that have been completed. It details the name of each project, the state where it is located, its total capacity, the year it was identified, and the time taken from identification to completion.

Project Name	State	Capacity (GW)	Announced Year	Completion Time (years)
Nagarjuna Sagar	Telangana	0.71	1970	15.08
Kadamparai	Tamil Nadu	0.40	1974	15.00
Ghatghar	Maharashtra	0.25	1985	23.17
Srisailam	Andhra Pradesh	0.90	1986	17.33
Bhira	Maharashtra	0.15	1995	2.42
Purulia	West Bengal	0.90	2002	5.83

If the projects currently under development follow a similar trajectory, the likelihood of

meeting the capacity estimates in the National Electricity Plan for the year 2031-2032 is low. We conducted a brief analysis to illustrate this point.

5 Expected increase in capacity

We use a crude back-of-the-envelope calculation method. We begin with an optimistic estimate of six years, as the most recently completed project, Purulia PSP, took around six years to be completed. Given that the average completion time was found to be 13 years, we also forecast for completion within 12 years. Lastly, as a more pessimistic scenario, we estimate that projects may take up to 24 years to be completed because the maximum time taken by the six completed PSPs was a little over 23 years.

We restrict our analysis to projects identified from 2019 because of two reasons; firstly, 2019 is the inflection point when it comes to the interest in the development of PSPs, and secondly, the policy environment has become more favourable in recent years. Moreover, 12 out of the 13 projects identified between 2000 and 2018 (Figure 1 and Table 10) have not yet been completed. Five have not begun implementation. This indicates that they have exceeded our estimated timelines of six or 12 years.

From the projects that were identified from 2019 onwards, we exclude projects that are marked as Stalled, Shelved, Abandoned, or No Information on CapEx. Shelved and Abandoned projects would not be revived, and for Stalled or No Information projects, their completion probability and status remain uncertain. Consequently, our analysis is limited to projects that have been identified but not yet begun implementation, and those that are currently under implementation. The results are presented in Table 13.

Table 13 Expected capacity addition (in GW)

This table forecasts the potential capacity additions in the country by 2027 and 2032, assuming that all projects identified from 2019 onwards are completed within 6, 12, or 24 years.

	Time to completion of projects		
Year	6 years	12 years	24 years
2027	29.72 GW	0.00 GW	0.00 GW
2032	107.64 GW	21.36 GW	0.00 GW

A total of 71 projects have been identified since 2019. Of these, 65 could potentially be completed and are in different stages of planning. If these projects were to be completed

in six years, then eight projects identified in 2019, six in 2020 and five in 2021 would be completed by 2027. For example, MP 30 Gandhisagar PSP in Madhya Pradesh was identified in November 2019 and is currently under implementation. If it takes six years to complete, a total capacity of 1440 MW will be added by November 2025. Similarly, the six projects identified in 2020 will have been completed by 2026 while the five identified in 2021 will be completed in 2027. The total capacity addition from these projects will amount to 29.72 GW by 2027. By 2032, all 65 projects will have been completed and the total capacity addition will amount to 107.64 GW. This suggests that the targets set by the CEA, as outlined in Table 3, are achievable.

However, as shown in Table 10, no projects identified after 2010 have been completed to date, indicating that these projects are likely to take longer than six years to complete. If we estimate completion in 12 years, none of these projects are expected to be completed by 2027. By 2032, 14 projects will have been completed, adding a total capacity of 21.36 GW. In this scenario, the requirements are unlikely to be fulfilled. If it takes a project 24 years to complete, no capacity addition will occur either by 2027 or 2032. These predictions rely on simplistic assumptions, and it is still possible that some of the projects identified between 2011 and 2019 reach completion. Nonetheless, they offer some indicative insights into the likelihood of capacity additions.

6 Past experience with hydropower

Delayed execution and the problem of stressed assets in the power sector, especially thermal coal-based power plants, have been significant enough to warrant Parliamentary oversight.[40] However, the problem of stressed assets is not limited to thermal power plants, and the Standing Committee on Energy (Committee) has also recognised the delay in the execution of hydropower plants.

In 2019, the Committee expressed concern about the slow development of hydropower. It found that out of 37 hydropower projects, 16 were stalled, of which 10 were stalled because of financial constraints.[41] In 2020-21, the Standing Committee sought information from the Ministry of Power regarding the status of power projects being implemented by public sector companies.[42] It found that many thermal, hydro and transmission projects were delayed

[40]Standing Committee on Energy, Stressed/Non-Performing Assets in the Electricity Sector (7 March 2018) ⟨https://tinyurl.com/yfzmfbtn⟩.

[41]Standing Committee on Energy, Hydro Power (4 January 2019) ⟨https://tinyurl.com/49uu8vf2⟩.

[42]Standing Committee on Energy, Delay in execution/completion of Power Projects by Power Sector

and suffered serious time and cost overruns. In the context of hydroelectric projects, 13 such projects were being developed by CPSUs, and most of these were significantly behind schedule. Details of time and cost overruns have been given in the table below.

Table 14 Delay in power projects

This table presents the data for time and cost overruns for 13 hydropower projects being run by CPSUs.

Sector	Projects		Overruns	
	Total	Delayed	Cost	Time
Hydro	13	12	31,530 Cr.	1250 months

Source: 19th Report, Standing Committee on Energy, (2020-21)

6.1 Exploring the reasons for time and cost overruns

Investments in electricity infrastructure, particularly hydropower, are risky ventures, for they often exceed the anticipated budgets. Sovacool et al (2014), in an international comparison, assessed the construction costs of 401 electricity infrastructure projects and found that hydroelectric dams and nuclear reactors have the greatest amount and frequency of cost overruns.[43] The study included 61 hydroelectric dams and found that these projects experienced a total of 148.6 billion (USD) in cost overruns and exhibited a mean cost escalation of 70.6 percent. The Indian experience aligns with this finding. The Standing Committee had identified the reasons behind the delay in hydropower projects, which include: (i) bottlenecks in land acquisition, (ii) environment and forest-related issues, (iii) rehabilitation and resettlement issues, (iv) inadequate infrastructural facilities, (v) local law and order, (vi) fund constraints and (vii) geological surprises amongst others.[44]

Research on PSPs in India attributes the delay in completion to the high cost of commissioning PSPs, which in turn is affected by the time taken to procure environmental clearances, the long gestation period and the poor recovery from existing price mechanisms.[45] We looked at the projects in our dataset which were identified before 2020, and found similar reasons for delay (Table A.2 in Appendix A.2).

Companies (5 August 2021) ⟨https://eparlib.nic.in/bitstream/123456789/811570/1/17_Energy_19.pdf⟩.

[43]Benjamin K Sovacool, Alex Gilbert, and Daniel Nugent, "An international comparative assessment of construction cost overruns for electricity infrastructure" [2014] Energy Research and Social Science.

[44]Delay in execution/completion of Power Projects by Power Sector Companies (n 42).

[45]Centre for Study of Science and technology Policy, Study on Pricing Mechanism for Energy Generated by Pumped Hydro Energy Storage (PHES) in India (2021) ⟨https://shorturl.at/3XDoH⟩.

It has been argued that to make PSPs economically viable and recognise the grid stability services they offer, they should be treated as regulatory assets owned by the load despatch centres.[46] The MoP issued guidelines in 2019 aimed at reducing the incidence of cost and time overruns in the development of hydropower plants, exhorting developers to follow international best practices and delegate adequately so that projects are completed on time.[47] These measures, however, do not consider the construction risks associated with large electricity infrastructure projects sufficiently. The next section demonstrates that technologies like solar and wind are substantially less prone to the risk of time and cost overruns.

6.2 Comparing hydropower with other renewable technologies

We study the time taken for completing hydro projects vis-a-vis other RE projects using the data from CapEx. When analysing the completion time of projects, the problem of censoring arises. Censoring refers to the phenomenon wherein an individual drops out of a study or the study period ends before the event can be observed. In this context, three types of censoring can occur: (i) for projects that are stalled, it is unclear whether they will be revived and completed or ultimately abandoned, (ii) "no information" projects are lost to our analysis and (ii) for projects that are still under implementation at the time of the study, their future completion status and timing remain unknown. Focussing solely on completed projects and excluding these censored cases introduces the risk of selection bias. To address censored projects, we employ Kaplan-Meier Survival analysis.[48]

Our findings show that hydropower projects have a lower completion rate and longer gestation periods when compared with projects that involve other renewable technologies, chiefly solar and wind. Table 15 presents the precise numbers.

[46] IRADe, Role of Pumped Hydro Energy Storage in India's Energy Transition (2019) ⟨https://tinyurl.com/23hr643x⟩.

[47] Ministry of Power, Guidelines to reduce the incidence of time and cost overruns in Hydro Power Projects (8 November 2019) ⟨https://powermin.gov.in/sites/default/files/uploads/Orders/G.2.1.PDF⟩.

[48] The precise methodology is further detailed in Appendix A.3.

Table 15 Completion rate and completion time for all RE projects

This table presents the completion rates and times for various types of renewable energy projects. The completion rate is calculated by dividing the number of completed projects by the total number of projects identified. The summary statistics for completion times are derived from the Kaplan-Meier model, which accounts for censored projects to estimate the minimum, median, mean, and maximum durations for project completion.

		Completion Time (years)			
RE Type	Completion Rate (%)	Min	Median	Mean	Max
Hydro	23.20	0.17	16.67	10.56	50.00
Solar	42.12	0.08	2.17	3.82	10.83
Wind	48.83	0.17	2.00	3.06	8.50
Others	32.72	0.50	3.75	3.98	12.17

The earliest time by which half of the hydropower projects get completed is almost 17 years, whereas for solar and wind projects, it is about two years. This gap is substantial as well as statistically significant. While it is acknowledged that hydropower projects generally have longer construction timelines, the International Energy Agency reports an average construction period of five to 10 years.[49] Therefore, a median completion time of 17 years points to considerable delays. Additionally, as shown in Table 15, hydropower projects also have the lowest completion rate at 23%. This further highlights the under-performance of hydropower projects compared to other renewable energy sources.

The PSP guidelines clearly mandate that developers must begin the construction of the project within two years from the date of allotment of the project. Failure to do so puts projects at risk of being cancelled by the state government in question. Given that the guidelines were notified in 2023, it remains to be seen how many developers adhere to the timelines prescribed under the guidelines.

7 Conclusion

The policy environment has become conducive to the development of energy storage systems in general and PSPs in particular. It has resulted in increased participation from the private sector in developing PSPs. Our analysis suggests that mere identification of potential and developer interest in investment is not a guarantee that the notional capacity would be added. There are many stages in the development of a PSP, and only a few projects have advanced

[49] International Energy Agency, Hydropower Special Market Report: Analysis and forecast to 2030 (2021) ⟨https://tinyurl.com/2y7futjz⟩.

through them. As this paper goes to publication, six PSPs have been completed, and only 17 PSPs in our dataset are under implementation. The poor track record of completion of PSPs, coupled with the delay in completing hydropower projects, suggests that the storage capacity estimated in the National Electricity Plan may not be completed on schedule.

A Appendix

A.1 Reevaluating project classification

There are seven projects that CMIE CapEx classifies as Under Implementation, but according to CEA, they are at other stages of development like ToR granted and under survey and investigation. Table A.1 lists these projects and the specific events that led CMIE CapEx to categorise them as Under Implementation.

Table A.1 Comparing project status between CEA and CMIE CapEx

This table lists the projects that CMIE CapEx has categorised as Under Implementation but, according to CEA, have not progressed to DPR Concurred or Under Construction stages.

Project Name	CEA Categorisation	Reason for CMIE CapEx to list it as Under Implementation
Sashnai Off-Stream Closed Loop PSP	ToR Granted	Prime Minister laid the foundation stone in February 2024
Maharashtra PSP	Under S&I	Letter of Intent (LoI) received from MSEDCL in September 2024
Sonbhadra Off-Stream PSP	Under S&I	Prime Minister laid the foundation stone in February 2024
Nimbaj PSP	Under S&I	Letter of Intent (LoI) received from Power Company of Karnataka Ltd. in December 2021
Chitravati PSP	Under S&I	Construction started by Adani Green in March 2024
Saundatti PSP	Under S&I	Environment clearance received in September 2022
Sillahalla (Nilgiris) Stage 1	Under S&I	Budgetary allocation done in February 2019 (Tamil Nadu budget sanctioned funds to the DPR preparation of this project)

A.2 Reasons for delays of PSPs

Table A.2 presents the reasons for delay of the PSPs. The information has been sourced from various publicly available sources.[50]

[50]CEA, Review of Tehri Pumped Storage Scheme in Uttarakhand on 20th November 2021 (2021) ⟨https://cea.nic.in/wp-content/uploads/hpm/2022/06/T_Report_Nov21_MT.pdf⟩; Dialogue Earth, Hydro project in India resurrected despite threats to livelihoods (2022) ⟨https://dialogue.earth/en/energy/turga-pumped-hydro-project-india-resurrected-despite-threats-forests-livelihoods/⟩; Down to Earth, West Bengal: Illegal acquisition of forest land for Turga and Bandu Pump Storage Projects, claim tribal residents (2023) ⟨https://shorturl.at/6cgcr⟩; Indian Express, Andhra Pradesh: Take off trouble comes up for upper Sileru pumped storage project (2021) ⟨https://shorturl.at/HNYQm⟩; Land Conflict Watch, Review of Tehri Pumped Storage Scheme in Uttarakhand on 20th November 2021 (2023) ⟨https://shorturl.at/DvxaB⟩; Down to Earth, LT loses legal battle against KPCL over Sharavathi pumped storage project in Karnataka (2024) ⟨https://shorturl.at/bdaGV⟩; The Economic Times, EAC to Visit Site before Giving Nod for Kodayar Project in Tamil Nadu (2023) ⟨https://shorturl.at/V2f1o⟩; The Hindu, Drop pumped storage hydroelectric projects granted to various private entities in Fifth Schedule region, HRF urges Andhra Pradesh government (2023) ⟨https://tinyurl.com/bdrf6se⟩.

Table A.2 Reasons for delay in completion

This table presents the PSPs initiated before 2020 that are undergoing delays. It lists the name of the project, ownership details, current status, year of announcement and the reason for delay.

Project	Ownership	Year of announcement	Current status	Reason for delay
Tehri PSP	Private	1987	Under implementation	Delay in construction (geographical difficulties) and cost escalations
Turga PSP	Public	2012	Under implementation	Litigation: Land acquisition violated the 2006 Forest Rights Act
Bandhu PSP	Public	2013	Announced	Opposition from local communities
Sillahalla (Nilgiris) Stage 1 PSP	Public	2013	Under implementation	Opposition from local communities and refusal to give up land
Upper Indravati PSP	Public	2015	Under Implementation	Delay in receiving clearances and cost escalations
Koyna Stage 4 PSP	Private	2016	No information	Slow progress and funds constraint due to cost escalations
Balimela PSP	Public	2016	Announced	Delay in receiving forest clearance
Sharavathy PSP	Public	2017	Under implementation	Litigation: tendering disputes
Upper Sileru PSP	Public	2017	Announced	Cost escalations
Kodayar PSP	Public	2019	Announced	Land acquision and forest clearance issues
Yerravaram PSP	Public	2019	Announced	Opposition from local communities

A.3 Kaplan-Meier methodology

For our analysis of comparing completion time of hydropower projects with others, we used the Kaplan-Meier Curve, which is a non-parametric method to estimate survival probabilities, given by the following equation:

$$S(t_i) = S(t_{i-1})(1 - \frac{d_i}{n_i}) \tag{1}$$

where, d_i is the number of events at t_i and n_i is the number of entities that haven't witnessed the event before t_i.

An event occurs when a project is completed. A project is censored when it is either stalled, is a No Information project or is still undergoing by the time our study ends. The period of our analysis is January 1957 to December 2024. The survival time has been calculated as follows:

- For completed projects, the time between the date of initiation to the date of completion.
- For stalled projects, the time between the date of initiation to the date of getting stalled.
- For projects with no information, time between the date of initiation to the date of the last update.
- For ongoing projects, date of initiation to the last date of our study, ie. December 2024.

Table A.3 Number of completed and censored projects

The table presents the number of completed and censored projects for each type of RE project.

RE Type	Completed	Censored
Hydro	328	960
Solar	1173	1540
Wind	561	555
Others	137	330