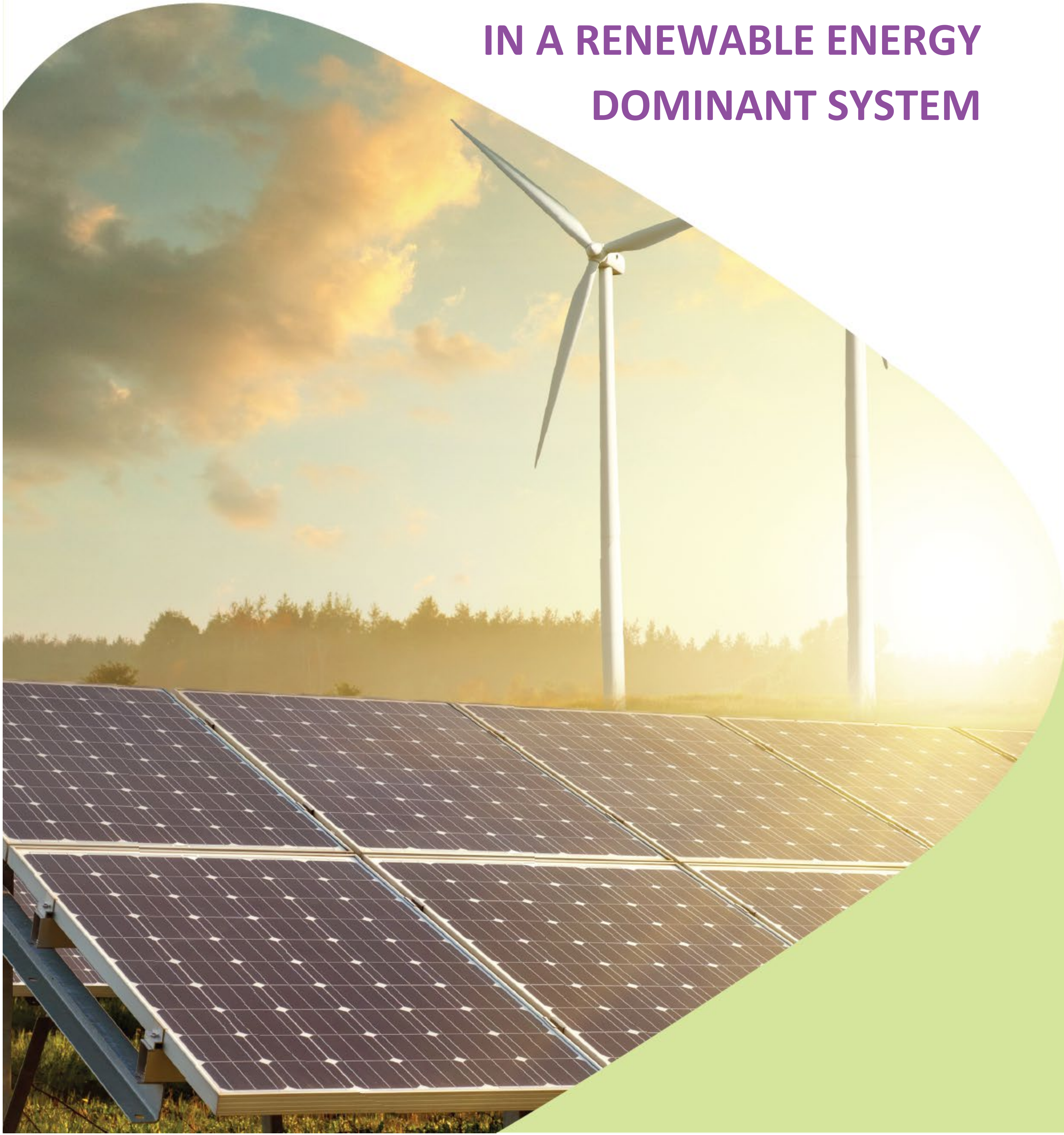
IETP
India Energy Transformation Platform
Decarbonising India

ENVISIONING THE ROLE AND OPERATIONS OF VARIOUS TECHNOLOGY OPTIONS IN A RENEWABLE ENERGY DOMINANT SYSTEM



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India Energy Transformation Platform (IETP)

The India Energy Transformation Platform is a multi-stakeholder group of experts in the field of energy, technology and policy. The Platform identifies crucial developments and technology solutions to look at long-term pathways for decarbonising India's energy sector up to 2050. IETP was conceptualised by the Swiss Agency for Development and Cooperation (SDC) and Shakti Sustainable Energy Foundation (SSEF), with Center for Study of Science, Technology and Policy as the secretariat. In its first year, the Platform identified four themes - decentralised energy systems, renewable energy technologies, industrial process heating and urban space cooling - to look at non-linear, transformational technology and policy solutions for decarbonising India.

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RE	Renewable energy
MNRE	Ministry of New and Renewable Energy
SECI	Solar Energy Corporation of India
GAIL	Gas Authority of India Limited
NTPC	National Thermal Power Corporation
PFC	Power Financing Corporation
REC	Rural Electrification Corporation
Li-ion	Lithium ion
FCEV	Fuel Cell Electric Vehicle
PSU	Public Sector Undertaking
CPSU	Central Public Sector Undertaking
CNG	Compressed Natural Gas
GHG	Greenhouse Gas
GDP	Gross Domestic Product
Gt	Giga Tonne
GW	Giga Watt
CRI	Commercial Readiness Index
TRL	Technology Readiness Level
R&R	Resettlement and Rehabilitation
MoU	Memorandum of Understanding
R&D	Research & Development
CUF	Capacity Utilization Factor
EPC	Engineering, Procurement & Construction

1 Executive summary

India has more than doubled its installed renewable energy capacity since 2014 and currently accounts for nearly 35%[1] of total installed power generation capacity (MNRE, 2019). India targets to increase this to about 40% by 2030 and the share of RE in total power generation capacity may increase to over 80% by 2050[2] (Economic Times, 2019). Further, achieving these goals would also require decarbonisation of sectors, such as transport, that are traditionally fuelled by fossil-fuel sources. This change is nothing short of a paradigm shift and India's energy sector is going through a transition to align with a RE-dominant power system. The objective of this study is to identify technologies that are key to achieving an integrated RE dominated energy system by 2050 and develop pathways for these technologies to be developed, commercialised, and scaled-up.

As part of this study, twenty-seven (27) technologies encompassing storage, generation and sector coupling were evaluated based on a three-stage evaluation process. Storage and sector coupling technologies are required for making the power system flexible to integrate intermittent generation from RE sources such as solar and wind.

In the evaluation process, the first two stages were used to shortlist the technologies based on inherent technical characteristics and the ability to be deployed in India. In the third stage, the shortlisted technologies were compared based on the utility each technology offers to the system.

The various storage technologies evaluated as part of this process can offer complementary services to the power system. For instance, battery storage systems are suited for short-term, quick response requirements while pumped hydro storage is suited for long term storage. The figure below shows the properties offered by various classes of storage technologies. On the other hand, various battery storage technologies compete for offering similar services.

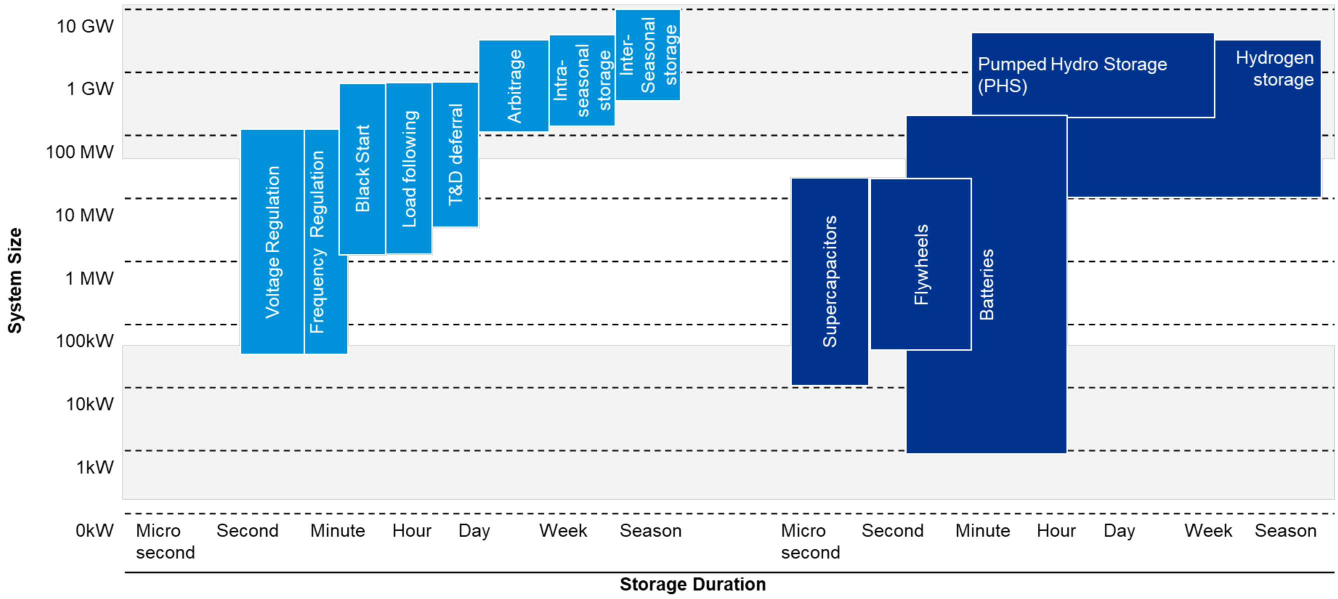


Figure 1: Storage technologies by application

The nature of storage system required at various levels for RE integration was established through a modelling approach. For the modelling approach adopted at the state level, it was observed that depending on the load profile and RE generation potential in the state, both short-duration as well as long-duration storage solutions may be required for different states. The magnitude of storage requirements across states may vary, however,

[1] Including large hydro
[2] Source: Shakti Foundation, IETP

the nature and flexibility characteristics of storage solutions is likely to remain the same. Three technologies, viz., power to hydrogen, pumped hydro storage and vanadium redox flow batteries were identified as key technologies required for facilitating India's transition to a RE dominant system.

The policy actions for facilitating deployment of such technologies should adopt a three-pronged approach as shown in the figure below:

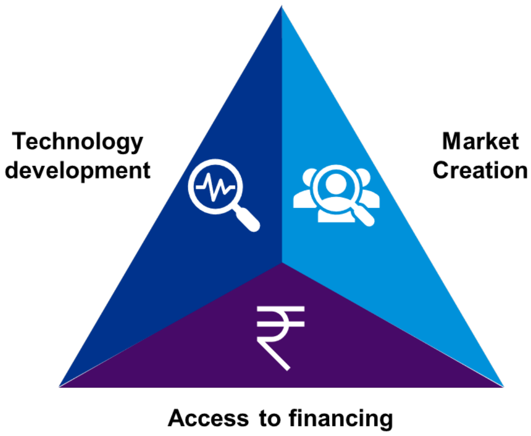


Figure 2: Framework for policy recommendations

The approach to policy making should involve investment in technology development while focussing on market creation by providing access to finance. This would result in a virtuous cycle for facilitating the scale-up of technologies. This framework was adapted to develop policy recommendations for the top three technologies, as shown in the table below.

Summary of policy recommendations by technology

Table 1: Policy recommendations by technology

Technology	Focus area	Policy recommendations
Power to hydrogen	Demand creation	• Mandates for blending of hydrogen in CNG fuel (H-CNG) to be used in heavy-duty vehicles • Pilot scale implementation of fuel cell electric vehicle buses
	Infrastructure development for hydrogen storage and transport	• R&D projects to design and implement cost-effective hydrogen storage technologies • Encourage co-operation between companies such as SECI, GAIL and NTPC for pilot scale electrolyser installations powered by RE
	Access to low cost financing	• Expand hydrogen corpus fund through contribution for PSUs producing hydrogen from fossil fuels • Facilitate access to low-cost financing from Power Finance Corporation (PFC) and Rural Electrification Corporation (REC) for commercial implementation of hydrogen infrastructure
Vanadium redox flow battery	Supply side interventions	• Incentivise domestic industries such as alumina refining to recover vanadium from process waste • Incentivise domestic mining companies to mine vanadium ores for domestic manufacture of electrolyte

	Demand side interventions	• Enable battery storage systems to stack revenue from multiple sources – including participation in wholesale markets • MNRE may mandate battery storage systems for large solar parks
Pumped hydro storage	Land acquisition and clearances	• Set up committee with representatives from Central and State Govt. to facilitate land acquisition • Identify potential sites for setting up pumped hydro storage plants as regional 'balancing asset' close to existing large RE generation sources
	Market enablement	• Pumped storage could also be treated as a transmission asset operated by the transmission companies • Ministry of Power and MNRE should standardise long-term contracts for multiple states to access a regional storage asset • MNRE could provide standardised bidding documents for inviting tenders for renewable energy projects combined with long-term storage facilities such as pumped hydro

Broadly, at a system level the following steps must be taken to ensure development of new technology options.

i. Develop roadmap for concurrent deployment of complementary storage solutions including pumped storage, power to hydrogen as well as batteries

A detailed plan for deployment of various storage options is required to guide investments in technology development as well as commercial deployment (in case of mature technologies). Given the current state of technical and commercial maturity of the chosen technologies, the timeline for commercial deployment is expected to be as shown in the figure below.

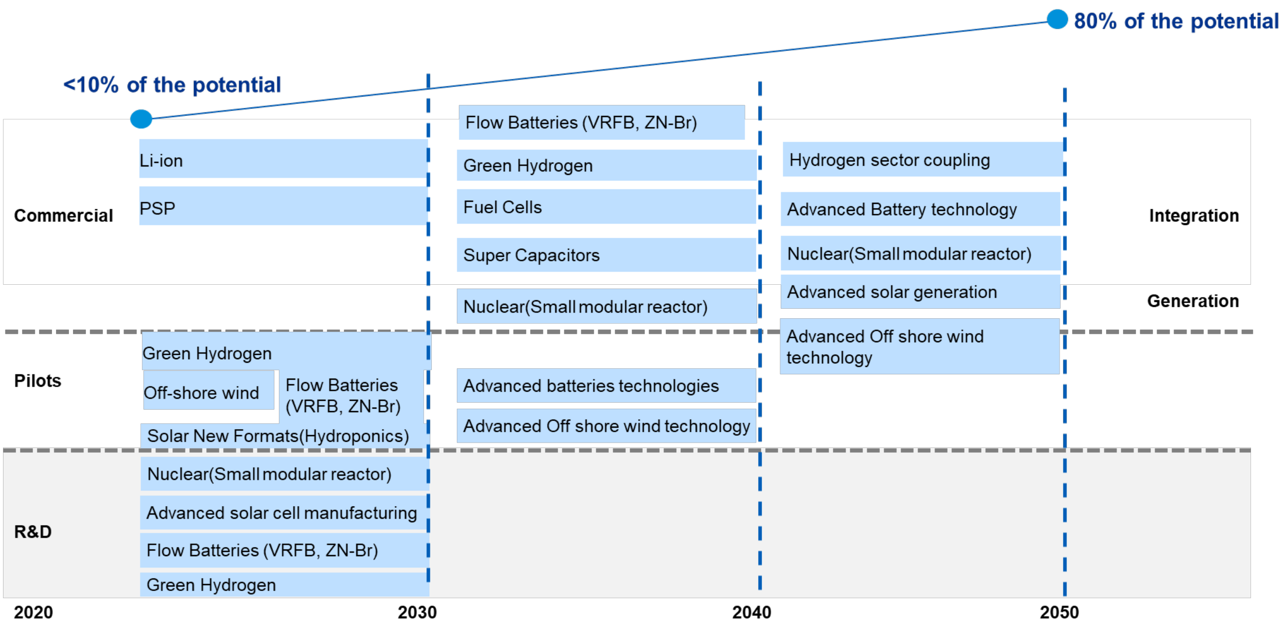


Figure 3: Potential pathway for technology deployment

While some of the mature technologies such as Li-ion and pumped hydro storage could be deployed commercially in the short term, majority of the other technologies are currently in the research phase. The need for detailed deployment roadmap for the key categories of shortlisted technologies are briefly described below.

- **Battery storage**: As a mature technology, Li-ion may address current storage needs, but may exacerbate India's energy-security woes. Battery storage solutions, which can be developed using domestic resources, such as vanadium redox flow batteries could be developed as a grid-scale storage alternative. This technology offers several advantages such as long life with negligible degradation of electrolytes and electrodes, operational safety, and flexible design.
- **Power to hydrogen**: For such new technologies, the roadmap should detail timeline and pathway for technology commercialisation. Currently, hydrogen is produced using fossil fuels, predominantly for use in fertilisers and oil refining industries. In India, FCEV is at the cusp of commercialisation, with vehicle models being launched and more expected in the short-term. In this context, the short-term focus should be on increasing the use of hydrogen as a transport fuel.
- **Pumped Hydro storage**: A re-assessment of the potential for pumped storage hydro power stations may be done and specific sites to future development of pumped storage projects need to be identified and pre-feasibility report of the same may be prepared. Capacity development targets for pumped storage may also be prescribed to bring in investment clarity to investors.

ii. Standard guidelines for procurement and market participation of storage solutions

Assets such as pumped hydro, grid scale battery storage system are highly capex intensive. Policy measures to distribute the capex investment among multiple stakeholders could incentivize installation of storage systems. These systems could also be treated as transmission assets and their costs could be recovered as part of transmission charges. In the case of pumped hydro, alternate ownership models may also be adopted with the Government taking over site evaluation and land acquisition process while private entities/PSUs are involved only in building the asset. This would help lowering the risk for private entities and thereby improving access to financing. New contracting options could be introduced, such as bundling RE generation with pumped storage asset to providing round the clock power supply.

Further, policies enabling participation of storage assets in wholesale power markets are required to ensure efficient utilization of these assets in increasing flexibility of the overall power system. Storage systems can provide various services to the grid depending on their response times. Systems with short response times (in seconds) such as batteries, could provide ancillary services such as frequency control and voltage control and could also be used as primary control reserves for balancing the grid. However, policies should detail compensation structures for such services provided by storage systems. Further, policies should permit storage system to be used for multiple purposes for maximizing their utilization and in turn improving economic viability of these assets.

iii. Mandate profitable CPSUs to invest certain percentage of turnover for R&D in technologies to be selected by Ministries/NITI Aayog

Central Public sector undertakings (CPSUs) could be used to fund research efforts into new technology options. The CPSUs could play an anchor role in streamlining efforts from academia and private sector into technology development. For example, in the case of hydrogen, the Ministry of Petroleum and Natural Gas set up such a fund with a corpus of Rs.100 crores with contribution from OIDB and oil PSUs to support research and development in Hydrogen as an auto fuel. This corpus was used to conduct research with collaboration from automakers and international agencies in using hydrogen as an auto fuel. As a result of the research efforts, Indian Oil R&D set up country's first hydrogen refueling station.

iv. Focus on demand creation for new age emerging technologies such as hydrogen

Sustained demand for new technologies/solutions can be better achieved through market creation than through subsidies. In the case of hydrogen, a phased approach could be adopted to transition diesel-powered heavy-duty vehicles into hydrogen powered FCEVs. As a first step, in cities with existing fleet of CNG buses, policy mandating blending of hydrogen in CNG fuel (H-CNG) should be introduced. Meanwhile, in the short term, investments should focus on R&D for lowering the cost of electrolyzers. Growth in demand for hydrogen as a fuel coupled with technology development would push the industry towards commercialization of power to hydrogen infrastructure.

2 Objectives

India has more than doubled its installed renewable energy capacity since 2014 and currently accounts for nearly 35% of total installed power generation capacity. India targets to increase this to about 40% by 2030 and the share of RE in total power generation capacity may increase to over 80% by 2050. Further, achieving these goals would also require decarbonization of sectors, such as transport, that are traditionally fuelled by fossil fuel sources. This change is nothing short of a paradigm shift and India's energy sector is transitioning to align with a RE dominant power system. New, disruptive technologies are necessary for powering this transition. This study evaluates such technology options that would be required to develop and sustain a RE dominant power system in the long term. The broad outcomes of this study are outlined in the schematic below.

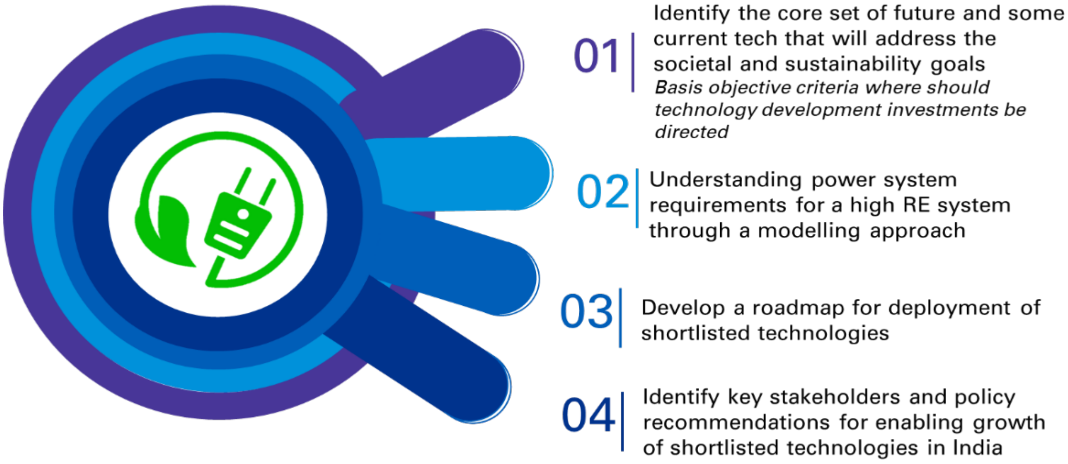


Figure 4: Objectives of the study

The objective of this study is to identify technologies that are key to achieve an integrated energy system by 2050 and develop policy recommendations for development and scale-up of these technologies. A list of 27 technologies across generation, storage and sector coupling were evaluated to identify top three technologies where future development investments should be focused upon. Additionally, the study takes a modelling approach to understand the criticality of storage technologies in a RE-dominant power system. The study also covers policy initiatives to foster research and drive investments towards the shortlisted technologies. Further, key stakeholders across relevant ministries and agencies were also mapped to these policy recommendations.

3 Context

Globally, CO_2 emissions are estimated to be about 34 Gt per annum at present. Carbon emissions should reduce by 45% by 2040 for meeting climate goals as per the Paris agreement and limiting the increase in temperature to less than 2degC above pre-industrial levels. In contrast, global gross GDP is expected to double, contributing to more carbon emissions over the next two decades. Therefore, there is an urgent need to reverse the direction of carbon accretion while ensuring economic growth.

India is currently the third largest in terms of greenhouse gas emissions, only behind China and the US. India's GDP increased by over 357% and GHG emissions increased by 180% from 1990-2014. India's GHG's emissions relative to GDP is twice the global average. This reflects the pressing need for reducing the emission intensity of GDP. As part of the intended Nationally Determined Contribution, India intends to achieve the following goals by 2030 (shown in figure below).

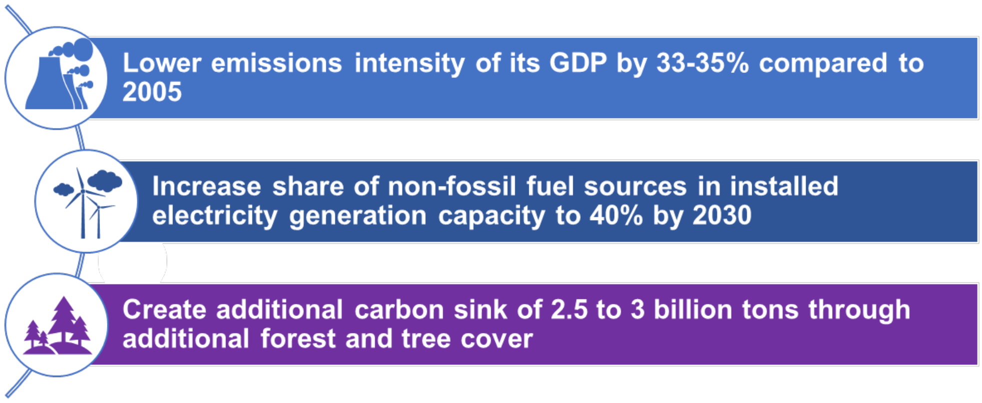
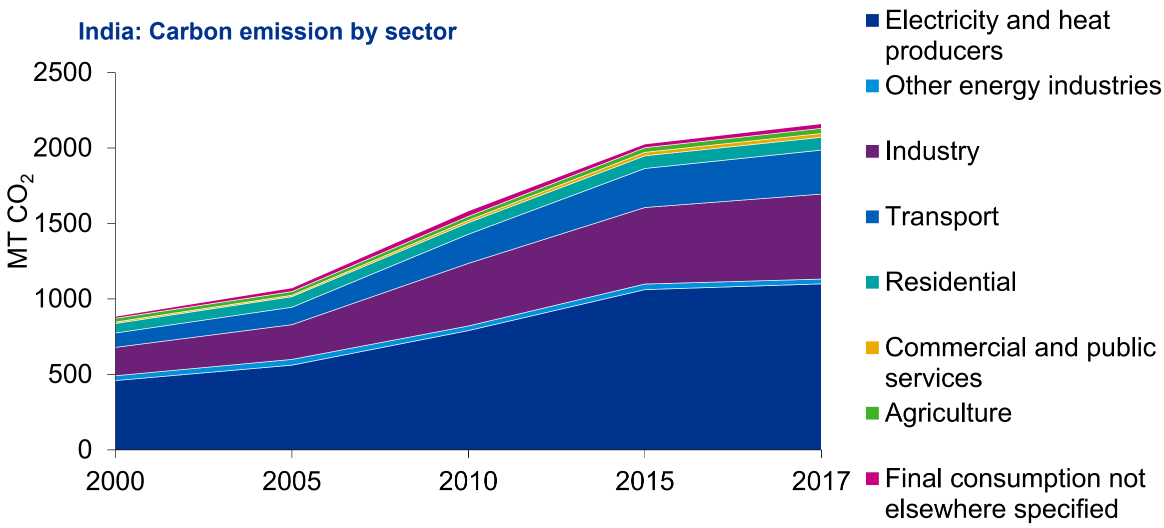


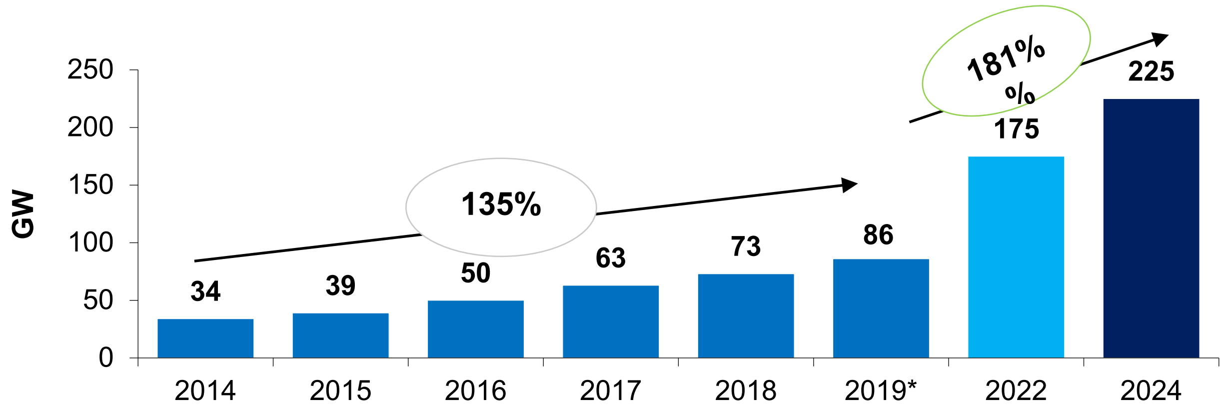
Figure 5: India's Intended Nationally Determined Contribution

India has made significant strides in these areas over the past decade. India's energy intensity reduced by 13% during the period 2012-2017 compared to the G20 average decline of 11% during the same period (TERI, 2018). The following chart shows carbon dioxide emissions by sector and the electricity sector is the largest contributor to carbon emissions. Since 2010, the growth rate of emissions in sector has been slowing owing to increasing RE generation.



Source: IEA

Figure 6: Carbon emission by sector in India



Source: KPMG Analysis

Figure 7: Yearly progress in installed RE capacity in India

In terms of renewable energy capacity additions, India has more than doubled its installed RE capacity since 2014. As of December 2019, India has about 86GW of installed renewable energy capacity and about 45GW of large hydro capacity. Renewables including large hydro currently contribute to about 35% total installed electricity generation capacity. The chart below shows yearly progress in installed RE capacity. Currently, India ranks 4th in the world in terms of installed RE capacity (excluding large hydro) and about USD 50 billion investments since 2014. India has a target of achieving 175GW of installed RE capacity by 2022 and further it to 225GW by 2024 (excluding large hydro).

Table 2: Installed RE capacity by technology in India as on Dec 2019

Technology	Capacity (GWp, as on Dec 2019)
Wind Power	37.5
Solar Power - Ground Mounted	31.4
Solar Power - Roof Top	2.3
Small Hydro Power	4.7
Biomass (Bagasse Cogeneration)	9.9
Waste to Power	0.1
Total	**85.9**

Source: MNRE

Sector coupling and storage for meeting flexibility requirements

With increase in economic development and population growth, India's primary energy demand is expected to increase by 156% from 2019 to 2040, accounting for 11% of global primary energy demand. Majority of this growth in energy demand is projected to be met by increase in power generation. Power generation is expected to grow by 207% and renewables are expected to account for 80% of generation capacity by 2040 (BP , 2019).

Despite the progress made over the last decade, several challenges persist in the Indian electricity sector. Several consumers face challenges regarding quality and reliability of power supply. Rural households continue to rely on biomass for cooking fuel. Sectors such as transportation, heating continue to rely heavily on imported fossil fuels. Such cross-sectoral challenges can be tackled by investments into technology that enable efficient integration of renewable energy into the power system and increase its prominence by displacing usage of fossil fuels across sector directly or through conversion/storage.

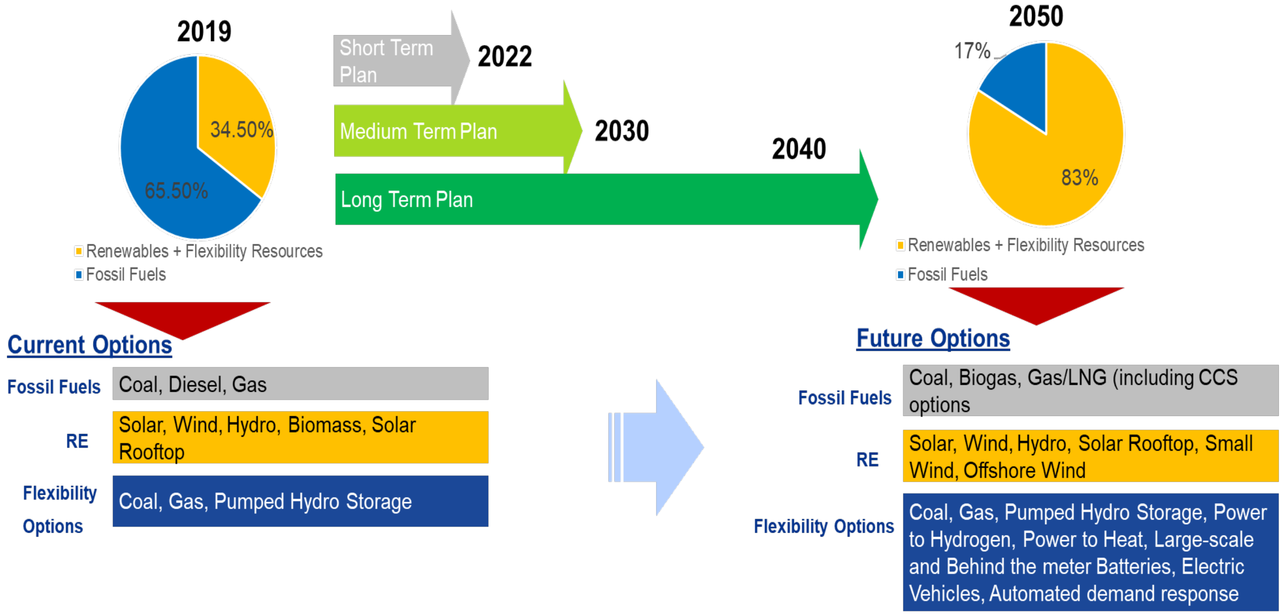


Figure 8: Role of technology options in a RE dominant power system

Integrating power generation from variable, intermittent sources such as solar and wind require in improving flexibility of the current power system. The above figure shows current and future technology options for integrating renewable energy. At present, most of the focus on renewable energy is in the power sector, while efforts in end-use sectors are concentrated around improving energy efficiency. On the other hand, in the future, renewable energy and flexibility resources would cater to baseload demand with fossil fuels providing balancing supply. A new approach towards policy making and investments are required that look at deployment of RE based generation assets while creating flexibility options to ensure its integration.

Storage technologies and sector coupling are two key solutions that are imperative for making the system flexible. Globally, storage technologies have been gaining traction for managing RE intermittency and adding flexibility to the power system. Some technologies, such as Li-ion batteries, have reached maturity at a global level. Over the past few years, several large-scale Li-ion battery installations have been implemented owing to significant decline in costs. With increasing generation from renewable energy sources, various types of storage solutions will be required for providing services such as ancillary services, balancing reserves, load shifting etc. In addition to batteries, solutions such as pumped hydro storage, compressed air storage and thermal storage technologies will be required to cater to various needs of a RE dominant power system.

Sector coupling, through electrification of sectors such as transport, building heating, is a key solution to achieve the twin goals of power system flexibility as well as reduction in carbon emissions. Additionally, growth in use of renewable energy in other end-use sectors would also help in reducing reliance on fossil fuel imports. Currently, the transportation sector is leading this transition towards electrification. Over the coming decades, technologies such as power to hydrogen and power to heat will be required for lowering fossil fuel consumption and in increasing flexibility of the power system.

In this context, 27 different technologies across generation, sector coupling, and storage were considered and top three technologies were shortlisted, considering the needs of India's power system. The following section briefly describes the broad set of technologies considered for this study.

4 List of technologies for evaluation

The long list of technologies that were evaluated as part of this study are listed in the table below.

Table 3: List of technologies evaluated

Category	Sub-category	Technology
Generation	Wind generation	Offshore Wind
	Nuclear generation	Small Modular reactors
		Sodium fast cooled nuclear reactor
		Miniature fusion reactor
		Molten salt nuclear reactor
		Gas cooled fast nuclear reactor
		Lead cooled fast reactor
		Very high temperature nuclear reactor
		Supercritical water-cooled reactors
Storage	Electrochemical storage	Zn-Br Hybrid Flow Battery
		Sodium sulphur battery
		Vanadium flow battery
		NaNiCl battery (ZEBRA)
		Li-ion battery
		Aqueous sulphur flow battery
		Metal-air battery
	Mechanical storage	Pumped hydro
		Gravity based energy storage
		Compressed air energy storage
		Flywheels
	Thermal storage	Liquid air energy storage (LAES)
		Electric thermal energy storage
		Standalone molten salt energy storage
		Salt hydrates heat storage
	Electrical storage	Graphene supercapacitors
Sector coupling	Sector coupling	Hydrogen fuel cells
		Power to hydrogen

Detailed description of these technologies is included in the annexure.

5 Evaluation process

The chosen technologies were evaluated based a variety to factors to understand their importance for a RE-dominant power system in an Indian context. A three-stage evaluation process was used to rate the technologies. The schematic below describes the overall evaluation process.

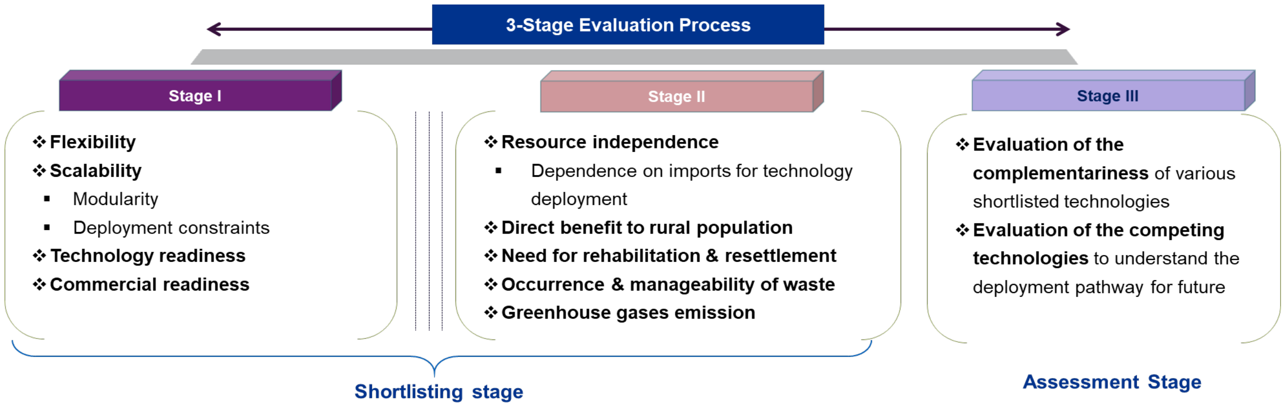


Figure 9: Technology evaluation process

The first two stages were used to shortlist the technologies based on inherent technical characteristics and the ability to be deployed in India. In the third stage, the shortlisted technologies were compared based on the utility each technology offers to the power system.

The detailed list of criteria used to shortlist technologies in Stage I and Stage II is described in the tables below.

Table 4: Stage I evaluation

Stage I Evaluation criteria	Description
Flexibility needs addressed	Flexibility need addressed in terms of duration and spectrum and whether a technology can be applied for fulfilling seconds-minutes, minutes-hours, hours-days flexibility needs. Each of the solutions proposed in the framework targets different flexibility needs ranging from the second and minute level (real-time) to the hour and day level for optimizing VRE generation. Flexibility needs of greater time horizon (weeks-months) are used in more seasonal contexts.
Modularity	This refers to the modularity which the technology can operate in in terms of size i.e; whether it can typically be set up at a kW scale, MW scale or GW scale or all three. The technology should have the ability to be installed in any required scale. Technology with higher modularity will be preferable since incremental demand needs can be easily managed without large-scale incremental investments.
Absence of deployment constraints	Certain technologies would have deployment constraints such as long gestation period, land acquisition related challenges or other specific technical requirement which could make deployment challenging in India

Technology readiness level	Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a given technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress. Technologies which are out of the lab stage and at a TRL of 4 and above have been considered.
Commercial readiness index	Commercial Readiness Index: Evaluation of stage of commercial maturity of a tech & scaling prospects within a global context. The technology should be at a certain level of commercial readiness to be deployed in the short or long term. The CRI is a framework developed by the Australian Renewable Energy Agency (ARENA) that aims to complement the Technology Readiness Levels (TRLs) by assessing the commercial maturity of technologies.

The shortlisted technologies after stage I evaluation were evaluated based on the following stage II criteria.

Table 5: Stage II evaluation

Stage-II evaluation criteria	Technology description
Resource independence	Reflects the ability of the technology to be deployed in India, without dependence on imports for its deployment.
Potential for manufacturing	Reflects the potential of the technology to be manufactured in India
Ability to improve inclusion	Reflects the technology's ability to benefit rural population
Absence of rehabilitation and resettlement requirements	Reflects the land requirement for deployment of the technology and the importance of the land surrounding typical project sites for providing livelihood resources and services to adjacent communities
Occurrence and manageability of waste	Reflects the level of waste generated from technology usage as well as the potential national capabilities to manage the disposal of the respective types of non-emission hazardous waste
Lack of global and local pollutants/emissions	Reflects the total quantum of local (Sox, NOx, PM 2.5) and global (GHG emissions) pollutants generated by the technology during its operation.

The shortlisted technologies after stage-I and II were assessed in stage-III based on their complementarity and competitiveness. For instance, storage technologies such as pumped hydro and Li-ion batteries provide complementary services. Li-ion batteries and most electrochemical battery storage systems typically offer short-duration storage to the tune of few hours. On the other hand, pumped hydro storage can be used for long duration/seasonal storage lasting for several days. Although both these technologies fall under the category of storage, their end-uses are different. Alternatively, technologies that provide similar solutions are viewed as competing with one other. Amongst these technologies, the ones best suited for implementation in an Indian context would be preferred.

6 Shortlisting of Relevant Technologies

6.1. Stage I evaluation

The technologies that were shortlisted after stage I evaluation are listed in the table below.

Table 6: Technologies shortlisted after stage I evaluation

Category	Technology
Storage	Hydrogen fuel cells
Storage	Graphene supercapacitors
Storage	Li-ion battery
Sector coupling	Power to hydrogen
Generation	Offshore wind
Storage	Zn-Br hybrid flow battery
Storage	NaNiCl battery
Storage	Vanadium flow battery
Storage	Pumped hydro
Storage	Aqueous sulphur flow battery
Storage	Sodium sulphur battery

Storage technologies dominated the first order shortlist compared to generation technologies. Most of these technologies rank high on factors such as flexibility, technology readiness level and absence of deployment constraints. Generation technologies, besides offshore wind, were dominated by nuclear reactors. Majority of these nuclear reactors have a low technology and commercial readiness level and/or have deployment constraints in terms of access to fuel. Hence, these technologies did not make the cut. A brief rationale for each of the selected technologies is listed in the table below. Detailed scoring for all technologies that were studied are included as part of the annexure.

Table 7: Evaluation rationale for shortlisted technologies in Stage I

Technology	Flexibility offered	Modularity	Absence of deployment constraints	Technology readiness	Commercial readiness
Hydrogen fuel cells	▪ Response time in seconds ▪ Can operate for longer than 24 hours	Fuel cells range in output from <1kW to hundreds of MW	Low gestation period, no specific land requirements	Commercially available technology; TRL:9	Competitive market with several applications; CRI: 4
Graphene supercapacitors	Response time is very fast (<ms), however duration is also very low (~minutes).	Capacitors can be found at the ~10 kW scale to the MW scale.	Low gestation period, no specific land requirements	TRL: 9	Multiple projects using this tech, globally currently CRI: 3

Li-ion battery	Response time is within milliseconds and discharge duration can reach 8 hours.	Applications vary from 0.001–100MW	Low gestation period, no specific land requirements	TRL: 9	Commercial grid scale projects exist. CRI: 6
Power to hydrogen	Response time is typically in seconds	Electrolyzers range from ~kW to >100MW scale	Requires water for electrolysis; no other constraints	TRL: 9	CRI: 5-6
Offshore wind	Offshore wind can provide frequency response services (i.e. fast response with duration of < 1 hour)	Offshore Wind Farms operate in the scale of several MW (e.g. a single turbine) up to GW	Should be deployed on the ocean	TRL: 8-9	CRI: 5-6 for fixed foundation; LCOE of floating foundation is still higher than fixed
Zn-Br hybrid flow battery	Response time in milliseconds and duration up to 10h	Projects could range from 200kW up to 5 MW	Low gestation period, no specific land requirements	TRL: 9	CRI: 3; Used for small scale applications
NaNiCl battery	Response time is expected to be in minutes with storage duration for several hours	Power ratings range from kW to MW scale.	Low gestation period, no specific land requirements	TRL: 9	Several grid scale projects are in operation. CRI: 3
Vanadium flow battery	Response time in sub seconds with response duration set to hours	Projects exist in the range of 0.03MW up to 100 MW	Low gestation period, no specific land requirements	TRL: 8; Tech has been commercialized with trials under	CRI:3, Commercial projects are underway
Pumped hydro	Response time of the system is system specific and ranges from seconds to minutes	Low modularity since the tech is only implemented at large scale	High gestation period and can be deployed only in certain terrain	Mature technology TRL: 9	Wide commercial applications. CRL: 5
Aqueous sulphur flow battery	Response time expected to be within seconds	Expected to be like Li-ion/flow batteries	Low gestation period, no specific land requirements	Tech still at lab scale. TRL: 4	CRI: 1
Sodium sulphur battery	Response time in sub-second range, with about 6 hours of storage duration	Projects range from 200kW-50MW	Only 1 supplier globally, creating supply constraint	TRL: 8	The technology has been demonstrated at over 190 sites, primarily in Japan, including some commercial trials. CRI: 3

6.2. Stage-II evaluation

All technologies shortlisted after stage-I were evaluated based on another set of criteria that primarily reflect the ability of the technology to be deployed in India. Three technologies were eliminated from the top eleven shortlisted after stage-I evaluation. The top eight technologies are listed in the table below.

Table 8: Technologies shortlisted after Stage II evaluation

Category	Technology
Sector coupling	Power to hydrogen (Hydrogen fuel cells and Alkaline electrolyzers)
Storage	Zn-Br hybrid flow batteries
Generation	Offshore wind
Storage	Vanadium flow battery
Storage	Pumped hydro
Storage	Li-ion battery
Storage	NaNiCl battery
Storage	Graphene supercapacitors

Most of these technologies rank high on its ability to be manufactured in India and thereby improve India's energy security. Despite ranking high on technical and commercial maturity, storage technology such as NaS batteries were not included in this shortlist owing to challenges in domestic manufacturing. The rationale for ranking these technologies is listed in the table below. Detailed scoring for other technologies is included in the annexure.

Table 9: Evaluation rationale for shortlisted technologies in Stage II

Technology	Resource independence	Ability to increase rural inclusion	Absence of resettlement & rehabilitation requirement	Occurrence & manageability of waste	Lack of global and local pollutants
Power to hydrogen	Hydrogen can be produced in India	Does not directly impact rural inclusion as fuel cells & electrolyzers are centralized installations	No R&R required	Waste management measures for fuel cells have been developed	Operating emissions are low if hydrogen is produced from water
Zn-Br hybrid flow batteries	Resources available in India	Battery sizes vary from 200kW-5MW currently. Can be deployed near a rural area to generate employment	No R&R required	Electrolyte can be recycled & used for a new battery	No operating emissions
Offshore wind	Wind turbines are manufactured locally	As a centralized source of power generation, it does not directly benefit rural segment	No R&R required	Guidelines are in place for turbine disposal	No operating emissions

Vanadium flow battery	India has Vanadium reserves	Can be deployed near a rural area to generate employment	No R&R required	Electrolyte can be recycled	No operating emissions
Pumped hydro	Components can be sourced locally	Centralized storage asset, does not impact rural inclusion	Requires significant R&R	Limited waste generation	No operating emissions
Li-ion battery	Rely primarily on imports for Lithium	Can be used to improve energy access in rural areas	No R&R required	Li electrolyte is a toxic waste requiring proper handling	No operating emissions
NaNiCl battery	Raw materials are available	Primarily developed for EVs; impact on rural inclusion may be limited	No R&R required	Electrolyte can be recycled	No operating emissions
Graphene supercapacitors	Can be manufactured locally	Short duration storage typically used for ancillary services. Does not increase rural inclusion	No R&R required	Recycling these supercapacitors requires specialised technology, which is currently not available in India.	No operating emissions

6.3. Stage III – Assessment of complementary and competing technologies

Among the shortlisted technologies after the two-step process, certain storage technologies offer complementary services while certain others compete for providing similar services. Energy storage technologies can serve a variety of applications based on their response time and duration of storage. Storage technologies classified based on their duration of storage is shown in the chart below.

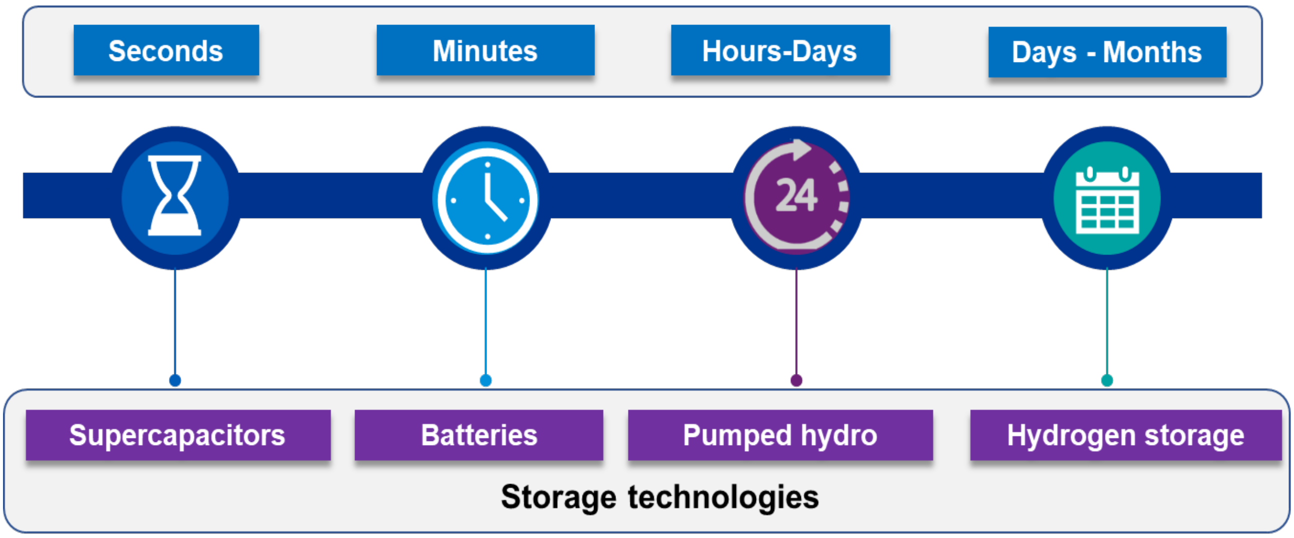


Figure 10: Applications of various storage technologies

Supercapacitors: Supercapacitors can respond in sub-second timeframes, making it suitable for providing primary frequency response to the grid. During frequency deviations away from utility set points, supercapacitors rapidly inject power to balance the grid for a short duration before other reserves can be activated. Supercapacitors may support other longer duration storage systems such as batteries in a RE-dominant power system.

Batteries: Battery energy storage systems can store energy for up to a few hours and have quick response time (in the tune of seconds). Batteries can be used for frequency/voltage response as well as store surplus generation from RE plants for use during peak demand periods.

Pumped hydro: Pumped hydro storage is the most commonly deployed storage system today. Pumped hydro would be critical to providing a round the clock (RTC) renewable energy generation solution.

Hydrogen storage: Surplus generation from RE can be used to run electrolyzers to generate hydrogen through electrolysis of water. Hydrogen, so generated, can also be used as a fuel for transport and in industries.

A summary of various complementary energy storage technologies is shown in the table below.

Table 10: Comparison between complementary energy storage technologies

Parameters	Supercapacitors	Batteries	Pumped Hydro Storage	Hydrogen Storage
Duration of Storage	Seconds-Minutes	Minutes - Hours	Hours - days	Hours- months
Response time	Milliseconds	Seconds	Minutes	Seconds
Modularity	Medium (kW-MW scale)	High	Limited on account of minimum critical size	High (Depending on the method of electrolysis)
Technology Readiness Level	Medium	Low - Medium	High	Low
Commercial Readiness Level	Medium	Medium - High	High	Low
Entry and exit costs	Low entry barriers, low lock-in period and relative ease of exit	Low entry barriers, reversible decision with a low lock-in period and relative ease of exit	High entry barriers, irreversible decision with a high lock-in period, high exit costs	High entry barriers, high lock in period and high exit costs
Operating Life	~5-10 years	~10 Years	~35-40 Years	~20 years
Gestation period	Low	Low	High	High
Outage rate	Low	Low	High due to moving parts	Unknown due to limited implementation

Given that these classes of storage systems address different issues that is expected to arise in a RE dominant power system, it is imperative that such assets are deployed concurrently. Later sections in the study focus on policy recommendations to enable deployment of three key complementary storage technologies - batteries, pumped hydro and power to hydrogen.

Comparison between various battery storage technologies

Battery storage systems have a typical storage capacity ranging from a few kWh to hundreds of MWhs and can be deployed by power generators and distribution/transmission operators. Deployment of battery storage technology has seen traction across various geographies, with the US and European countries, being the global leaders.

Different type of battery storage systems can be used for providing services to the grid. Therefore, it is important to identify the right application, for different battery storage types. The table below compares properties and applications of the various battery storage systems that were shortlisted in the previous two stages.

Table 11: Comparison of battery technologies

	Li-Ion battery	Zn-Br flow battery	Vanadium redox flow battery	NaNiCl battery
Modularity	High (0.001–100MW)	Medium (200kW - 5 MW)	High (0.03MW up to 100 MW+)	Medium (kW-MW scale)
Duration of storage	Mins - Hours	Mins - Hours	Mins - Hours	Hours
Technological Readiness Level	High	High	High	High
Commercial Readiness Level	High	Medium (Testing at utility scale in Australia)	Low (Yet to be contracted at a commercial scale)	High
Response time	<seconds	<seconds	<seconds	<seconds
Energy Density (Wh/kg)	85-200	50-80	10-30	100-120 Wh/kg
Lifetime (years)	5 - 15	5 - 20	5 - 20	<15 years
Depth of discharge	80-95%	100%	100%	>85%
Efficiency (%)	85-94	60-80	65-75	80-95%
Self-Discharge, %/day	0.2-0.3	~0.08-0.33	~0 – 0.05	0.1-0.2
Safety Concerns	Safety concerns due to over-heating & toxicity	Safety concerns on toxicity of bromine	Safety concerns over toxicity of electrolyte	Battery has to be heated to 270-350degC
Expected Cost Reduction	60% ($62/kWh by 2030)	66% ($102/kWh by 2030)	66% ($306/kWh by 2030)	60% ($200/kWh by 2030)
Applications	Mobile phone battery – grid scale storage	Mini grid-grid scale	Mini grid-grid scale	EVs, mini-grid, transmission grids

Some battery storage technologies, especially Lithium-ion (Li-ion) batteries, have reached the maturity stage and have seen significant growth in the past few years. The significant decline in costs for various battery storage technologies has been the key driver, for deployment of large-scale battery storage systems. However, India would have to rely on imports owing lack of domestic lithium reserves. From an energy security standpoint, sodium batteries offer an attractive alternative. Raw materials required for this battery are available in abundance and the technology has also been commercially implemented. However, the technology has been mostly tested in mobile applications and its use in stationary storage is being studied. Further, such high temperature cells, typically face issues pertaining to ageing mechanism due to corrosion of materials used in the storage system. Also, the battery requires energy for maintaining high temperature required for the cell operations and have lower cycle life than Li-ion batteries.

Flow batteries, on the other hand, show negligible degradation due to cycling. These batteries use liquid electrolytes stored in tanks whose size determines the energy storage capacity. These batteries can be operated at ambient temperatures, offer deep discharge rates, long cycle life and do not have any operational safety issues. In case of vanadium redox flow battery, the electrolyte can be recycled thereby reducing the toxicity concerns. Vanadium redox flow battery has been used in large scale applications around the world. India has vanadium reserves and industries such as alumina refineries also employ processes to recover vanadium. Although the raw materials required for zinc bromide flow batteries are cheaper than vanadium redox, zinc bromide batteries offer lower cycle lifetime, higher self-discharge rates and are susceptible to corrosion issues. Therefore, vanadium redox flow battery system represents a better grid scale battery storage alternative for India.

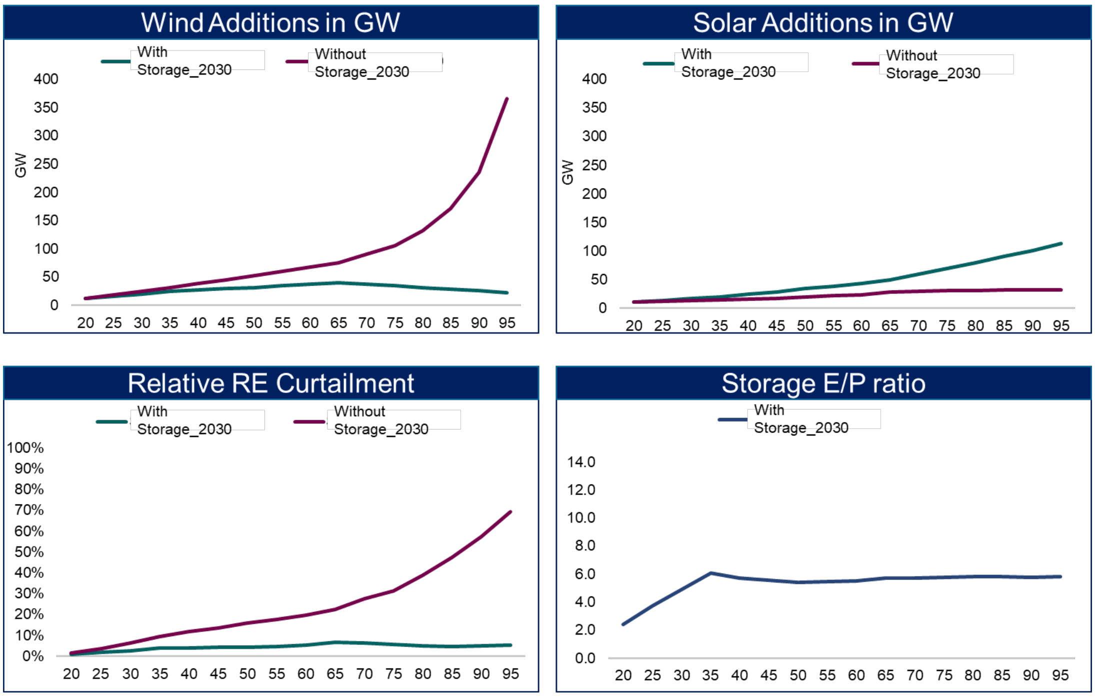
7 Modelling approach to understand power system requirements

Role of storage in providing power system resilience

India has been witnessing a steady increase in extreme weather events and this trend is expected to continue given the steady increase in global temperatures. India is the fourth among 10 most affected countries in terms of human impact of natural disasters. India has incurred a total economic cost of Rs.4.38 lakh crores due to natural disasters since 1990. Electricity infrastructure, a key building block for economic development, is susceptible to damage due to extreme weather events. In May 2019, cyclone Fani in Odisha caused severe damage to electricity infrastructure disrupting power supply to over 25 lakh families for more than five days (Outlook, 2019). Over the coming decade, storage assets would be required to improve reliability and resilience of the power system by serving as a backup, especially to manage such extreme weather events. In the longer term, with increase in renewable energy generation, grid scale storage assets would play a critical role.

Role of storage in RE dominant power system

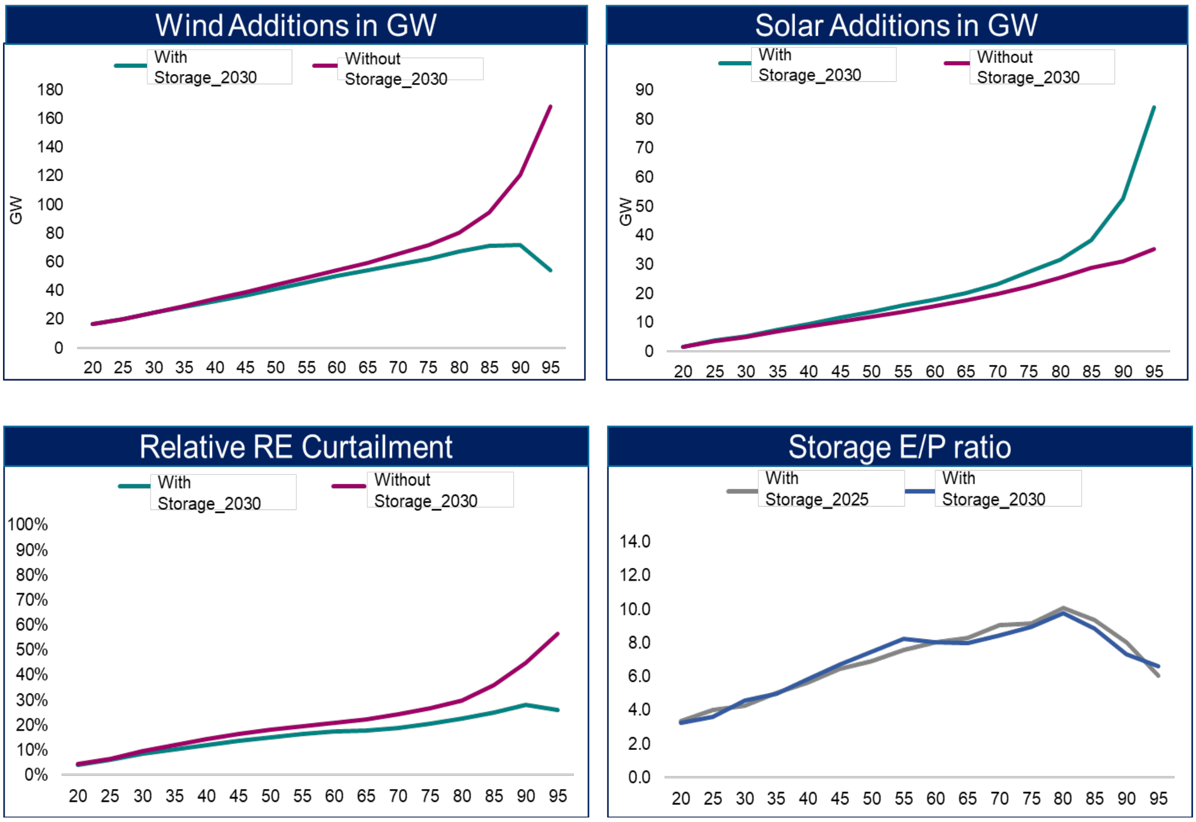
Storage solutions play a non-negotiable role for efficient integration of generation from renewable energy sources. Absence of storage assets would result in RE curtailments leading to poor utilization of renewable energy assets. The nature of storage would vary based on characteristics of the power system under consideration. The following charts show the impact of storage on RE curtailment and RE capacity additions required at a certain percentage of RE integration in two Indian states with varying load characteristics. The first state (state – 1) has significant variations in its intraday load curve, while state-2 has a relatively flat load curve.



Source: KPMG Analysis

Figure 11: Impact of storage on RE integration for a state with significant intra-day variations in load curve (State -1)

shows that, at high levels of RE integration, a storage system offering about 4-6 hours of storage would significantly reduce RE curtailment and result in a steep reduction in need for wind installations. In the absence of storage, RE curtailment could reach 70% at very high levels of RE penetration.



Source: KPMG Analysis

Figure 12: Impact of storage on RE integration for a state with flat load curve (State-2)

Figure 11 shows the impact of storage for a state with relatively flat load curve. In such states, storage would help in reducing RE curtailment by about 40%. Storage systems would support significantly higher solar generation to reach high levels (>90%) of RE penetration while requiring lower levels of wind additions. In this state, the nature of storage system varies at with increase in RE penetration. The duration of storage required increases with RE penetration until a certain level (~80%), beyond which systems with storage capacity for a shorter duration are better suited.

The key takeaways from this analysis are as follows:

i. Storage system have a significant impact on reducing curtailment and optimizing the amount of capacity addition required to achieve high levels of RE penetration

ii. Nature of storage system required varies based on load profile in the region. Some cases require long duration storage systems such as pumped storage while some require shorter duration storage systems such as batteries.

iii. Given the variation in need, complementary storage technologies should be looked at concurrently

Pumped hydro storage and Vanadium redox flow batteries were prioritized among other storage technologies based on their ability to add flexibility, ability to be implemented in India and complementarities offered to meet varied system needs. The following sections briefly describe the current scenario and policy recommendations to stimulate investments towards development of the shortlisted technologies.

Key takeaways from the evaluation process

Based on the evaluation process, the following three technologies emerged as the best suited solutions (among the initial consideration set) for a RE-dominated power system in India:

1. Power to Hydrogen and hydrogen fuel cells
2. Pumped hydro storage
3. Vanadium redox flow batteries

Investments into research and enabling polices should be formulated to ensure large scale deployment of these technologies

8 Power to hydrogen: Technology overview & Policy recommendations

Technology overview

Hydrogen can be produced via several processes such as Steam Methane Reforming (SMR), coal gasification, renewable liquid reforming (using ethanol) and electrolysis of water. This section focuses on production of hydrogen through electrolysis using electricity generated from renewable energy sources.

When electricity produced from renewable energy sources is used, the hydrogen becomes a carrier of renewable energy, complementary to electricity. There are two common types of electrolyzers: Alkaline electrolyzer and proton exchange membrane electrolyzer while Solid Oxide Electrolyser (SOE), a third type of electrolyzer, is currently in the research phase. This electrolyzer holds the promise for better efficiency compared the other two but has a significantly higher capex.

Table 12: Brief description of electrolysers

	Alkaline	PEM	SOEC
Development status	Commercial	Commercial medium and small-scale applications (<300kW)	Under research & development phase
Brief description	▪ Transport of hydroxide ion through electrolyte ▪ Hydrogen generated at cathode ▪ A liquid alkaline solution of sodium or potassium hydroxide used as electrolyte	▪ Water reacts at the anode to form oxygen and hydrogen ions (protons) ▪ Electrons flow through an external circuit and hydrogen ions selectively move across the PEM to the cathode ▪ Electrolyte is a solid speciality plastic material	• Water at the cathode combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions • The oxygen ions pass through the solid ceramic membrane and react at the anode to form oxygen gas and generate electrons for the external circuit • A solid ceramic material used as the electrolyte
Operating temperature	100-150 °C	70-90 °C	700-800 °C
Capex	US$500-1400/kWe	US$1100-1800/kWe	US$2800-5600/kWe
Electrical efficiency	63-70%	56-60%	74-81%

Electrolysers can help integrate VRE into power systems, as their electricity consumption can be adjusted to follow wind and solar PV power generation, where hydrogen becomes a source of storage for renewable electricity. Thus, they offer a flexible load and can also provide grid balancing services (upwards and downwards frequency regulation) while operating at optimal capacity to meet demand for hydrogen from industry and the transport sector or for gas grid injection. The various end use sectors of hydrogen are shown in the chart below. Given the variety of end-uses, hydrogen could effectively result in sector coupling or electrification of sectors.

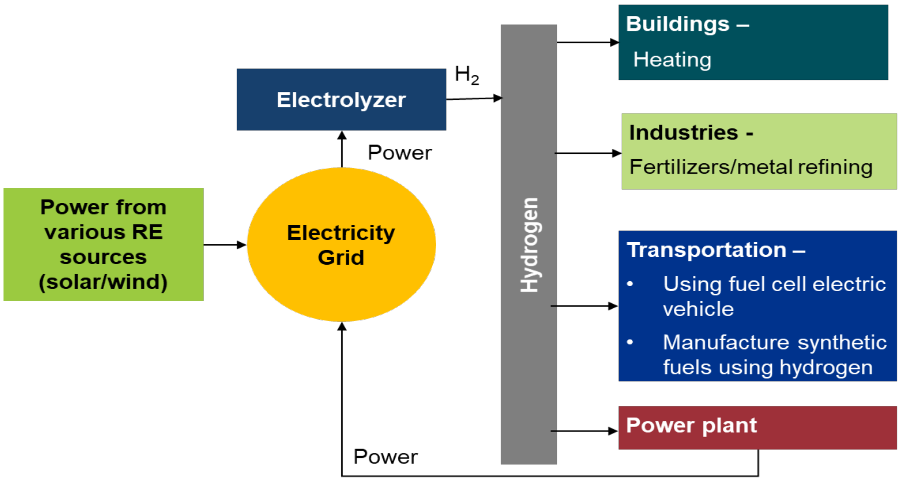
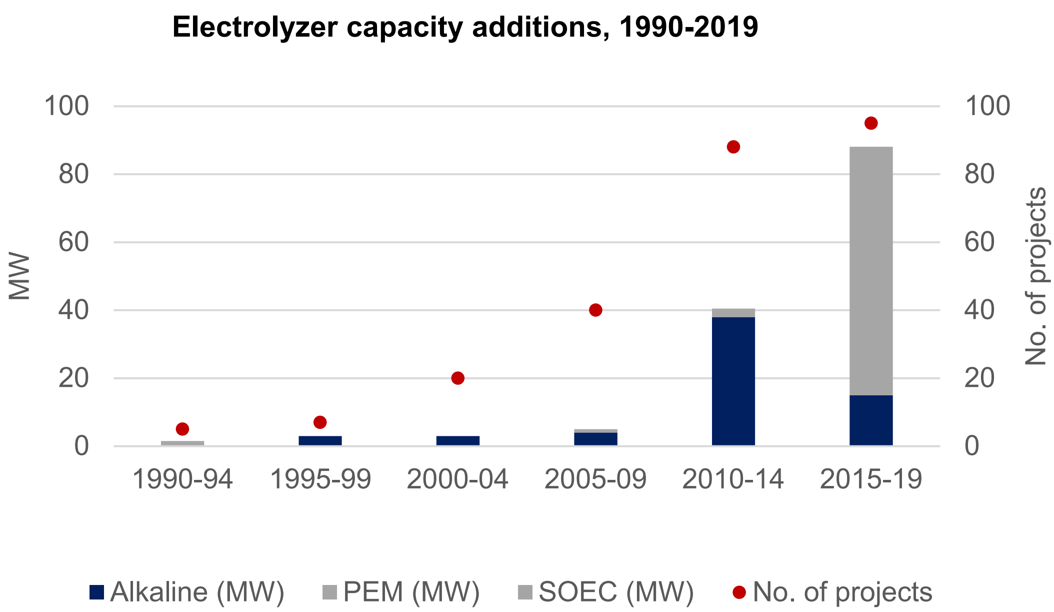


Figure 13: Power to Hydrogen

Current status of deployment and cost curves

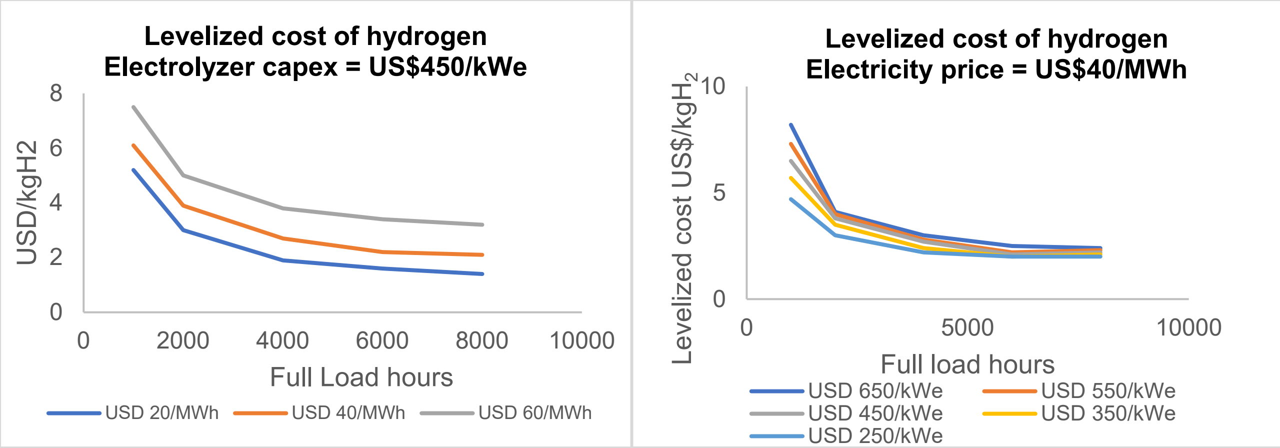
Currently, electrolysis accounts for less than 0.1% of dedicated hydrogen production globally and about 2% of total global hydrogen is created as by-product of chlor-alkali electrolysis in the production of chlorine and caustic soda. The following charts show development of electrolyser capacity additions across the globe from 1990-2019. Electrolyser installations in the last two years are valued at USD 20 - 30 million per year. Majority of the projects installed thus far have been enabled by significant support from Government. The average size of these projects increased from under 0.4MW in 2010-14 to nearly 0.9MW in 2015-19. This is still below the size required to enter to accelerated scale up.



Source: (IEA, 2019); Capacity additions are cumulated over the specified 5-year periods

Figure 14: Electrolyzer capacity additions

The levelized cost of hydrogen from electrolysis depends on the capex cost of electrolyzer, cost of electricity and other operational parameters such as load factors. These costs vary by region and hence, there is significant regional variation in hydrogen production costs. The chart below compares levelized cost of hydrogen production for different electrolyzer costs and electricity costs.



Source: (IEA, 2019)

Figure 15: Levelized cost of hydrogen

The electrolyser stack accounts for about 50-60% of the total capex cost. In certain cases, depending on the type of electrolyser and quality of water, desalination/water purification units maybe required further increasing the costs. Currently, the cost of hydrogen produced using electrolysis is expected to be nearly twice as that from fossil fuel sources.

Technical innovation along with large scale manufacturing will lead to reduction in capital cost of electrolyzers. As the load hours increase, the cost of electricity will have a greater impact than capex cost on the levelized cost of hydrogen. Therefore, low cost electricity available to operate an electrolyzer at high utilization is necessary for reducing levelized cost of hydrogen.

Hydrogen fuel cells

Hydrogen produced using electrolysis can be converted back to electricity using fuel cells. Fuel cells use hydrogen as fuel to generate electricity and water as by products. These have found application in transport as fuel cell powered electric vehicles. The global fuel cell electric vehicle (FCEV) stock reached 11200 units at the end of 2018, with sales of around 4000 in that year (80% more than in 2017). The US and China are leading the race to increasing use of FCEVs. China produced about 2000 FCEV powered small trucks in 2018 and has set a target of 1 million FCEVs by 2030. Similarly, the US also targets achieving 1 million FCEVs from its current level of 5900 such vehicles. A robust hydrogen storage and transport network is a pre-requisite for successful deployment of FCEVs. With increase in hydrogen production capacity and robust distribution infrastructure, the cost of hydrogen fuel would decline thereby making FCEVs an attractive alternative to fossil fuel powered vehicles. Policy initiatives are required to stimulate investments towards research and development of electrolyzer and fuel cell systems and for building hydrogen infrastructure in India.

Policy recommendations

The areas of focus for policies to develop an ecosystem around power to hydrogen technologies can be classified as shown in figure below.

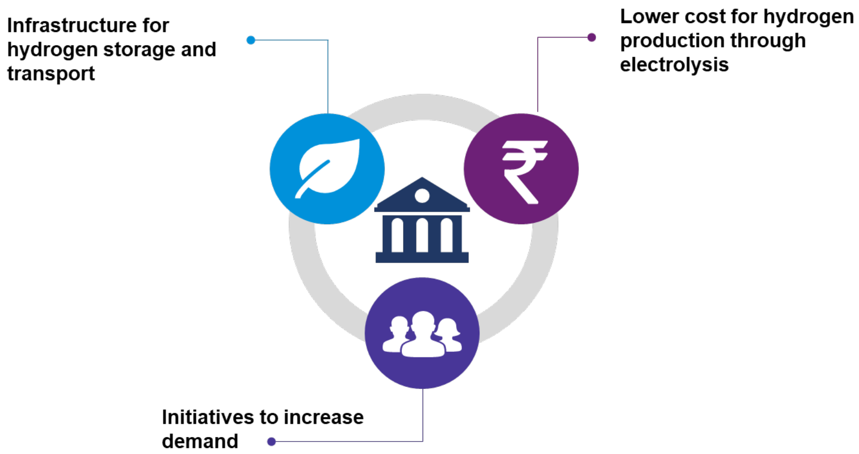


Figure 16: Policy measures for power to hydrogen

1. Lower cost of hydrogen through electrolysis

Access to preferential financing/low cost debt for investments in production of green hydrogen

The high capex cost necessitates incentives in the form of access to low cost debt at least in the initial years of scale-up. Countries such as China, Australia, US and the EU have facilitated low cost debt to investment in electrolysis processes through financial institutions or a clean energy fund. New financing models, led by industry and private investment agencies, are also emerging in this domain. For instance, Hyundai Motor has entered into a MoU with Beijing Tsinghua R&D institute to create a Hydrogen Energy Fund. The fund aims to attract investment from venture capital firms for driving investments in the overall hydrogen ecosystem.

Additionally, low cost debt could be made available to large renewable energy projects with electrolyser for producing hydrogen. With an electrolyser, the risk of curtailment significantly reduces for large RE projects, justifying a lower cost of debt. The hydrogen so produced could be used in varied applications such as fuel for transport or as a feedstock in industry. Further, this would offer an additional benefit of incentivising electrolyser set up closer to RE projects thereby minimising transmission losses. Alternatively, such RE plants could use hydrogen purely for the purpose of storing excess electricity generated and convert the hydrogen back to electricity for use during periods of low to no generation.

2. Initiatives to increase demand

Policy interventions are required to create a market for green hydrogen to pull investments into the sector. The nature of interventions would vary based on the end-use applications, and the current level of technology maturity in each application. The two key applications of power to hydrogen systems can be broadly classified into the following categories:

i. Fuel cell electric vehicles

Hydrogen fuel cell trucks and buses can replace the conventional diesel-powered vehicles without compromising on mileage. The long range provided by hydrogen powered fuel cell vehicle would be ideally suited for heavy duty vehicles such as buses and trucks. On the other hand, battery electric vehicles could be a cheaper alternative for light duty vehicles such as passenger cars. In India, FCEV is at the cusp of commercialization, with vehicle models being launched and more expected in the short-term. Tata Motors in partnership with Indian Oil recently launched Starbus, a bus powered by hydrogen fuel cells. At this juncture, policy push is required to create demand for large scale deployment of these vehicles.

A phased approach could be adopted to transition diesel-powered heavy-duty vehicles into hydrogen powered FCEVs. As a first step, in cities with existing fleet of CNG buses, policy mandating blending of hydrogen in CNG fuel (H-CNG) should be introduced. A trial of H-CNG buses is expected to begin with buses in Delhi in a few months (early 2020). This would help in reducing emissions as well cutting down consumption of imported fossil fuels. Meanwhile, ongoing research on lowering the cost of hydrogen should be continued for enabling the complete transition to FCEVs. Also, in the first phase, gas grid should be expanded in cities with no/limited access to the grid currently. As the cost of hydrogen reduces and consistent supply of green hydrogen is ensured, policy mandate could be widened to transition all diesel fuelled vehicles into hydrogen powered FCEVs.

In the long term, as cost of hydrogen fuel cell vehicles reduce, it could penetrate the light vehicles segment as well. Lower cost compared to battery electric vehicles and a reliable hydrogen supply and distribution infrastructure are critical factors for FCEVs to succeed in the light vehicles segment.

ii. Green hydrogen in industries

Reinstate Hydrogen Corpus fund to invest in renewable power to hydrogen demonstration projects

Globally, major end-uses of hydrogen in industries include – oil refining (33%), ammonia production (27%), methanol production (11%) and steel production (3%). India produces over 3 million metric tonnes of hydrogen primarily for captive use in its oil refining and ammonia industries. A part of this hydrogen production could be produced from electrolysers powered by renewable energy. The estimated capex requirement for producing 5% of the hydrogen from renewable energy is shown in table below.

Table 13: Estimated capex requirement for power to hydrogen

Parameter	Units	Value
Hydrogen production	tonnes/year	3,000,000[3]
	tonnes/day	8,219
Electricity required for hydrogen	kWh/kgH_2	51[4]
% of hydrogen production through electrolysis (assumed)	%	5%
MWh required	MWh	20,959
Average CUF (assumed)	%	18%
Required capacity	MW	13.3
Solar project capex	Rs cr/MW	4[5]
Estimated capex requirement for solar PV	**Rs. Cr**	**53**
Capex for alkaline electrolyzer	USD/kWe	900[6]
Estimated capex requirement for alkaline electrolyzer	**Rs. Cr**	**83.7**
Total estimated capex requirement for power to hydrogen	**Rs. Cr**	**137**

[3] https://www.energy.gov/sites/prod/files/2014/03/f10/cng_h2_workshop_11_das.pdf
[4] http://www.fsec.ucf.edu/en/consumer/hydrogen/basics/production-solar.htm
[5] Based on data from recent SECI tenders
[6] The future of hydrogen, IEA, June 2019

The estimated capex requirement would vary based on the specific implementation scenario. Even smaller scale, demonstration facilities can be implemented within oil refineries and ammonia plants operated by public sector undertaking companies. A corpus fund could be created with contribution from various oil refining companies as well as fertilizers producing companies to fund such demonstration projects. In FY10, the Ministry of Petroleum and Natural Gas set up such a fund with a corpus of Rs.100 crores to support research and development in Hydrogen which could substitute natural gas as a transport fuel. This corpus was used to conduct research with collaboration from automakers and international agencies in using hydrogen as an auto fuel. As a result of the research efforts, Indian Oil R&D set up country's first hydrogen refuelling station. A similar fund with an expanded corpus could be instituted for demonstration plants. Since demonstration plants are capex intensive, the corpus should be expanded through participation from PSUs under the Ministry of Chemicals and Fertilizers.

3. Infrastructure for hydrogen storage and transport

For the near-term, standards should be set for blending in hydrogen with CNG in the national gas grid. These standards should include purity, permissible pressure/volume at the point of injection. Currently, IOCL is commissioning a H-CNG plant based on compact reforming process which uses natural gas as feedstock. To enable transition to green hydrogen, cost-effective technology for injecting hydrogen into the gas grid should be studied.

Research on more efficient fuel cells such as solid oxide fuel cells, polymer electrolyte membrane should be continued. MNRE's 2016 report on Hydrogen energy and fuel cells suggests that lack of low-cost hydrogen supply and infrastructure challenges are two key challenges slowing down R&D of fuel cells. The ministry could identify certain institutes for development of fuel cell research and facilitate a hydrogen off-take agreement for research purposes from a nearby industry. Currently, various institutes are funding research programs into fuel cell development across the country. This could be restructured by MNRE with each institute focusing on a specific aspect within the broader hydrogen economy.

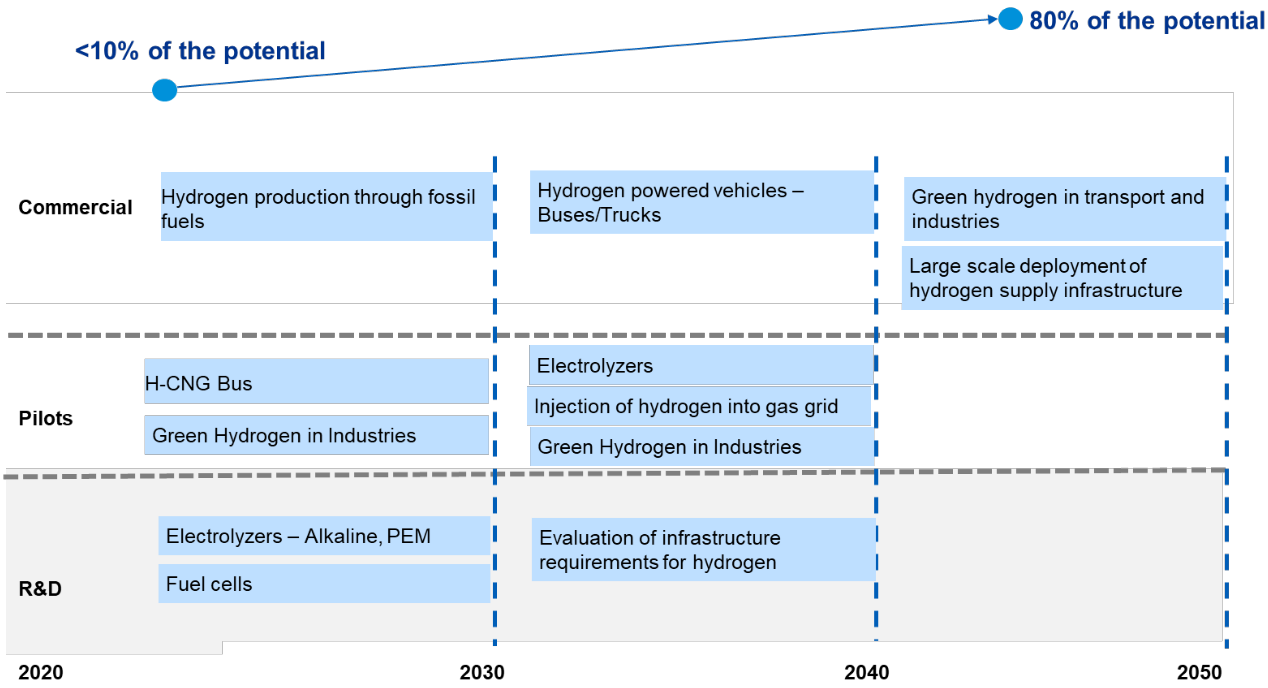
The MNRE should fund R&D projects to design and implement various hydrogen storage technologies such as - high pressure gas cylinders, solid state storage materials. Partnerships/technology transfer co-operations with international agencies could fast track the R&D phase.

Regulations pertaining to storage, handling and transportation of CNG should be amended to include H-CNG in the near term. Based on R&D outcomes, regulations regarding safe storage and transport of hydrogen should be established in the long term. Globally, standards have been set for electrolyzer technologies and fuel cells. India could also adopt similar standards and codes issued by International Organization for Standards.

Implementation roadmap for power to hydrogen in India

The pathway for India to adopt power to hydrogen solutions in the long term would begin with increasing use of hydrogen in sectors such as transport. In the short term, India should focus on blending hydrogen with CNG to power buses or other commercial vehicles. This would help in increasing the acceptance of hydrogen as a fuel. Given that electrolyzer technology has not attained maturity in India, the initial years may require increased use of fossil fuels (such as natural gas) to produce hydrogen. Meanwhile, investment should be directed towards research efforts for developing electrolyzers and improving fuel cell efficiencies and thereby reducing costs.

In the mid-term, focus should be on commercializing FCEVs deployment and pilot scale implementation of electrolyzers powered by electricity from renewable energy sources. Over the mid-term, hydrogen produced through electrolyzers should reach cost-competitiveness with hydrogen produced from fossil fuels. This would automatically incentivize uptake of green hydrogen in industries. Alternatively, industries could be pushed towards green hydrogen through policy measures/incentives for a limited period. But, cost-competitiveness of green hydrogen would be necessary to sustain this demand. During these years, plans for infrastructure development for supply of hydrogen should be put in place.



Source: KPMG Analysis

Figure 17: Technology deployment pathway for hydrogen

Finally, over the long term, deployment of green hydrogen and sector coupling should be commercialized across the country. Implementation of country wide deployment of hydrogen infrastructure should also be rolled out.

9 Pumped Hydro Storage: Technology overview & Policy recommendations

Technology overview

Pumped hydro storage installations store electricity by pumping water to an upper reservoir and discharge electricity as the water moves down through a turbine. The technology can be implemented either as open loop or closed loop systems. Open loop projects are connected to a free-flowing water source. On the other hand, closed loop systems consist of two reservoirs at different levels, isolated from a free-flowing water source. This technology has been in use since the 20th century, and currently represents over 90% of installed energy storage capacity across the globe. Over 130GW of pumped hydro projects have been installed worldwide with typical size of each installation ranging from 100MW to few GW.

Globally, pumped hydro storage projects currently account for over 90% of the total storage capacity in the world. In India, the Central Electricity Authority has identified potential pumped hydro storage sites with a potential capacity of over 96GW. Currently only about 4.8GW operational and another 6GW in the pipeline. Some of the projects currently under development in India are as shown in the table below.

Table 14: Pumped Hydro Storage projects under development in India

Project	State	Technology	Size (MW)	Total cost (INR crore)	Cost per MW (INR crore/ MW)	Notes
Turga	West Bengal	Closed loop	1000	6,922	6.9	• Pre-construction activity started from Oct 2016 • Loan agreement for 1st tranche loan signed between Govt of India and JICA
Tehri	Uttarakhand	Open loop	1000	2,979	3.0	Under construction
Malshej Ghat	Maharashtra	Open loop	700	2,695	3.8	• Includes IDC & financing cost of Rs.298.86 cr (May 2010 price level) • Excludes transmission cost of Rs. 130.65 cr (May 2010 price level) • Current status: DPR prepared, awaiting commitment from state Govt.
Pinnapuram	Andhra Pradesh	Closed loop	1200	5,468	4.6	Under construction
Sardar Sarovar	Gujarat	Open loop	1200	16,000	13.3	Construction of tail reservoir

Sharavathy	Karnataka	Closed loop	2000	4,862	2.4	• Low cost due to use of existing upper and lower reservoirs • Current status DPR under preparation

The capex cost of pumped hydro storage assets varies based on site specific characteristics in addition to other costs such as financing, EPC and power evacuation costs.

Considering that only ~11% of the potential has been explored, pumped hydro storage represents a significant opportunity as a storage solution. Despite several policy initiatives over the last 15 years, installation of pumped hydro systems has remained sluggish. Pumped hydro projects, like hydro power projects, also face inordinate delays due to delays in approval processes, social issues related to resettlement and rehabilitation and interstate water disputes among others. However, given its utility as a long duration storage facility, pumped hydro projects are required for efficient integration of variable renewable energy generation sources such as solar/wind.

Policy recommendations for Pumped Hydro Storage

Given that the technology is already mature, policy push for pumped hydro storage projects should be geared towards removing bottlenecks in implementation and enhancing revenue generation opportunities for these assets. Policy recommendations can be broadly categorized into two major focus areas as shown in the figure below.

Figure 18: Policy recommendations for pumped hydro storage

Land acquisition and clearances

'Hydro power committees' to facilitate land acquisition

Several hydro projects have run into delays and cost overruns primarily due to delays in land acquisition required for the plants. There is a need for improving efficiency of the land acquisition and the overall project approval process. Improving co-ordination between the various governmental agencies is essential for speeding up this process. A dedicated committee should be instituted to ensure co-ordination between various state and central governmental agencies. This committee could be formed by the Ministry of New and Renewable Energy (MNRE) with representatives from each state nodal agencies and state irrigation and energy departments. Representation from state government is critical to facilitate obtaining necessary approvals in the state.

Site evaluation to establish pumped hydro storage assets as a regional balancing asset

Pumped hydro storage systems can be planned as a regional storage asset used for balancing the regional grid. The regional transmission operator could own and operate the asset with contribution from states in the region. This would help in sharing the burden of investment. As a first step, balancing requirements should be assessed at the regional level and site evaluation should be undertaken for setting up a regional pumped hydro storage asset. Active involvement of state governments in the process could lead to preparation of bankable DPRs and provide access to better financing.

China has taken this approach and has mandated at least one pumped storage in each province of the country. Currently, China leads the world in terms of pumped hydro installations with 29GW of installed capacity. The Chinese Government takes a role in assessment of provincial/regional requirements and site selection. The provincial governments are also involved in facilitating the project as well as contributing to financing. Asia's largest pumped hydro project, located in China, was developed using this regional approach. The project has a capacity of 1800MW and received partial funding from Shanghai, Zhejiang, Jiangsu and Anhui provinces (PwC, 2018).

Market enablement

Policies push is required to create a market for pumped hydro storage projects with an objective to reduce the risk of investment and increase sources of revenue generation. The recommendations are briefly described below:

Table 15: Recommendations for market creation for pumped hydro

Policy measure	Description
Operating pumped hydro storage as a transmission asset	Pumped storage could also be treated as a transmission asset operated by the SLDC/RLDC. The costs of pumped hydro could be added to transmission charges thereby ensuring returns on the project and making it an attractive investment.
Standardize contracts to bundle RE with pumped storage assets	MNRE could provide guidelines for inviting tenders for renewable energy projects along with long duration storage facilities such as pumped hydro. Such assets could be operated as a flexible, schedulable generation asset for providing round the clock power supply.
Ministry of Power and MNRE should standardize long term contracts for multiple states to access a regional storage asset	A special purpose vehicle could be formed to operate the storage asset as per the system operators' direction to provide services both to the system operator as well as the wholesale market

Implementation roadmap

Policy measures to facilitate deployment of pumped storage systems should be taken up in the short term. Given its technical maturity, policy measure to resolve implementation challenges would facilitate faster deployment of these storage assets. Pumped hydro could be deployed in the short term to cater to long duration storage required for increasing RE integration in the grid.

10 Vanadium redox flow battery: Technology overview & Policy Recommendations

Technology overview

Among flow battery technologies, the vanadium redox flow battery represents a relatively mature technology. In this system, the electrolyte is stored in tanks and is pumped through a cell stack during charge discharge cycle. Power of flow batteries can be adjusted by varying the number of cells stacked while energy can be adjusted by varying the electrolyte volume. These batteries typically do not degrade over charge-discharge cycles and in case of vanadium flow batteries, the electrolyte can also be recycled. Vanadium redox batteries have a cycle life of over 10,000 cycles and life of the asset is expected to be over 15 years (US Dept of Energy, 2019). Key advantages of flow batteries are summarized in the chart below. Additionally, given Vanadium is locally available in India, these batteries could be manufactured locally.

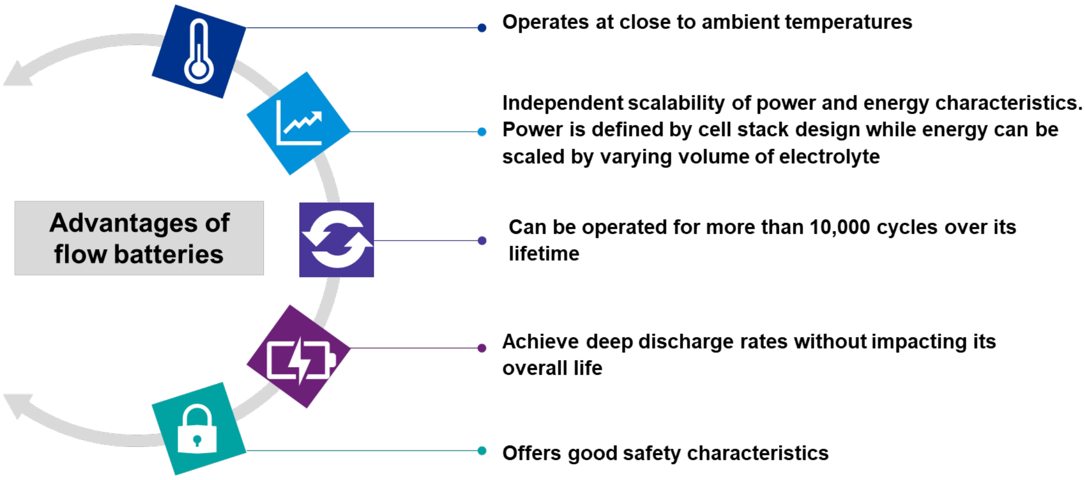
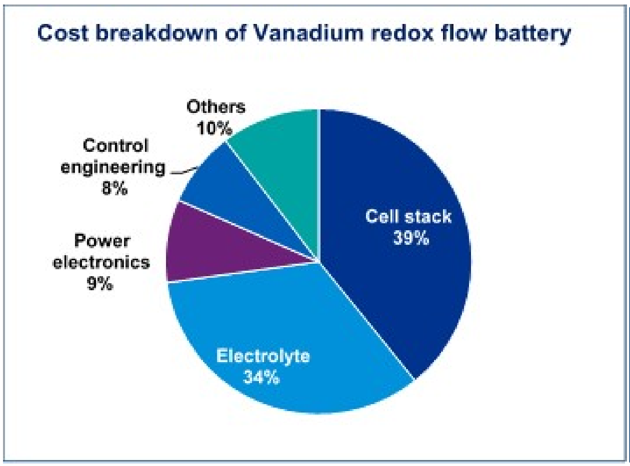


Figure 19: Advantages of flow batteries

The capital cost of flow battery is dominated by the cost of cell stack containing electrolytes and membrane and pumps required to move electrolyte between tanks. The split among various cost components is as shown in chart below. The chart below also displays projected capital costs for such projects in 2025.



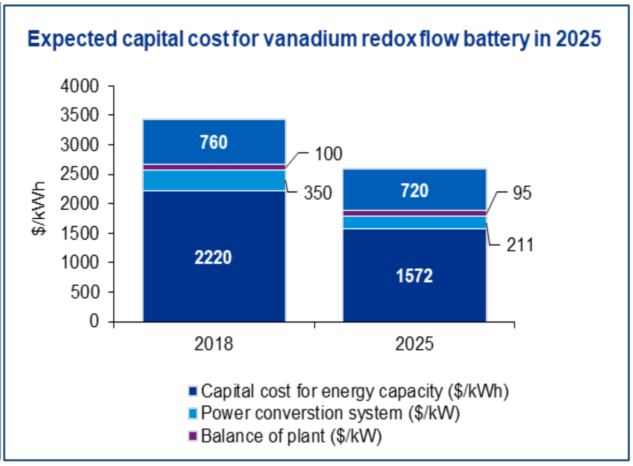


Figure 20: Cost breakdown for vanadium redox flow battery

Source: IRENA, Cost of Energy Storage

Policy recommendations for Vanadium Redox flow battery

The key focus of short-term policy measures should be towards reducing the overall cost of vanadium redox flow batteries. Demand side policy interventions are also required to facilitate market development for storage services. Broadly, policy interventions can be categorized into two as shown in the figure below.

Figure 21: Policy recommendations for Vanadium Redox Flow Battery

Policies to facilitate supply of vanadium ore

Efforts in the short-term should be focussed on research efforts for cost-effective domestic manufacture of electrolyte. India has about 25 million tonnes of known vanadium reserves and it can also be recovered from in steel manufacturing and alumina refining. Incentivizing domestic production of vanadium is the first step in enabling domestic manufacture of electrolyte for VRFB batteries.

Incentivize domestic industries such as alumina refineries, petcoke gasification to recover vanadium from process waste

Currently, vanadium is primarily used in steel manufacturing for the purpose of hardening steel. The ore is mined largely in China, Russia and South Africa for manufacture of specialty steel alloys. The smelter slag produced as part of this process can be used to recover vanadium. Vanadium can also be recovered from other industries such as alumina refining and petcoke gasification. This recovery process has been implemented at an alumina refining plant in India.

Electrolyte produced using vanadium recovered from such sources are expected to improve cost competitiveness of the battery storage system. Globally, research efforts made towards using lower grade/recycled vanadium indicate that it could result in significant cost reduction (by up to 40%) compared to mining vanadium for electrolyte manufacture. Therefore, policies that provide an economic incentive for domestic industries to recover vanadium are required to kickstart electrolyte manufacturing in the country. Standardizing offtake agreements for recovered vanadium for the purpose of electrolyte manufacture could be a potential economic incentive for domestic industries to engage in vanadium recovery. Access to local, low cost raw material is a key pre-requisite for creating a domestic battery manufacturing ecosystem. This would also help India take a step towards energy security in the long run compared to expending significant resources in import of Lithium for manufacture of Li-ion batteries.

MNRE and Ministry of Mines could work together to increase mining of Vanadium ores and facilitate domestic manufacture of electrolyte

Alternatively, MNRE could work with the Ministry of Mines to identify existing vanadium reserves in India and implement measures to increase vanadium mining. Although this would prove to be more expensive, it would help in the initial stages of setting up domestic manufacturing of electrolyte in the short to medium term. Meanwhile, research efforts could focus on developing advanced processes using low purity vanadium recovered from industrial processes.

In addition to these initiatives, measures should be taken to encourage research partnerships between academia and industry for deployment of demonstration projects for flow batteries in the short term.

Policy measures to create an enabling market for storage assets

Revenue generation

Battery storage systems can be used for a variety of services such as energy shifting, ancillary services and offer additional benefits such as reduction in RE curtailment and T&D investment upgrade deferral. The compensation for such benefits would drive investments in setting up battery storage systems. Enabling participation of battery storage systems in wholesale markets would be critical to ensure optimal utilization of the asset. On the other hand, clear tariff/compensation structures should also be defined for such services provided by battery storage systems. The tariff determination process for these services should consider all the benefits offered by battery storage systems. Key benefits that should be accounted for are shown in the table below:

Table 16: Benefits of battery storage systems

Key Benefits	Description
Avoided cost of maintaining reserves	Battery storage system can be used in lieu of operating reserves (spinning and non-spinning reserves), which are typically fossil fuel-based power plants
Avoided cost of greenhouse gas emissions	Using battery storage systems in lieu of fossil fuel reserves would result in lower greenhouse gas emissions
Avoided cost of RE curtailment	Battery storage systems could absorb surplus RE generation, thereby reducing revenue losses for RE generators
Energy security	Battery storage helps substitute power generation from imported fossil fuels with lower cost renewable energy generation

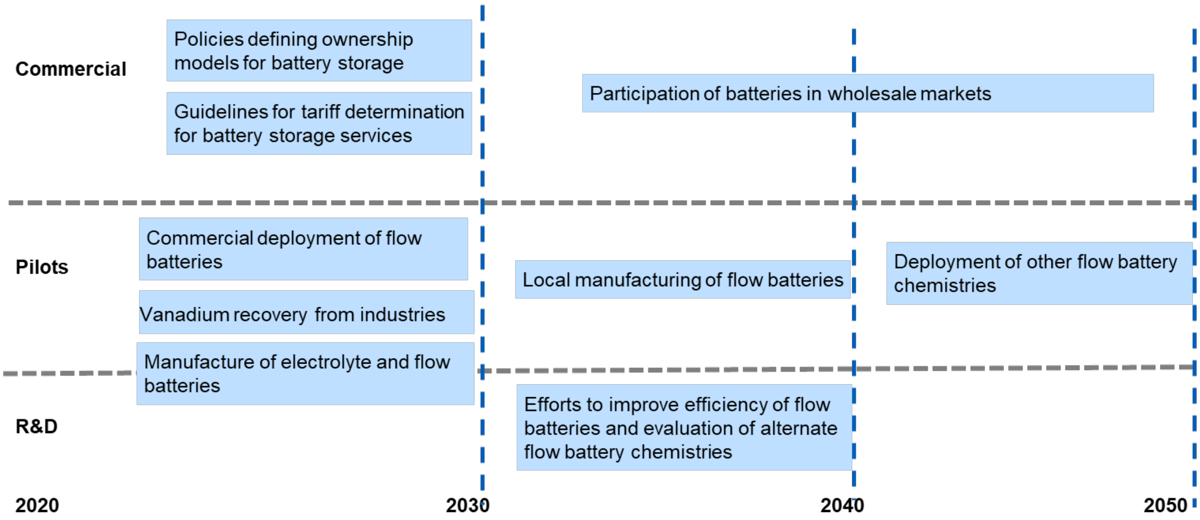
Further, tariff mechanisms such as time of use pricing could help in improving pricing transparency. For instance, under a time of use price regime, a battery system could earn higher revenues by supplying power during hours of peak demand when RE generation is low.

Ownership structure

Regulations defining ownership and operational structures are required to enable optimal utilization of these assets. Battery storage assets should be allowed to offer multiple services for participation in wholesale markets. Battery storage systems can be owned and operated by the transmission operator and use the assets for participation in markets for providing grid support services. Alternate ownership models can also be explored which allows for multiple users to share the asset and hence reduce capex burden on any one stakeholder. The largest battery storage project implemented in Hornsdale Power Reserve (HPR), Australia, provides services to the developer Neoen, Tesla and the Government of South Australia. The battery has a 129MWh capacity with a maximum discharge of 100MW. The battery is contracted to operate in different ways to meet needs of the grid – three hours of output at 30MW is reserved for load shifting and 70MW is reserved for maintaining grid stability. Renewable energy developers could invest in battery storage systems and provide 'battery storage as a service' to grid operators. Such innovative models enabling multiple players to make optimal use of the battery storage system can be standardized.

Implementation roadmap

The following chart describes the potential technology deployment pathway for flow batteries. In the short to medium term, the focus should be on developing polices enabling market participation of storage systems. Research efforts, in the short term, should be focused towards developing electrolyte manufacturing process. Over the medium term, demonstration and pilot scale installations could be deployed. Learnings from pilot scale implementations should be used for scaling up to commercial installations in the long term.



Source: KPMG Analysis

Figure 22: Implementation roadmap for vanadium redox battery storage technology

11 Conclusion

India's progress towards limiting greenhouse gas emissions would lead to significant increase in renewable energy penetration in India's overall energy markets. Storage systems and sector coupling technologies would play a critical role in enabling India's transition to a RE dominant future. Within these domains, focus should be on technologies that offer complementary benefits to the power system and can be indigenously manufactured. Current challenges lie in enabling indigenous manufacturing and deepening power markets to create revenue sources for these technologies. Therefore, policy push should focus on creating an ecosystem that facilitates end to end deployment of new technologies. Three technologies viz., power to hydrogen, pumped hydro storage and vanadium redox flow batteries were identified as key to facilitate large scale integration of renewable energy into the grid. The recommendations at an overall system level for developing new technologies are summarized below.

1. Develop roadmap for concurrent deployment of complementary storage solutions including pumped storage, power to hydrogen as well as batteries
2. Standard guidelines for procurement and market participation of storage solutions
3. Mandate profitable Central Public Sector Undertaking (CPSUs) companies to invest certain percentage of turnover for R&D – technologies to be selected by Ministries.
4. Focus on demand and infrastructure creation support for new age emerging technologies such as hydrogen.

12 Annexures

Detailed Technology description

1. **Offshore wind:** Wind farms constructed on the ocean to harvest wind energy to generate electricity. Windspeeds in the ocean are faster than on land and tend to be more consistent resulting in better CUFs compared to land based wind storage plants. Offshore wind plants typically use a fixed foundation structure where the structure is embedded directly to the sea floor. This is the preferred solution for waters up to 50m deep and has been installed in the coastlines of UK, Denmark etc. Floating structures are preferred for locations with greater depth. Such structures are commonly used in the oil and gas industry where the floating infrastructure is anchored in water up to 4,000m deep. India aims to install at least 5,000MW of offshore wind energy by 2022 and 30,000MW by 2030. The Government's initial estimates suggest that the coastline in Gujarat has offshore wind potential of 106,000MW and Tamil Nadu's coastline has a potential of 60,000MW.
2. **Nuclear reactors:** The study includes nuclear generation technologies as it is a non-fossil fuel, base load generation source. Nuclear reactors would complement the variable generation sources such as solar/wind in a RE-dominant system. The following types of nuclear reactors were evaluated in this study
    a. **Small modular reactors:** Modular nuclear reactors which can provide flexibility to the power system when combined with variable RE. These reactors typically have capacities under 300MWe. These units typically have short construction times and require relatively lesser land for construction
    b. **Sodium fast cooled nuclear reactors:** A Sodium-cooled Fast Reactor (SFR) is a type of nuclear reactor that utilizes molten sodium metal as the reactor coolant, and it allows for high power density with a low coolant volume. An SFR can achieve a core power density of around 300 MW/m3 compared to 100 MW/m3 offered by pressurized water reactors.
    c. **Miniature fusion reactors:** Nuclear fusion reactors aim to exploit the energy released by fusing deuterium and tritium atoms. Fusion has been demonstrated in tokamak reactors, but a commercial reactor capable of safely sustaining a fusion reaction has been under development for decades.
    d. **Molten salt nuclear reactor:** These are a class of nuclear fission reactors in which the primary nuclear reactor coolant and/or the fuel is a molten salt mixture. The fuel such as thorium/uranium is dissolved in the coolant as fuel salt which can be easily reprocessed online. Given its abundant thorium deposits, India is examining designs for an Indian Molten Salt Breeder Reactor.
    e. **Gas cooled fast nuclear reactor**: This system is a high-temperature, helium-cooled, fast-spectrum reactor supporting a closed fuel cycle. The coolant is chemically inert, neutronically transparent, and remains in the gas phase. The reactor would use uranium carbide (UC) fuel with 6.5% average enrichment and has a 30-year refueling cycle. The design has one loop and utilizes two shutdown systems, control drums, and separate shutdown rods. It would use the PCS for normal decay heat removal from the reactor vessel with the passive direct auxiliary cooling system (DRACS). The fuel would be a vented porous uranium carbide clad in silicon carbide.
    f. **Lead cooled fast reactor**: The lead (or lead-bismuth) fast reactor uses a molten metal coolant with excellent heat transfer properties. The high boiling point of lead allows operation at near-atmospheric pressures. Neither lead nor lead-bismuth react chemically with water. However, lead corrodes metallic structures, and significant research must be undertaken in qualifying alloys and in chemistry control. Lead also has a high-melting point that puts the system at risk of freezing if the temperature is not actively maintained. The lead-bismuth eutectic melts at a lower temperature, but neutron capture by the bismuth results in radioactive polonium production, a significant radiological hazard.
    g. **Very high temperature nuclear reactor**: The very-high-temperature reactor (VHTR), or high-temperature gas-cooled reactor (HTGR), is a Generation IV reactor concept that uses a graphite-

moderated nuclear reactor with a once-through uranium fuel cycle. The VHTR is a type of high-temperature reactor (HTR) that can conceptually have an outlet temperature of 1000 °C. The reactor core can be either a "prismatic block" or a "pebble-bed" core. The high temperatures enable applications such as process heat or hydrogen production via the thermochemical sulfur–iodine cycle.

h. **Super critical water-cooled reactor**: Superheated coolant emerging from the core can be sent directly to a turbine without separation and drying and returned to the core as feedwater. Furthermore, reactor coolant pumps are not required (just feedwater pumps), and thus the primary loop is much simpler compared to a BWR. The SCWR operates at higher temperatures than today's LWRs and can potentially achieve higher efficiencies (about 45%). Water at a supercritical temperature (about 510°C) and pressure (25 MPa) served as both coolant and moderator. All designs under investigation by GIF member countries are at the pre-conceptual stage and face challenges. The SCWR uses water as a coolant and thus can draw upon 50 years of operational experience and research infrastructure with conventional LWRs and fossil plants that use supercritical water-based power conversion.

3. Storage technologies

Electrochemical storage

a. **Zn-Br flow battery:** A ZBFB cell consists of two compartments separated typically by a microporous membrane. Electrodes at each side of the cell (one at the zinc side; one at the bromine side) are made of carbon plastic composites, given that metal electrodes would suffer corrosion in the presence of a bromine-rich environment. Two external tanks pump the aqueous electrolyte towards the cell stacks during charging and discharging.

b. **NaS battery:** NaS batteries utilise liquid active materials and a solid ceramic electrolyte made of beta-aluminium (β"-Al2O3 sodium-ion-conducting membrane). They are called high-temperature batteries, because high temperatures are required to keep the active materials in a liquid state. Typically, the anode material in this structure is molten sodium (Na) and,thus, the battery in this family of storage systems is known as the "sodium beta" or "sodium beta alumina" battery. In the case of the sodium sulphur (NaS) battery, the cathode for the most common configurations is molten sulphur.

c. **NaNiCl battery:** The sodium nickel chloride battery (often referred to as ZEBRA), has a similar operating principle to NaS storage. It has a good energy density and low maintenance. It uses BASE as the primary ceramic electrolyte, and a secondary electrolyte (NaAlCl4) is used to aid sodium ion transfer. The NaNiCl battery is mostly being investigated as suitable for battery-electric vehicles, but there is also research into a high energy version for grid scale storage.

d. **Vanadium flow battery:** The vanadium redox flow battery (VRFB) storage mechanism involves redox reactions in the cell that are fed by active ionic vanadium materials from the tanks, resulting in electron transference in the circuit. The ion-selective membrane within the cell separates the electrolytes on each side of the cell to prevent ion cross-contamination. The design stops reactant ion species on either side of the cell, while ensuring that hydrogen ions (H+) can cross the membrane to maintain electric neutrality in the cell.

e. **Aqueous sulphur flow battery:** Aqueous sulphur flow batteries show potential to be a scalable, long duration battery storage technology that uses low cost materials to achieve a low-cost base. The ambient-temperature flow battery uses low-cost polysulfide anolytes in conjunction with lithium or sodium counter-ions and an air or oxygen breathing cathode. The project storage economics are similar to those for pumped hydro and CAES, but with lower geographical footprint and without the geographical constraints.

f. **Metal air battery:** The metal air batteries use a metal as anode, air (oxygen) as cathode and water as an electrolyte. A graphene rod is used in the air cathode of the batteries. These batteries offer better energy density than Li-ion batteries which makes it better suited for electric vehicles. However, there are several complications associated with metal anodes, catalysts and electrolytes that restrict its widespread application.

g. **Li-ion battery**: Lithium ion (Li-ion) battery is an electrochemical storage technology with a cathode made of lithium metal oxide (e.g., LiCoO2, LiMO2) and anode made of graphitic carbon. The electrolyte is a non-gaseous liquid which contains lithium salts. In this technology, li-ions move from the negative electrode to the positive electrode during discharge and back when charging. Li-ions are good candidate for applications and services that necessitate short response time and high energy density. Li-ion batteries are among the most developed and deployed storage technologies in the energy market today and contribute remarkably to revenue generations.

Mechanical storage

b. Pumped hydro storage: Electricity is used to raise a mass of water and store energy as gravitational potential energy which is released to generate electrical energy via generator. This is the most commonly deployed storage technology across the world. Pumped hyrdo projects can be installed as an open loop system, along the flow of a river or as a closed loop system with upper and lower reservoirs which does not hinder the natural flow of a river.

c. **Gravity based energy storage:** Gravity based energy storage is based on storing electricity by lifting a large mass (such as rocks, concrete blocks). The stored energy is discharged by releasing the concrete block. It is typically implemented as a hydraulic energy store where water pumps are used to lift rocks and as the rocks are released, water is forced through a turbine to generate electricity.

d. **Compressed air energy storage (CAES):** A CAES system stores energy by using off-peak electricity to compress air and store it in a reservoir. Although large, steel, aboveground containers can be built to use as a reservoir for the compressed air, naturally occurring salt caverns often provide a more cost-effective alternative. The compressed air is heated, expanded, and released to a combustor in a gas turbine during peak demand periods to generate electricity.

e. **Flywheels:** Flywheel Energy Storage (FES) store electrical energy as the rotational energy in a heavy mass. Systems typically consist of a large rotating cylinder supported on a stator. Typical Flywheels run 15 – 30 min but recent developments in power electronics have increased the duration of flywheel up to 4 hours. Flywheels are used in inverters and grid systems for large energy storage, with very fast charge / discharge times.

Thermal storage

f. Liquid air energy storage: LAES uses liquid air or liquid nitrogen as a storage medium. Air turns liquid at -196 C and can be easily stored into containers at a large scale. Exposure to ambient temperatures causes rapid re-gasification and a 700-fold expansion in volume, which is used to drive a turbine and generate electricity.

g. Electric thermal energy storage: Solid-state thermal storage utilises rocks as an energy storage medium. It is fed with electrical energy which is converted into hot air by means of a resistance heater and a blower that heats the rock. When demand peaks, it uses a steam turbine for the re-electrification of the stored energy. Thermal energy can be stored for longer periods up to one week. In addition, the storage capacity of the system remains constant throughout the charging cycles.

h. **Standalone molten salt energy storage:** This storage system is typically associated with concentrated solar plants. Heat generated from solar thermal systems is used to heat molten salt stored in large tanks. The molten salt is mixed with cold fluid to recover the stored thermal energy.

i. **Salt hydrates heat storage:** Salt hydrates heat storage uses phase change materials to store heat. Salt hydrates have advantages such as high energy storage density, high latent heat and incombustibility.

Electrical storage

a. **Graphene supercapacitors:** Graphene is often suggested as a replacement for activated carbon in supercapacitors, in part due to its high relative surface area (which is even more substantial than that of activated carbon). The surface area is one of the limitations of capacitance and a higher surface area means a better electrostatic charge storage. In addition, graphene-based supercapacitors will utilize its lightweight nature, elastic properties and mechanical strength.

Sector coupling

Power to hydrogen: Electricity is used to split water to generate hydrogen in an electrolyzer. When electricity produced from renewable energy sources is used, the hydrogen becomes a carrier of renewable energy, complementary to electricity. Surplus electricity can be used to generate hydrogen which can be used as a fuel in transport and raw material in industries.

Hydrogen fuel cells: Hydrogen fuel cells are used to convert hydrogen into electricity. Power to hydrogen and hydrogen fuel cells can also be used as a storage mechanism for storing surplus RE generation. However, the round-trip efficiency of these cells is lower than batteries. The round-trip efficiency is expected to be around 40-50% for converting hydrogen back to electricity.

Annexure: Stage – I evaluation

Technology Name		Flexibility	Scalability			Commercial Readiness
	Level 1 score	Flexibility need addressed	Modularity	Absence of deployment constraint (gestation, land, any specific technical requirements not fulfilled)	Technological Readiness Level	Commercial Readiness Index
Hydrogen Fuel Cells	15	High	High	High	High	High
Li-ion Battery	15	High	High	High	High	High
Power to Hydrogen	13	Medium	Medium	High	High	High
Floating Offshore Wind	13	Medium	Medium	High	High	High
Vanadium Flow Battery	13	High	High	High	High	Low
Graphene Supercapacitors	12	Low	High	High	High	Medium
Offshore Wind (monopile)	12	Medium	Low	High	High	High
Zn-Br Hybrid Flow Battery	12	High	Low	High	High	Medium
NaNiCl Battery (ZEBRA)	11	High	Medium	Low	High	Medium
Pumped Hydro	11	High	Low	Low	High	High
NaS	11	High	Low	Low	High	High
Aqueous sulfur flow battery	11	High	High	High	Low	Low
Flywheels	10	Low	Low	High	High	Medium
LAES	10	Medium	Low	High	High	Low
Salt Hydrates Heat Storage	9	Medium	Medium	Low	High	Low
Metal-Air Battery	9	High	Low	High	Low	Low
Small Modular Reactors (SMR)	8	Medium	Low	High	Low	Low
CAES	8	Medium	Low	Low	High	Low
Sodium Fast Cooled Nuclear Reactor	7	Medium	Low	Medium	Low	Low
Gravity-Based Energy Storage	7	High	Low	Low	Low	Low
Miniature fusion reactors	7	Low	High	Low	Low	Low
Stand-alone Molten Salt Thermal Storage	7	High	Low	Low	Low	Low
Molten Salt Nuclear Reactor	6	Medium	Low	Low	Low	Low
Gas Cooled Fast Nuclear Reactor	6	Medium	Low	Low	Low	Low
Lead-cooled Fast Reactors	6	Medium	Low	Low	Low	Low
Very High Temperature Nuclear Reactor	6	Medium	Low	Low	Low	Low
Supercritical-Water-cooled Reactors	6	Medium	Low	Low	Low	Low

Annexure: Stage – II Evaluation

Type	Overall score	Resource Independence	Ability to increase inclusion	Absence of requirement for rehabilitation and resettlememt	Occurrence and manageability of Waste	Lack of global and local pollutants emissions
The specific technology in question		Reflects the ability of the technology to be deployed in India, without dependence on imports for its deployment.	Reflects the technology's ability to benefit rural population	Reflects the land requirement for deployment of the technology and the importance of the land surrounding typical project sites for providing livelihood resources and services to adjacent communities	Reflects the level of waste generated from technology usage as well as the potential national capabilities to manage the disposal of the respective types of non-emission hazardous waste	Reflects the total quantum of local (Sox, Nox, PM 2.5) and global (GHG emissions) pollutants generated by the technology during its operation.
Hydrogen Fuel Cells	14	High	Medium	High	High	High
Zn-Br Hybrid Flow Battery	14	High	Medium	High	High	High
Alkaline Electrolyser (ALK)	13	High	Low	High	High	High
Floating Offshore Wind	13	High	Low	High	High	High
Offshore Wind (monopile)	13	High	Low	High	High	High
Vanadium Flow Battery	13	Medium	Medium	High	High	High
Pumped Hydro	11	High	Low	Low	High	High
Li-ion Battery	11	Low	High	High	Low	High
NaNiCl Battery (ZEBRA)	11	High	Low	High	High	Low
Graphene Supercapacitors	11	High	Low	High	Low	High
Hydrogen Proton Exchange Membrane (PEM) Electrolysis	11	Medium	Low	High	Medium	High
Aqueous sulfur flow battery	11	High	Low	High	Low	High
NaS	10	High	High	Medium	Low	Low

References

BP . (2019). *BP Energy Outlook 2019 - India.* Retrieved from BP: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2019-country-insight-india.pdf

Bertuccioli, L., Chan, A., Hart , D., Lehner, F., Madden, B., & Standen, E. (2014). *Study on development of water electrolysis in the EU.* Fuel Cells and Hydrogen Joint Undertaking.

Economic Times. (2011, July). *Vedanta recovers Vanadium from Red mud.* Retrieved from https://economictimes.indiatimes.com/industry/indl-goods/svs/metals-mining/vedanta-recovers-vanadium-from-red-mud-denies-any-discharge-to-river/articleshow/9102466.cms

Economic Times. (2019, November). Retrieved from https://economictimes.indiatimes.com/industry/energy/power/renewables-to-account-for-55-of-energy-mix-by-2030-minister/articleshow/72020507.cms?from=mdr

IEA. (2019, June). *Future of Hydrogen.* IEA. Retrieved from IEA.

IEA. (2019, May). *Nuclear Power in a Clean Energy System.* Retrieved from IEA.

MNRE. (2019). Retrieved from mnre.gov.in: https://mnre.gov.in/physical-progress-achievements

Office of Energy Efficiency & Renewable Energy. (2018). *Hydrogen Production: Electrolysis*. Retrieved November 13, 2018, from https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis

Outlook. (2019, May 8). *Five Days After Cyclone Fani Hit Odisha, Lakhs Still Without Electricity, Towns Plunged Into Darkness*. Retrieved from Outlook: https://www.outlookindia.com/website/story/india-news-five-days-after-cyclone-fani-hit-odisha-lakhs-still-without-electricity-towns-plunged-into-darkness/330010

PwC. (2018). *Accelerating hydropower development in India for sustainable energy security.*

TERI. (2018, November). *India's NDC - Discussion Paper.* Retrieved from TERI: https://www.teriin.org/sites/default/files/2018-12/India%27s%20NDCs%20Key%20Messages.pdf

US Dept of Energy. (2019, July). *Energy storage technology and characterization report.* Retrieved from energy.gov: https://www.energy.gov/sites/prod/files/2019/07/f65/Storage%20Cost%20and%20Performance%20Characterization%20Report_Final.pdf

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Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Agency for Development and Cooperation SDC

www.eda.admin.ch/sdc