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India-Denmark



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अध्यक्ष तथा पदेन सचिव भारत सरकार
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FOREWORD

The world is focusing on environmental issues, especially climate change and therefore, the idea of growing sustainably has taken center stage globally. India being an active participant has already started taking several initiatives towards sustainable development and green energy transition towards achieving net-zero carbon emissions by 2070.

The demand for electricity is increasing with the increase in economic activity. Availability of affordable and reliable power is a key factor in sustainable growth of the country. Meeting the increasing demand along with the green energy transition is an opportunity as well as a challenge for the country. The intermittent nature of Renewable energy (mainly Solar and wind) has forced the policy makers to look towards storage technologies to achieve the net-zero goal.

An MoU has been signed between Ministry of Power, Govt. of India and Ministry of Climate, Energy & Utilities, Kingdom of Denmark on 5th June, 2020 which was renewed in 2025 to develop and promote strategic and technical cooperation in the energy sector for mutual benefits. Under this MoU, first Technology Catalogue was published in 2022 which focused mainly on conventional technologies.

I am happy to note that the Indian Technology Catalogue on Energy Storage has been prepared. The catalogues would make the relevant data of energy storage technologies publicly available to all stakeholders. The technology catalogue may therefore be used as a guiding database comprising inputs from across the Indian power sector.

This technology catalogue focuses specifically on energy storage solutions—key emerging and critical technologies essential for enabling deep decarbonization and flexible grid integration in the evolving Indian power system.

This technology catalogue has been reviewed by key stakeholders from the Indian power sector and Government institutions to ensure that the information is up to date and adapted to Indian conditions.

I would like to thank all the stakeholders for their cooperation in timely providing their valuable inputs, making this publication possible. I would also like to thank the team of officers from the IRP Division, CEA, along with the experts from Danish Energy Agency for their excellent work. I trust that this Technology Catalogue will fulfill the expectations and needs of all stakeholders engaged in the sustainable development of the power sector.

(Ghanshyam Prasad)

New Delhi
7 Aug 2026



Adrian Lübbert
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Foreword

The global energy transition is ongoing. As countries deploy renewable electricity at unprecedented scale, energy systems are becoming increasingly dynamic and interconnected. Achieving the goals of the Paris Agreement requires not only continued expansion of clean generation, but also the integration solutions that ensure renewable energy can be delivered reliably, affordably and securely. Energy storage stands at the centre of this next phase.

For countries with rapidly growing energy demand, such as India, storage technologies are becoming essential to maintain system stability, reduce curtailment, manage peak demand and enable deeper electrification. As the power system evolves, the ability to shift energy across hours, days or seasons will be critical to ensuring that renewable energy is used efficiently and that consumers continue to receive a stable supply. Storage is therefore not an add-on, but a foundational element of modern power systems. This is particularly relevant in the Indian context, where strategic choices will need to balance near-term deployment with long-term system transformation.

The technologies in this field are developing quickly—battery costs are declining, new chemistries are emerging, and long-duration storage solutions are progressing toward commercialisation. In such a fast-moving landscape, long-term planning and policy decisions should rely on transparent, comparable and up-to-date data. Without a shared evidence base, planning processes risk being fragmented, and investments may not align with the evolving capabilities of storage technologies.

This Technology Catalogue on Energy Storage addresses that need. It provides a uniform, publicly accessible reference for the cost and performance of key storage technologies, ranging from lithium-ion batteries and alternative chemistries to pumped storage and emerging long-duration options. It offers a shared analytical foundation for government institutions, system planners, research organisations and private stakeholders, supporting coherent planning across India's future energy system.

The catalogue has been developed jointly under the India–Denmark Energy Partnership through close collaboration between the Central Electricity Authority of India and the Danish Energy Agency. It applies a robust methodology and adapted to Indian conditions through an open and technically rigorous process. Storage affects all parts of the energy system—generation, grids, markets and consumers—and therefore demands a coordinated, transparent approach.

Publishing an energy storage catalogue now is timely. India's power system is expanding rapidly; renewable penetration is rising; and new market mechanisms are being designed to value flexibility and system services. Decisions taken in the coming years on storage technologies and deployment pathways will have long-lasting implications for system reliability, economic efficiency and decarbonisation. A robust evidence base is crucial for these choices.

It is therefore a pleasure, together with our partners at CEA, to present this first edition of the Indian Technology Catalogue on Energy Storage. We trust that it will strengthen long-term energy planning and

support the development of sound policies and investments that enable India's transition to a secure, flexible and sustainable energy system.



(Adrian Lübbert)

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Disclaimer

This technology catalogue is developed using best available data at the time of publication. The data can be used as desired, but no liability should accrue to the authors of the publication.

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Acronyms

A-CAES	Adiabatic Compressed Air Energy Storage
AA-CAES	Advanced Adiabatic Compressed Air Energy Storage
AC	Alternating Current
AP	Acidification Potential
BESS	Battery Energy Storage System
BHEL	Bharat Heavy Electricals Limited
BMS	Battery Management System
BNEF	Bloomberg New Energy Finance
BOP	Balance of Plant
BRPL	BSES Rajdhani Power Limited
BTU	British Thermal Unit
CAPEX	Capital Expenditure
CAES	Compressed Air Energy Storage
CCES	Compressed CO_2 Energy Storage
CEA	Central Electricity Authority
CFD	Computational Fluid Dynamics
CNF	Carbon Nanofiber
CSP	Concentrated Solar Power
Cumec	Cubic Meter per Second
DaCES	Danish Center for Energy Storage
DC	Direct Current
DEA	Danish Energy Agency
DoD	Depth of Discharge
DOE	U.S. Department of Energy
DSM	Deviation Settlement Mechanism
DSO	Distribution System Operator
EIB	European Investment Bank
EMF	Electromotive Force
EMS	Energy Management System
EPA	Environmental Protection Agency (U.S.)
EPC	Engineering, Procurement, and Construction
EPRI	Electric Power Research Institute
ESA	Energy Storage Association
ESS	Energy Storage System
EV	Electric Vehicle
GEAPP	Global Energy Alliance for People and Planet
GHG	Greenhouse Gas
GIS	Gas Insulated Switchgear
GO	Graphite Oxide
GWP	Global Warming Potential
HTF	Heat Transfer Fluid
IHA	International Hydropower Association
IEA	International Energy Agency

IEEFA	Institute for Energy Economics and Financial Analysis
IEC	International Electrotechnical Commission
IISc	Indian Institute of Science
IIT	Indian Institute of Technology
INR	Indian Rupee
IREP	Integrated Renewable Energy Project
KW	Kilowatt
LAES	Liquid Air Energy Storage
LCA	Life Cycle Assessment
LCO	Lithium Cobalt Oxide
LDES	Long-Duration Energy Storage
Li-Ion	Lithium-Ion
LIB	Lithium-Ion Battery
LFP	Lithium Iron Phosphate Battery ($LiFePO_4$)
LMO	Lithium Manganese Oxide
LTO	Lithium Titanate Oxide
MOP	Ministry of Power
MoU	Memorandum of Understanding
MPa	Megapascal
MW	Megawatt
MWac	Megawatt Alternating Current
MWh	Megawatt-hour
NCA	Nickel Cobalt Aluminum Oxide
NMC	Nickel Manganese Cobalt
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
OPEX	Operational Expenditure
PBAs	Prussian Blue Analogues
PCS	Power Conversion System
PHS	Pumped Hydro Storage
PSP	Pumped Storage Project
PNNL	Pacific Northwest National Laboratory
PtP	Power-to-Power Efficiency
PV	Photovoltaic
R&D	Research and Development
R&DD	Research & Development and Demonstration
RE	Renewable Energy
RES	Renewable Energy Sources
SAM	System Advisor Model
SCADA	Supervisory control and data acquisition
SEI	Solid Electrolyte Interphase
SENER	Spanish Engineering Company (Sociedad de Estudios y de Ingeniería, S.A.)
SIB	Sodium-ion Battery
SOC	State of Charge
T&D	Transmission and Distribution

TERI	The Energy and Resources Institute
TES	Thermal Energy Storage
THDC	Tehri Hydro Development Corporation India Limited
TMS	Thermal Management System
TRL	Technology Readiness Level
TSO	Transmission System Operator
UI-Assist	U.S.-India Collaborative for Smart Distribution System with Storage
UPS	Uninterruptible Power Supply
US DOE	U.S. Department of Energy
USD	U.S. Dollar
VRB	Vanadium Redox Flow Battery
VRF	Vanadium Redox Flow

Preface

Central Electricity Authority (CEA) has prepared the first edition of the catalogue containing data on technologies for energy storage. The catalogue may continuously be updated as technologies evolve, if data change significantly etc. All updates will be listed in the amendment sheet and in connection with the relevant chapters, and it will always be possible to find the most recent version on the Central Electricity Authority's website. In parallel with this publication, a Technology Catalogue for Green Fuels has also been released. Previously, in 2022, CEA published a Technology Catalogue for the Generation and Storage of Electricity.

The primary objective of publishing technology catalogues is to establish a uniform, commonly accepted and up-to-date basis for energy planning activities, such as future outlooks, evaluations of security of supply and environmental impacts, climate change evaluations, as well as technical and economic analyses, e.g. on the framework conditions for the development and deployment of certain classes of technologies.

With this scope in mind, it is not the target of the technology data catalogues to provide an exhaustive collection of specifications on all available incarnations of energy technologies. Only selected, representative, technologies are included, to enable generic comparisons of technologies with similar functions in the power system e.g. electricity storage in batteries.

Introduction to Power Storage

Power storage is a key technology to enable the next phase of the energy transition, driven by the large-scale deployment of variable renewable energy sources (VRES) like solar and wind power. The technologies presented in this chapter will help to cope with the integration challenges arising from intermittent generation sources: the need to both ensure the balance of production and consumption in real time maintaining the quality of supply and to store excess electricity over different time horizons (minutes, days, weeks).

While electrical energy storage systems are identified by the fact that they can be utilized to exchange power (the energy carrier) with the grid, different types exist depending on the energy form ultimately stored. They are illustrated in Figure 0-1.

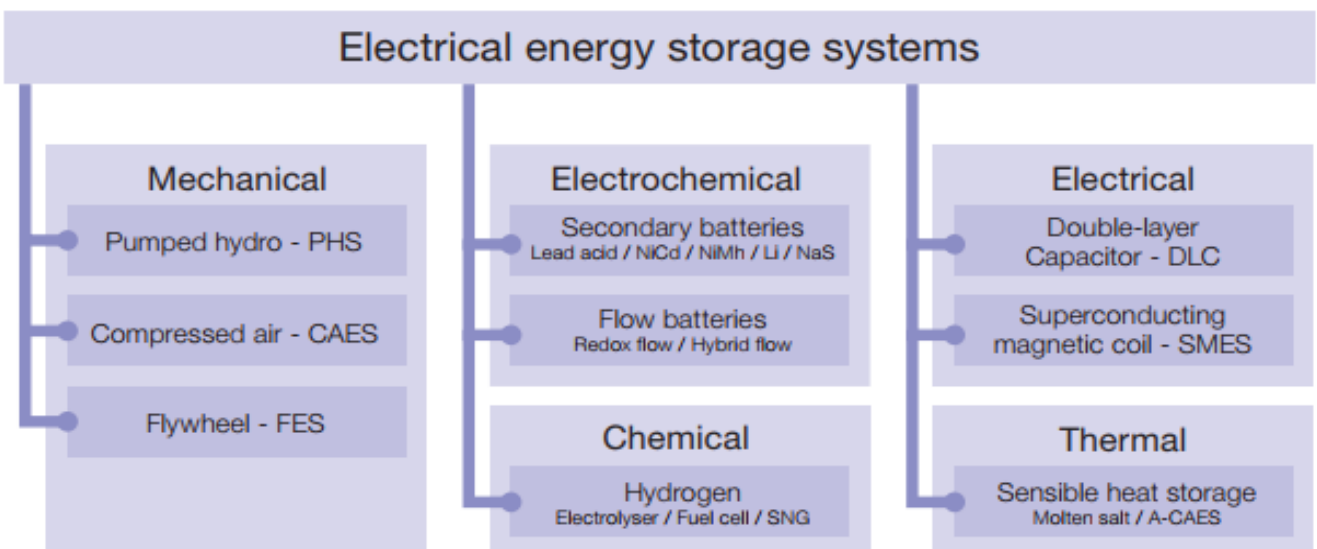

Figure 0-1: Classification of electrical energy storage systems according to energy from [1]. Note: Not all technologies are included in this technology catalogue.

Power storage characteristics and services

The services that storage technologies can provide vary and are inherently linked to the physical characteristics of the storage medium and system. One way to categorise storage technologies and their potential services is by their power rating and discharge duration at rated power. Table 0-1 summarises, for each electricity storage technology as of 2026, the technical power range, typical deployed project size, discharge duration, and deployment maturity. Around 2015, electricity storage technologies were commonly divided into two main groups: power-intensive and energy-intensive. Since then, the period 2015–2026 has brought major shifts in the power range and typical deployment scale of several technologies, and today only the three technologies shown at the bottom of Table 0-1 remain clearly power-intensive rather than energy-intensive.

Table 0-1: System power rating and discharge time at rated power for different storage technologies. T&D = Transmission and Distribution; UPS = Uninterruptible Power Supply. Maturity colours: green = Commercial & mature; orange = Commercial & growing; red = Emerging / niche. Power ranges reflect module or plant sizes for commercially available systems.

Technology	Full Technical Power Range	Typical Deployed Range	Discharge Duration	Deployment Maturity	Application Zone
Pumped Hydro [2] [3]	100 MW – 3,600 MW	200 – 2,000 MW	4 – 20 hours	**Commercial & mature**	*Bulk Power Management*
CAES [4]	50 – 400 MW	100 – 290 MW	2 – 20 hours	**Commercial & growing**	*Bulk Power Management*
Flow Batteries (VRB, ZnBr, Fe-Cr, new) [4] [5]	1 kW – 200 MW	0.5 – 30 MW	2 – 20 hours	**Commercial & growing**	*T&D / Load Shifting*
NaS Battery [4]	1 – 300 MW	5 – 50 MW	6 – 8 hours	**Commercial & growing**	*T&D / Load Shifting*
Li-Ion Battery (LFP / NMC) [6] [4]	1 kW – 4,000 MW	1 – 1,000 MW	15 min – 8 hours	**Commercial & mature**	*T&D / Load Shifting & Bulk*
Advanced Lead-Acid [4]	1 kW – 40 MW	100 kW – 10 MW	15 min – 8 hours	**Commercial & mature**	*UPS / T&D*
$NaNiCl_2$ (ZEBRA) [4]	1 kW – 10 MW	10 kW – 2 MW	30 min – 6 hours	**Commercial & growing**	*UPS / T&D*
NiCd / NiMH [4]	1 kW – 40 MW	10 kW – 5 MW	15 min – 8 hours	**Commercial & mature**	*UPS / T&D*
High-Power Flywheels [4]	100 kW – 20 MW	0.5 – 10 MW	5 sec – 30 min	**Commercial & growing**	*UPS / Power Quality*
High-Power Supercapacitors [4]	10 kW – 10 MW	50 kW – 2 MW	1 sec – 1 min	**Emerging / niche**	*UPS / Power Quality*
SMES [4]	10 kW – 100 MW	100 kW – 10 MW	1 sec – 5 min	**Emerging / niche**	*UPS / Power Quality*

Based on their characteristics and positioning, electricity storage technologies can be divided into two main categories: power-intensive and energy-intensive.

Power-intensive applications are required to provide ancillary services to the system in maintaining the balance of frequency and voltage or providing power quality. Power intensive applications do this by delivering large amounts of power for time periods on the scale of seconds or minutes, and thus, they are characterized by a high ratio of power to energy (short discharge times) and fast response.

Energy-intensive applications are used for storing large amounts of energy in order to match demand and supply, perform load leveling or reducing congestion in the network. These technologies are characterized by a lower ratio of power to energy (long discharge times) and used on an hourly to seasonal scale.

The distinction between technologies providing power or energy intensive services is not always clear. Some technologies, such as pumped hydro or Li-ion batteries, can provide both services.

The potential applications for electricity storage across the entire value chain are various. Some of these applications refer to more energy-intensive services, while others to power-intensive ones. The most important ones can be categorized as follows[1]:

- **Time-shift:** purchase of electricity when the price is lower to use it or sell it when the price is higher (also referred to as *arbitrage*). The effect is an increased demand in hours with lower load (*load levelling*), with advantages related to a reduction of the need for electricity production during the peak demand (*peak shaving*), resulting in a lower utilization of more expensive generators or avoiding capacity additions and a lower strain on the system. This service includes the potential provision of peak power to ensure system adequacy, when the power system is under stress[2].

- **Time-of-use management and self-consumption:** residential and small commercial application to maximize the self-consumption of solar photovoltaics or to shift the consumption in hours with lower tariffs. The application principle is similar to time-shift, but more small-scale and local and more often related to self-consumption.

- **RE capacity firming and production smoothing:** compensation of the fluctuations of the production from variable renewables (e.g. solar and wind) to obtain a more predictable and regular generation profile. Reduction of the balancing cost for the plant operator and, from a system perspective, reduced need for reserve and modulation/ramping of conventional plants.

- **Network support and investment deferral**: postponement of costly expansion of the power network thanks to the reduction of situations of overload and congestion in transmission or distribution networks if located and operated strategically in the grid. In connection to variable renewables, it refers also to the reduction of curtailed energy.

- **Primary regulation:** participation in the primary frequency regulation, ensuring that the balance between production and consumption is stabilised in the event of frequency deviations. The response time for the primary regulation is a few seconds (with full response typically within about 15 seconds). It is also referred to as Primary Frequency Response (PFR) or Frequency Containment Reserve (FCR).

- **Secondary regulation:** participation in the secondary frequency regulation, ensuring that the frequency is brought back to its nominal value after a major system disturbance. The response time of secondary regulation is typically within a few minutes (for example up to about 5–15 minutes, depending on system operator requirements). It is also referred to as Automatic Frequency Restoration Reserve (aFRR) and, in

[1] The list of descriptions and applications are based on elaborations from [1], [7] and [8].

[2] Provision of peak power is very similar to arbitrage in terms of requirements from the storage system, but it differs in the utilization rate. The service of peak power provision would be activated only during very few hours in the year, where the price is very high, to ensure adequacy and security of supply. This would be feasible only in the case storage, due to the lower battery costs, becomes competitive with gas or other peak technologies in terms of capital cost expenditure.

the Indian context, as Frequency Restoration Reserves (FRR) provided via Automatic Generation Control (AGC).

- **Tertiary regulation:** participation in the tertiary frequency regulation, which partially complements and replaces secondary reserve by re-scheduling generation. The response time must be about 15 minutes (depending on system operator requirements). It is also referred to as Manual Frequency Restoration Reserve (mFRR) and, in the Indian context, is implemented through tertiary reserve ancillary services (for example TRAS from suitable generation and storage resources).

- **Black-start:** service of re-establishment of the grid after a generalized black-out. It can be provided by plants that are able to start operation autonomously, i.e. without support from the grid, e.g. batteries (BESS), compressed air energy storage (CAES), flywheels, supercapacitors and hydro/pumped hydro storages, if paired with grid-forming inverters and appropriate controls.

- **Voltage support:** provision of reserve for the modulation of reactive power in specific nodes of the grid for voltage management purposes which can be provided by batteries (BESS), supercapacitor and flywheel systems, as well as CAES and hydro/pumped-storage units capable of supplying or absorbing reactive power via inverters or synchronous machines.

- **Power quality:** refers to a number of services related to the improvement of the quality of the power supplied. For example, improved voltage quality (compensation of voltage dips and distortion of voltage), reduction of the impact of distorting loads (e.g. harmonics, flicker) and shaving of localized power peaks (timescale of seconds), which can be provided by batteries (BESS), supercapacitor and flywheel systems, as well as other power-electronic storage units designed for fast active and reactive power control.

Main applications of different power storage technology groups

This section highlights the main services and approximate application shares for each technology group in 2024. The percentage shares are indicative synthesis values based on public literature and organisation reports, not directly reported global 2024 measured shares. The applications categories are not mutually exclusive. As installations may provide several services simultaneously depending on market design, technical configuration and dispatch requirements.

Utility-scale BESS the three main services provided by the global utility-scale fleet in 2024 are:

Electric energy time shift and arbitrage (app. 40-45%): The dominant application globally, with batteries charging on surplus renewable generation and discharging at peak demand. The US share was 41% in 2024 [9] and China, exceeded 43% [10], driven by co-location mandates for new wind and solar projects.

Renewables capacity firming and grid support (app.15-20%): Co-located or contractually linked storage smoothing variable renewable output and meeting grid connection requirements. The fastest-growing segment globally [10] [11].

Frequency regulation and ancillary services (app. 20-25%): Historically the entry point for utility-scale batteries but declining as markets saturate. The US share fell to 24% in 2024 [9] and UK ancillary revenues dropped from 84% to 20% of BESS income between 2022 and 2024 [12].

For pumped hydro storage, the three main services provided by the global fleet in 2024 are:

Electric energy time shift and arbitrage share (app.70-80%): The dominant application globally, with pumped hydro shifting bulk electricity from low-demand and surplus-renewable periods to peak-demand hours while providing large-scale load levelling [13] [14].

Renewables capacity firming and system balancing share (app. 10-20%): Pumped hydro increasingly absorbs excess wind and solar generation and releases it later, supporting renewable integration, balancing variability and reducing curtailment in high-VRE power systems [13] [15].

Ancillary services and black start share (app. 5-10%): A smaller but important share supports operating reserve, frequency response, voltage support and black start, reflecting pumped hydro's synchronous operation and grid-restoration capabilities [15] [16].

For electro-mechanical storages such as flywheel and compressed air, the three main services provided by the global fleet in 2024 are:

Frequency regulation and power quality share (app. 35-45%): Mainly driven by flywheels, this application values very fast response, high cycling capability and short-duration discharge for frequency control, voltage support and power-quality improvement [17].

Electric energy time shift, peak shaving and load management share (app. 30-40%): Mainly driven by CAES, this share covers bulk load shifting, peak shaving, arbitrage and longer-duration energy management where mechanical storage can complement batteries [18] [19].

Backup power, black start and ancillary grid support share (app. 15-25%): Electro-mechanical storage also supports backup supply, reserve provision, black start and other grid services, often stacked with the main applications above depending on plant design [17] [18] [19].

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1. Technology catalogue guideline

This catalogue addresses technologies for power storage. The focus is on the specific storage technology. Therefore, its interaction with the system and the combination with other technologies is not always considered. For example, hydrogen storage will be described as a gas storage system and not as a potential mean to store electricity and thus hydrogen storage is considered in the corresponding technology catalogue on green fuels. Each storage unit is defined by its energy carrier such that the boundary to the power system is the input and output of this same energy carrier. For example, while a battery stores chemical energy, it is in this catalogue for all intents and purposes defined as electricity storage. Therefore, the conversion from electricity to kinetic energy or chemical energy and back again is included in the storage technology.

Each chapter contains the necessary qualitative description and quantitative data to complete the storage of the energy carrier. The exact system boundaries and energy carrier being stored is defined for each technology in the qualitative description.

The main purpose of the catalogue is to provide generalized data for analysis of electricity systems, including economic scenario models and high-level planning.

These guidelines serve as an introduction to the presentations of the different technologies in the catalogue, and as instructions for the authors of the technology chapters. The following sections (1.1 and 1.2) explain the formats of the technology chapters, how data were obtained, and which assumptions they are based on. Each technology is subsequently described in a separate technology chapter, making up the main part of this catalogue. The technology chapters contain both a description of the technologies and a quantitative part including a table with the most important technology data.

1.1. Qualitative description

The qualitative description covers the key characteristics of the technology as concise as possible. The following paragraphs are included where relevant for the technology.

1.1.1. Brief technology description

Brief description how the technology works and for which purpose. This includes the form of energy stored, any potential storage medium and the application of the technology, as mentioned in the table in the introduction. Moreover, the type of services that the storage technology can provide is expressed (e.g. storage for production plants, primary frequency regulation, load shifting, etc.).

The system boundaries are identified in this section. In cases where the conversion units are not parts of the system, examples of typical conversion technologies used with the storage unit are mentioned.
An illustration of the technology is included, showing the main components and working principles.

1.1.2. Input/output

The form of energy input to be stored and the output(s).

1.1.3. Energy efficiency and losses

The energy conversion efficiency and energy losses such as idle losses, self-discharge (batteries), heat loss, mechanical loss, etc.

- Charge/discharge efficiency
- Round-trip efficiency

1.1.4. Regulation ability and other system services

This is relevant for electricity storage technologies, i.e. how fast they can start up and how quickly they are able to respond to demand changes (response time) or provide grid services. For electricity storage technologies, especially if suitable for power intensive application, the qualitative description includes the technology's capability for delivering the following power system services:

- Inertia
- Short circuit power
- Black start
- Voltage control
- Damping of system oscillations (PSS)

1.1.5. Typical characteristics and capacities

The characteristics are stated for a single unit capable of providing the storage service needed. In the case of modular technologies such as batteries, the unit is represented by a typical size of battery installation, to provide the service described.

The typical characteristics expressed are:

- Energy storage capacity, in MWh: amount of energy that can be stored
- Input and output capacities, in MW: rate at which the energy can either charge or discharge
- Energy density and specific energy, in Wh/m^3 and Wh/kg respectively

For some storage technologies, there is a certain share of total energy storage that has to be constantly kept in the storage unit to ensure low degradation or to maintain specific conditions (e.g. pressure, temperature).

For example, in electrical batteries there could be a lower bound for the state of charge (Depth of Discharge, DoD). In such cases, only the "active storage capacity" is specified, meaning the amount of energy between maximum and minimum level or usable energy. Information regarding the minimum required amount of electricity stored is also explained here.

Ranges for the different parameters could be indicated here if the technology has various typical sizes.

1.1.6. Typical storage period

Qualitative expression of how long the energy is typically stored in the unit, which is closely related to the application and the services provided. The storage period is typically in the range from hours or days to longer periods such as months or years.

1.1.7. Space requirement

The space requirement for the installation of the storage technology is expressed in m^2 per MWh. The space requirements may for example be used to calculate the rent of land, which is not included in the financial cost, since this cost item depends on the specific location of the plant.

1.1.8. Advantages/disadvantages

A description of specific advantages and disadvantages relative to equivalent technologies. Generic advantages are ignored; e.g. renewable energy technologies mitigating climate risks and enhance security of supply.

1.1.9. Environmental impact

Particular environmental characteristics are mentioned, for example special emissions or the main ecological footprints.

The use of critical, toxic or regulated materials is specified, this is especially important for batteries, but should also be considered for the other types.

1.1.10. Research and development perspectives

This section lists the most important challenges to further development of the technology. Also, the potential for technological development in terms of costs and efficiency is mentioned and quantified if possible. Indian research and development perspectives are highlighted, where relevant.

1.1.11. Examples of market-standard technology

Recent full-scale commercial projects in India, which can be considered market-standard, are mentioned, preferably with links. A description of what is meant by "market-standard" is given in the introduction to the quantitative description section (Section 1.2). For technologies where no market standard has yet been established, reference is made to best available technology in R&D projects. Similarly, if technologies are not available in India yet, best available technology internationally is included.

1.1.12. Projection of performance and costs

Cost reductions and improvements of performance can be expected for most technologies in the future. This section accounts for the assumptions underlying the cost and performance in 2024 as well as the improvements assumed for the years 2030, 2050 and 2070.

The specific technology is identified and classified in one of four categories of technological maturity, indicating the commercial and technological progress. These categories reflect the commercial and technological progress of the technology and inform the assumptions used for projections. They are explained in more detail below.

In formulating the section, the following background information is considered:

Data for 2024

In case of technologies where market standards have been established, performance and cost data of recently installed versions of the technology in India or the most similar countries in relation to the specific technology are used for the 2024 estimates.

If consistent data is not available, or if no suitable market standard has yet emerged for new technologies, the 2024 costs may be estimated using an engineering-based approach applying a decomposition of manufacturing and installation costs into raw materials, labour costs, financial costs, etc. International references such as the IEA, NREL etc. are preferred for such estimates.

Learning curves and technological maturity

Predicting the future costs of technologies may be done by applying a cost decomposition strategy, as mentioned above, decomposing the costs of the technology into categories such as labour, materials, etc. for which projections already exist. Alternatively, the development could be predicted using learning curves. Learning curves express the idea that each time a unit of a particular technology is produced, learning accumulates, which leads to cheaper production of the next unit of that technology. The learning rates also take into account benefits from economy of scale and benefits related to using automated production processes at high production volumes.

The potential for improving technologies is linked to the level of technological maturity. The technologies are categorized within one of the following four levels of technological maturity.

Category 1. Technologies that are still in the *research and development phase*. The uncertainty related to price and performance today and in the future is highly significant (e.g. wave energy converters, solid oxide fuel cells).

Category 2. Technologies in the *pioneer phase*. The technology has been proven to work through demonstration facilities or semi-commercial plants. Due to the limited application, the price and performance is still attached with high uncertainty, since development and customization is still needed. The technology still has a significant development potential (e.g. gasification of biomass).

Category 3. *Commercial technologies with moderate deployment*. The price and performance of the technology today is well known. These technologies are deemed to have a certain development potential and therefore there is a considerable level of uncertainty related to future price and performance (e.g. offshore wind turbines).

Category 4. *Commercial technologies, with large deployment*. The price and performance of the technology today is well known and normally only incremental improvements would be expected. Therefore, the future price and performance may also be projected with a relatively high level of certainty (e.g. coal power, gas turbine).

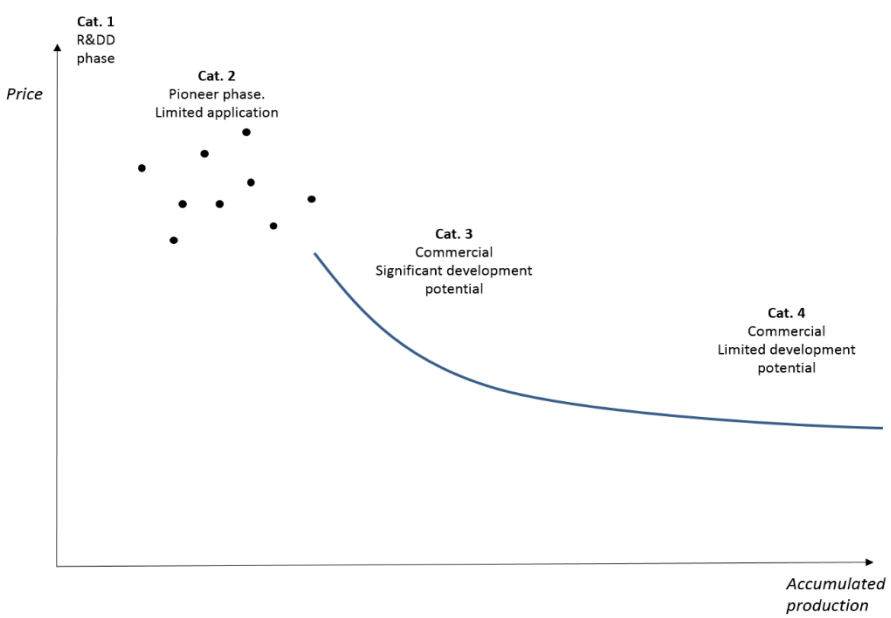

Figure 1-1: Technological development phases. Correlation between accumulated production volume and price.

1.1.13. Uncertainty

The catalogue covers both mature technologies and technologies under development. This implies that the price and performance of some technologies may be estimated with a relatively high level of certainty

whereas in the case of others, both cost and performance today as well as in the future are associated with high levels of uncertainty.

The uncertainty level could in general be described by referring to the maturity levels shown in Figure 1-1. This section of the technology chapters explains the main uncertainties of the data and identifies the areas where the uncertainty ranges in the quantitative description are based. This includes technological or market related issues of the specific technology as well as the level of experience and knowledge in the sector and possible limitations on raw materials. The issues should also relate to the technological development maturity as discussed above.

In the quantitative section, the level of uncertainty is illustrated by providing a lower and higher bound beside the central estimate. It should be noted, that projecting costs of technologies far into the future is a task associated with very large uncertainties. Thus, depending on the technological maturity expressed and the period considered, the confidence interval may be very large. It is the case, for example, of less developed technologies and long time horizons (2070).

1.1.14. Additional remarks

This section includes other information, for example links to websites that describe the technology further or provide key figures on it.

1.2. Quantitative description

To enable comparative analyses between different technologies it is imperative that data are actually comparable: All cost data are stated in fixed 2023 prices, excluding taxes and subsidies. The information given in the tables relates to the development status of the technology at the point of final investment decision (FID) in the given year (2024, 2030, 2040, 2050 and if possible 2070). FID is assumed to be taken when financing of a project is secured and all permits are at hand. The year of commissioning will depend on the construction time of the individual technologies.

A typical table of quantitative data is shown below, containing all parameters used to describe the specific technologies. The table consists of a generic part, which is identical for all storage technologies and a technology specific part, containing information which is only relevant for the specific technology. The generic part is included to allow for an easy comparison.

In the technology specific part all parameters relevant (for the energy modelling of) the specific technology not included in the generic are added. Each cell in the table contains only one number, which is the central estimate for the market-standard technology, i.e. no range indications. Uncertainties related to the figures are stated in the columns named *uncertainty*. To keep the table simple, the level of uncertainty is only specified for years 2024 and 2070.

The level of uncertainty is illustrated by providing a lower and higher bound. These are chosen to reflect the uncertainties of the best projections by the authors. The section on uncertainty in the qualitative description for each technology indicates the main issues influencing the uncertainty related to the specific technology. For technologies in the early stages of technological development or technologies especially prone to variations in cost and performance data, the bounds expressing the confidence interval could result in large intervals. The uncertainty is related to the market-standard technology; in other words, the uncertainty interval does not represent the product range (for example a product with lower efficiency at a lower price or vice versa). In case, it is relevant to include products of different product range, this should be done by including more data sheets.

The level of uncertainty is stated for the most critical figures such as investment cost and efficiencies. Other figures are considered if relevant.

All data in the tables are referenced by a number in the utmost right column (Ref), referring to source specifics below the table.

Notes include additional information on how the data is obtained, as well as assumptions and potential calculations behind the figures presented are included when relevant. Before using the data, please be aware that essential information may be found in the notes below the table.

The generic parts of the tables for storage technologies are presented below:

Technology	name/ description										
	2024	2030	2040	2050	2070	Uncertainty (2024)		Uncertainty (2070)		Note	Ref
Energy/technical data						Lower	Upper	Lower	Upper		
Application											
Energy storage capacity for one unit (MWh)											
Output capacity for one unit (MW)											
Input capacity for one unit (MW)											
Round trip efficiency (%)											
- Charge efficiency (%)											
- Discharge efficiency (%)											
Energy losses during storage (%/period)											
Forced outage (%)											
Planned outage (days per year)											
Technical lifetime (years)											
Technical lifetime (number of cycles)											
Construction time (years)											
Regulation ability											
Primary load support (% per 30 seconds)											
Secondary load support (% per minute)											
Minimum load (% of full load)											
Financial data											
Total investment cost (cr. 2023 INR per MWh)											
Total investment cost (cr. 2023 INR per MW output)											
- energy component (cr. 2023 INR/MWh)											
- capacity component (cr. 2023 INR/MW)											
- other project costs (cr. 2023 INR)											
Fixed O&M (% total investment)											
Variable O&M (2023 INR/MWh)											
Technology specific data											

1.2.1. Energy/technical data

Energy storage capacity for one unit

The storage capacity, preferably a typical capacity (not maximum capacity), represents the size of a standard unit in terms of electricity stored. It refers to a single unit capable of providing the storage service needed, e.g. a hydro plant or a battery installation.

In the case of a modular technology such as batteries, a typical size based on historical installations or the market standard is chosen as a unit. Different sizes may be specified in separate tables, e.g. small, medium and large battery installations.

As explained under “Typical characteristics”, the energy storage capacity refers only to the active part of the storage unit, i.e. the energy that can be used, and not to the rated storage capacity of the storage. Additional information on the minimum level of energy required (Depth of Discharge DoD) shall be stated in the notes.

The unit MWh is used for electricity storage capacity.

Output and input capacity for one unit

The nominal output capacity is stated for a full unit and refers to the active part of the storage. Any other information regarding the minimum level is specified in the notes. It is given as net output capacity in continuous operation, i.e. gross output capacity minus own consumption.

The nominal input capacity is stated for a full unit as well, i.e. gross input capacity minus own consumption. In case it is equal to the output capacity, the value specified will be the same.

The unit MW is used for all output and input capacities.

Charge and discharge efficiencies (round trip efficiency)

The efficiencies of the charging and discharging processes are stated separately in percentage where possible.

The round-trip efficiency is the product of charging and discharging efficiencies and expresses the fraction of the input energy, which can be recovered at the output, assuming no losses during the storage period. It represents the ratio between the energy provided to the user and the energy needed to charge the storage system.

For electricity storage, it is intended as AC-AC value, therefore including losses in the converters and other auxiliaries.

The round-trip efficiency enables comparisons of different storage technologies with respect to efficiency of the storage process. However, not including the losses during the storage period, it does not give a complete picture. Losses are covered below.

Energy losses during storage

The energy lost from the storage unit due to losses in a specific time horizon is specified here.

Technologies with different storage periods will show different behavior with respect to energy losses. Therefore, the period is chosen based on the characteristics of the technology (e.g. % losses/hour, % losses/day or % losses/year).

Losses are expressed as a percentage of the energy storage capacity (as defined above) lost over the timeframe chosen.

Auxiliary electricity consumption

For electricity storage, this component is already included in the overall round trip efficiency (AC-AC).

Forced and planned outage

Forced outage is defined as the number of weighted forced outage hours divided by the sum of forced outage hours and operation hours. The weighted forced outage hours are the sum of hours of reduced production caused by unplanned outages, weighted according to how much capacity was out.

Forced outage is given in percent, while planned outage (for example due to maintenance) is given in days per year.

Technical lifetime

The technical lifetime is stated in years and in number of round-trip cycles (charging + discharging) assuming the max DoD.

The technical lifetime is the expected time for which the storage facility can be operated within, or acceptably close to, its original performance specifications, provided that normal operation and maintenance takes place. During this lifetime, some performance parameters may degrade gradually but still remain within acceptable limits. For instance, efficiencies often decrease slightly (a few percent) over the years, and O&M costs increase due to wear and degradation of components and systems. At the end of the technical lifetime, the frequency of unforeseen operational problems and risk of breakdowns is expected to lead to unacceptably low availability and/or high O&M costs. At this time, the plant is decommissioned or undergoes a lifetime extension, which implies a major renovation of components and systems as required in making the storage unit suitable for a new period of operation.

The technical lifetime stated in this catalogue is a theoretical value inherent to each technology, based on experience. The expected technical lifetime takes into account a typical number of start-ups and shut-downs.

In real life, specific storage facilities of similar technology may operate for shorter or longer times. The strategy for operation and maintenance, e.g. the number of operation hours, start-ups, and the reinvestments made over the years, will largely influence the actual lifetime.

The lifetime is expressed in years for all the storage technologies. For electrical batteries it is expressed both in years and in number of cycles, since different utilization of the battery in terms of frequency of charge/discharge depth has an impact on its lifetime. This second figure is specified in the Technology Specific Data.

To calculate the technical lifetime in years for batteries based on the total number of cycles, a certain number of cycles per year has been assumed and is expressed in the notes.

Construction time

Time from final investment decision (FID) until commissioning completed (start of commercial operation), expressed in years.

1.2.2. Regulation ability

The electricity regulation capabilities of the technologies are described by various parameters:

- Primary load support (% per 30 seconds)
- Secondary load support (% per minute)
- Minimum load (% of full load)

1.2.3. Financial data

Financial data are all in INR, fixed prices, at the 2023-level and exclude all taxes and subsidies.

Indian data has been prioritized in developing this catalogue.

Investment cost

The investment cost is also called the engineering, procurement and construction (EPC) price or the overnight cost. Infrastructure and connection costs, i.e. electricity, fuel and water connections inside the premises of a plant, are also included.

The rent of land is not included but may be assessed based on the space requirements, if specified in the qualitative description.

The owners' predevelopment costs (administration, consultancy, project management, site preparation, approvals by authorities) and interest during construction are not included. The costs to dismantle decommissioned plants are also not included. Decommissioning costs may be offset by the residual value of the assets.

The total investment cost is reported on a normalized basis, i.e. cost per MWh of energy storage capacity and discharge capacity per MW. It is the total investment cost divided by, respectively, the energy storage capacity for one unit and divided by the discharge capacity, stated in the table.

For most of the storage technologies it is possible to identify three main cost components: an *energy* component, a *capacity* component and other fixed costs. Where possible, total investment costs is divided into these components.

The cost of the energy component includes all the costs related to the equipment to store the energy, which would incur in case of expanding the MWh rating of the system, for example battery modules or reservoirs in a pumped-hydro plant. The cost of the capacity component refers to the part of the equipment to condition or convert the energy carrier and make it available to the user or the grid, for example a converter and grid connection for a battery system or a turbine/pump and grid connection for a pumped hydro plant. This is the cost to increase the MW capability of the system. Finally, another cost component reflects the fixed costs related to the project, such as data management and control system, project engineering, other civil works, commissioning.

Summarizing, the components considered are the following:

- *Cost of Energy component* (C_E) [cr. INR/MWh]: cost related to the equipment to store the energy (incl. their installation).
- *Cost of Capacity component* (C_P) [cr. INR/MW]): cost related to the equipment to condition or convert the energy carrier and make it available to the user or the grid (incl. their installation).
- *Other project costs (C_{other})* [cr. INR]: includes fixed costs which do not scale with capacity or energy, such as those for data management and control system, project engineering, civil works, buildings, site preparation, commissioning.

In this catalogue, the ***Total investment cost*** is expressed in relative terms, in cr. INR/MWh, by dividing the Total Capital Expenditure by the *Energy storage capacity for one unit* in MWh.

$$Total\ Capital\ Expenditure = C_E * E_{SC} + C_P * P_{out} + C_{other} \qquad [cr.INR]$$

$$Total\ investment\ cost = \frac{Total\ Capital\ Expenditure}{E_{SC}} = C_E + \frac{C_P}{h} + \frac{C_{other}}{E_{sc}} \qquad [cr.INR/MWh]$$

where:

E_{SC} = Energy Storage Capacity for one unit [MWh]

P_{out} = Output capacity for one unit [MW]

$h = \frac{E_{sc}}{P_{out}}$ = unload hours [h]

For electricity storage applications with a power-intensive service, an alternative Total investment cost in cr. INR/MW is indicated in the Technology specific data, calculated by dividing the Total Capital Expenditure by the Output capacity for one unit ($Total\ Capital\ Expenditure/P_{out}$).

Cost of grid expansion

The costs for the connection of the storage unit to the system are included in the investment cost (shallow costs), while no cost of grid expansion or reinforcement is considered in the presented data (deep costs).

Business cycles

The cost of energy equipment shows fluctuations that can be related to business cycles. This was the case of the period 2007-2008 for example, where costs of many energy generation technologies surged dramatically. The trend was general and global. An example is combined cycle gas turbines (CCGT), where investments increased sharply from $400-600 per kW to peaks of $1250. When projecting the costs of technologies, it is attempted, as far as possible, to compensate for the effect of any business cycles, that may influence the current prices.

Economy of scale

A typical size of the storage unit is stated in the technology description and datasheet. No economy of scale or scaling rule is considered in this catalogue. Instead, the cost components for energy and capacity specified for the technologies is intended to be used in a limited range around the typical capacity and not, for example, for doubling the capacity.

In case a technology has a modular nature and could be scaled across different sizes, this will be specified in the specific technology chapter.

Operation and maintenance (O&M) costs

The fixed share of O&M can be expressed in two different ways.

1. The fixed share of O&M can be expressed in terms of percentage (%) of the Total investment cost, as defined in the previous paragraph and stated in the tables.

2. The fixed share of O&M is calculated as the cost per energy storage capacity for one unit per year (INR/MW/year), where the energy storage capacity is the one defined at the beginning of this chapter and stated in the tables.

It includes all costs which are independent of how the storage system is operated, e.g. administration, operational staff, payments for O&M service agreements, network or system charges, property tax, and insurance. Any necessary reinvestments to keep the unit operating within the technical lifetime are also

included, whereas reinvestments to extend the life are excluded. The cost of reinvestments to extend the lifetime of the storage unit may be mentioned in a note if the data is available.

The variable O&M costs (INR/MWh) are calculated as costs per MWh of energy effectively released by the storage. This includes consumption of auxiliary materials (water, lubricants, fuel additives), treatment and disposal of residuals, output related repair and maintenance, and spare parts (however not costs covered by guarantees and insurances).

For electricity storage technologies, auxiliary electricity consumption is included in the round-trip efficiency.

Planned and unplanned maintenance costs may fall under fixed costs (e.g. scheduled yearly maintenance works) or variable costs (e.g. works depending on actual operating time), and are split accordingly.

It should be noticed that O&M costs often develop over time. The stated O&M costs are therefore average costs during the entire lifetime.

Components of power storage cost

The system considered when defining the characteristics of the electrical energy storage - in particular its cost and efficiency performance - is the entire energy storage system including the connection to the grid. The system boundaries and the subdivision of the equipment in the three cost components, as defined in the *Investment cost* paragraph of the guideline, are shown below for different electricity storage technologies.

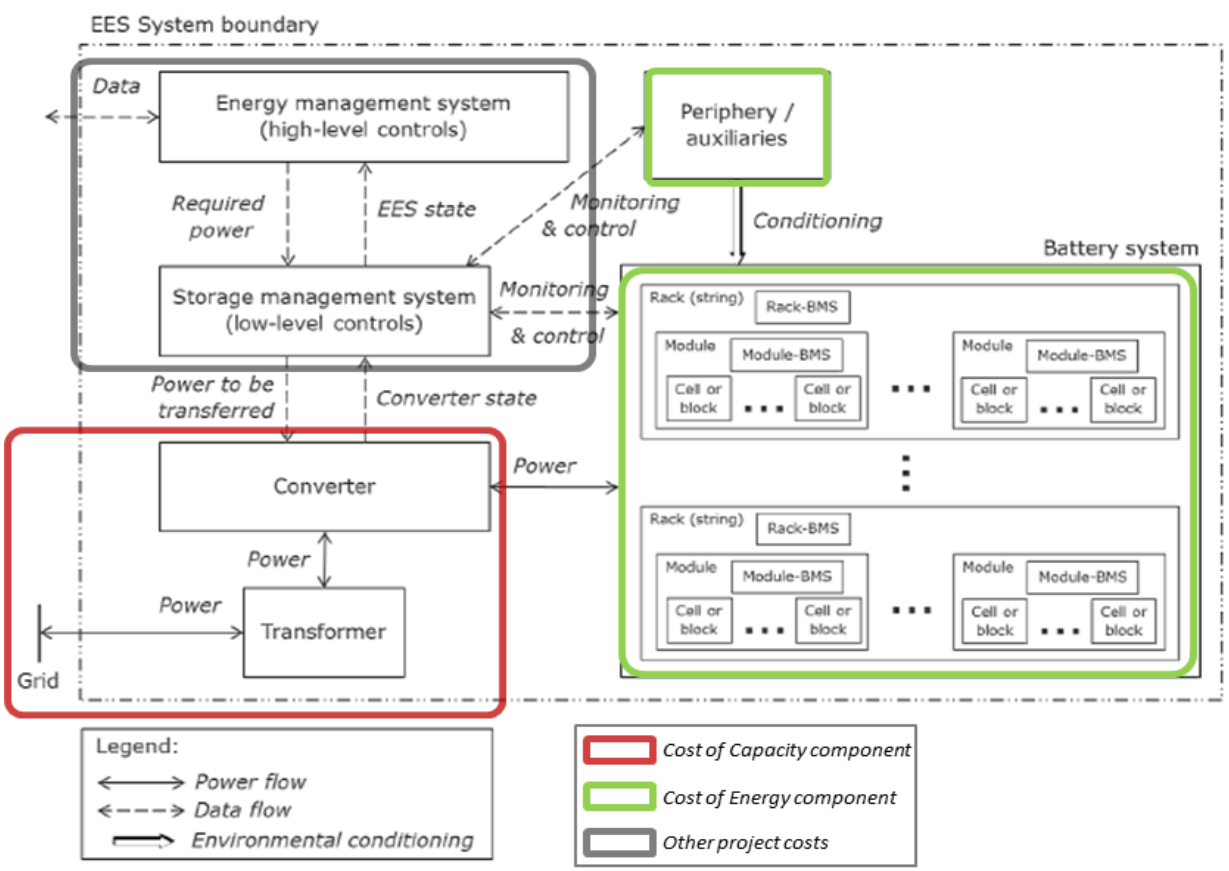

Figure 1-2: Components and their categorization for cell-based batteries, such as Li-ion. Source: elaboration of [5].

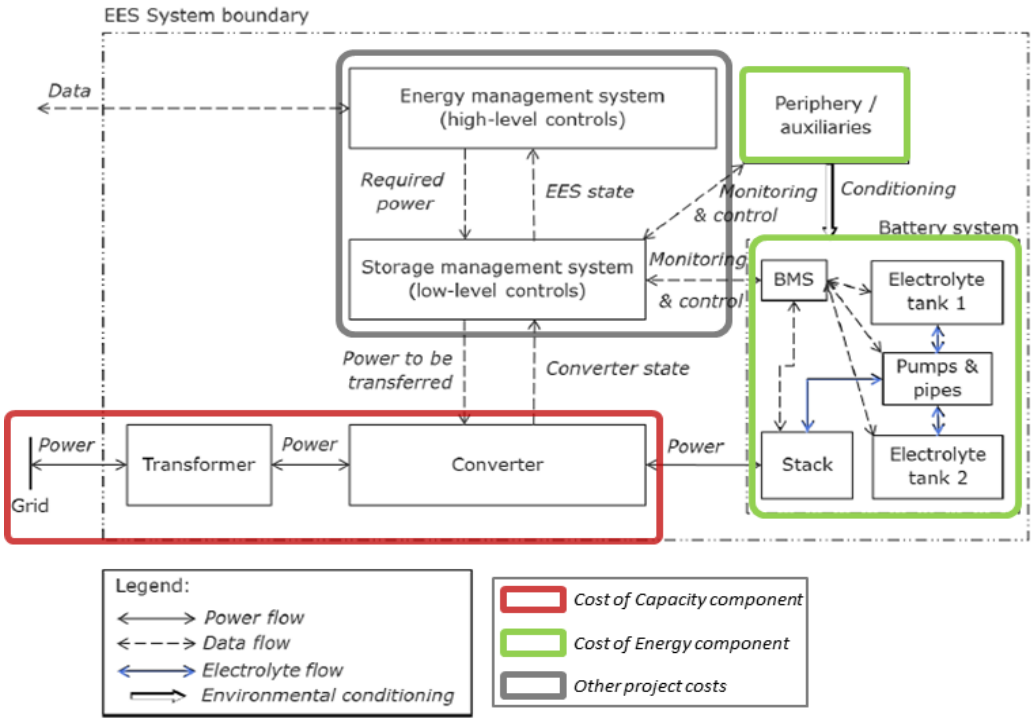

Figure 1-3: Components and their categorization for Vanadium-redox flow battery. Source: elaboration of [5].

Energy component

The energy component includes the following equipment and its installation:

- Cell-based batteries: battery modules, battery management system (BMS), local protection, racking frame/cabinet.
- Vanadium-redox: electrolytes, pumps and pipes, stack, battery management system (BMS).

For batteries and vanadium redox storage, auxiliaries for cooling are considered in the energy component since they need to be scaled when more cells or electrolytes are added to increase the energy storage capacity.

Capacity component

The capacity component includes the following equipment and its installation:

- Cell-based batteries and vanadium-redox: power conversion system (PCS), grid connection and protection.

Grid connection

The costs for the connection of the storage unit to the power system are included (shallow costs), while no cost of grid expansion or reinforcement (deep costs) is considered.

For system level application, unless otherwise stated, the connection is assumed to be at medium level voltage. The costs include: step-up transformer (low-medium voltage for BES), switchgears, breakers, meters and dedicated cabling to reach the connection point. In case of local level applications of BES, the transformer is not needed and the battery is normally connected to the low voltage, with a low cost for grid connection.

Power conversion system (PCS)

The power conversion system (or power conditioning system) ensures the bi-directional conversion AC to DC and DC to AC during charge and discharge respectively. This is done through a bi-directional inverter. To control the voltage level and avoid harmonics in the grid, a two-stage converter is sometimes used, complementing the inverter with a DC-DC converter to keep the inverter DC voltage constant [6].

An important design parameter is the voltage range in which the converter works. Today's applications are typically at 1000 V, but some 1500 V applications are emerging [7].

Among the reasons for a higher cost is the necessity for higher power performance and compliance to grid codes to provide ancillary services, bidirectional electricity flow and two-stage conversion, as well as the early stage of development and the fact that few manufacturers can guarantee turnkey systems [7].

In the future, with larger deployment of the technology and a move towards a more commercialized phase, the price of power conversion system (PCS) can be expected to drop, which is also the case for the module cost.

1.2.4. Technology specific data

Additional data is specified in this section, depending on the form of energy stored.

For storage technologies (batteries in particular) the power density (W/m^3) and energy density (Wh/m^3) are stated, as well as the specific energy (Wh/kg) and specific power (W/kg).

For power intensive applications, the total investment cost per MW is also stated, as an alternative figure to the total investment in INR/MWh (see Financial data paragraph above for clarification).

1.3. References

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2. Lithium-ion batteries for grid-scale storage

2.1. Brief technology description

A lithium-ion battery or Li-ion battery (abbreviated as LIB) can store electric energy as chemical energy. Both non-rechargeable and rechargeable LIBs are commercially available. The non-rechargeable LIBs (also called primary cells) have long shelf life and low self-discharge rates and are typically fabricated as small button cells for portable consumer electronics, arm watches and hearing aids. Rechargeable LIBs (also named secondary cells) are used in many consumer electronics and entered new markets such as electric vehicles and large-scale electricity storage. The rechargeable LIBs can also be used to supply power system level services such as primary frequency regulation, voltage regulation and load shifting, as well as for local electricity storage at individual households. In this catalogue the focus is on rechargeable LIBs.

A LIB contains two porous electrodes separated by a porous membrane. A liquid electrolyte fills the pores in the electrodes and membrane. Lithium salt (e.g. LiPF6) is dissolved in the electrolyte to form Li+ and PF6- ions. The ions can move from one electrode to the other via the pores in the electrolyte and membrane. Both the positive and negative electrode materials can react with the Li+ ions. The negative electrode in a LIB is typically made of carbon and the positive electrode is of Lithium metal oxide. By convention, the positive and negative electrode are also called the anode and the cathode respectively. Electrons cannot migrate through the electrolyte and the membrane physically separates the two electrodes to avoid electrons crossing from the negative to the positive electrode and thereby preventing internally short circuiting of the battery. The individual components in the LIB are presented in Figure 2-1.

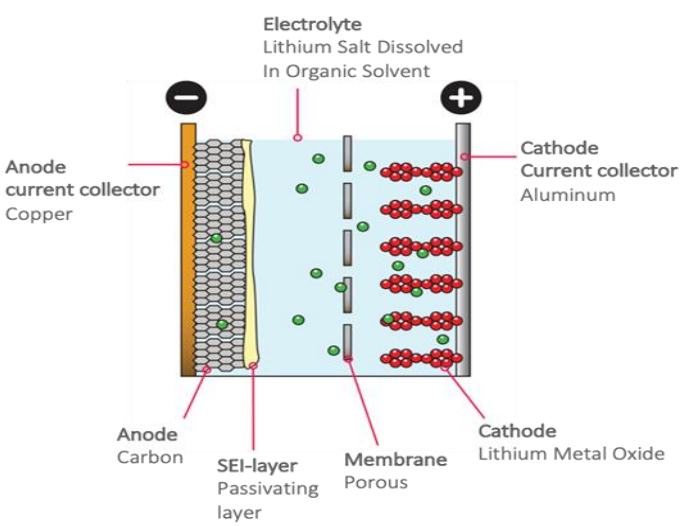

Figure 2-1: Schematic diagram of a typical LIB system displaying the individual components in the battery [1].

When the two electrodes are connected via an external circuit the battery start to discharge. During the discharge process electrons flow via the external circuit from the negative electrode to the positive. At the same time Li+ ions leave the negative electrode and flows through the electrolyte towards the positive electrode where they react with the positive electrode. The process runs spontaneously since the two electrodes are made of different materials.

The energy released by having one Li^+ ion and one electron leaving the negative electrode and entering the positive electrode is measured as the battery voltage times the charge of the electron. In other words, the

battery voltage - also known as the electromotive force: EMF - measures the energy per electron released during the discharge process. EMF is typically around 3-4 Volts and depends on the LIB cell chemistry, the temperature and the state of charge (SOC – see below). When a light bulb is inserted into the circuit, it primarily consumes the energy, leading to the dissipation of energy from the LIB. Substituting the bulb with a voltage source, such as a power supply, reverses the battery's operation, enabling energy storage.

The discharge and charge process are outlined in Figure 2-2. The battery is fully discharged when nearly all the Lithium have left the negative electrode and reacted with the positive electrode. If the battery is discharged beyond this point the electrode chemistries become unstable and start degrading. When the LIB is fully discharged the EMF is low compared to when it is fully charged. Each LIB chemistry has a safe voltage range for the EMF and the endpoints of the range typically define 0% and 100% state of charge (SOC), and the safe voltage range prevents complete Lithium removal. The discharge capacity is measured in units of Ampere times hours, and depends on the type and amount of material in the electrodes. Overcharging, or prolonged storage at high SOC also accelerates degradation.

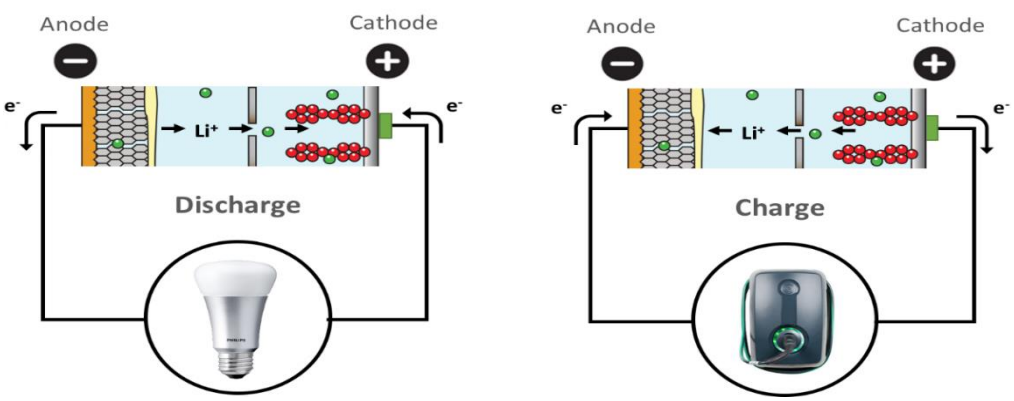

Figure 2-2: Schematic diagram of a LIB system in charge and discharge mode. During discharge the green Li+ ions move from the negative electrode (left side) to the positive electrode. The process is reversed during charge mode (right side).

The first lithium batteries were developed in the early 1970s and Sony released the first commercial lithium-ion battery in 1991. During the '90s and early 2000s the LIBs gradually matured via the pull from the cell-phone market. The Tesla Roadster was released to customers in 2008 and was the first highway legal serial production all-electric car to use lithium-ion battery cells. Further, around 2010 the LIBs expanded into the energy storage sector.

2.1.1. Li-ion Sub-Technologies

There are two prominent sub-technologies of Li-ion batteries that are dominating the International Li-ion market.

NMC Li-ion

The Nickel Manganese Cobalt (NMC) lithium-ion battery is a versatile and high-performance rechargeable energy storage technology. It belongs to the broader class of lithium-ion batteries and is renowned for its exceptional energy density, cycle life, and power output. NMC batteries utilize a combination of nickel oxide (NiO_2), manganese oxide (Mn_2O_4), and cobalt oxide (CoO_2) as cathode materials, carefully balanced to achieve desired performance characteristics.

NMC batteries have a higher energy density compared to LFP, meaning that they are capable of storing more energy in a small space. This makes them favourable for use in applications where space and weight are a priority, such as portable electronic devices, tools, and electric vehicles. Figure 2-3 shows a NMC Li-ion battery.

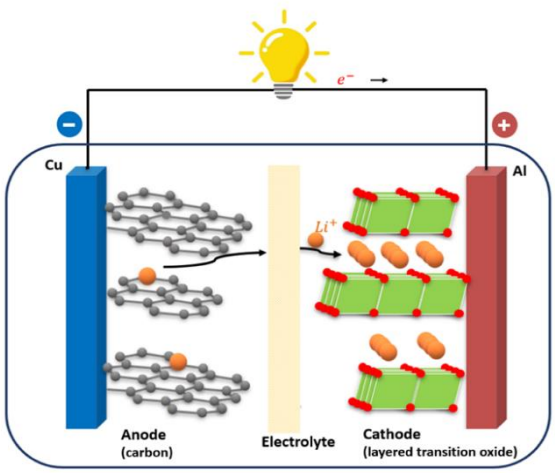

Figure 2-3: NMC Li-ion battery [2].

LFP Li-ion batteries

The lithium iron phosphate battery ($LiFePO_4$ battery) or LFP battery (lithium ferrophosphate) is a type of lithium-ion battery using lithium iron phosphate ($LiFePO_4$) as the cathode material, and a graphitic carbon electrode with a metallic backing as the anode. Because of their lower cost, high safety, low toxicity, long cycle life and other factors, LFP batteries are finding a number of roles in vehicle use, utility-scale stationary applications, and backup power. Figure 2-4 shows the charging and discharging of LFP battery.

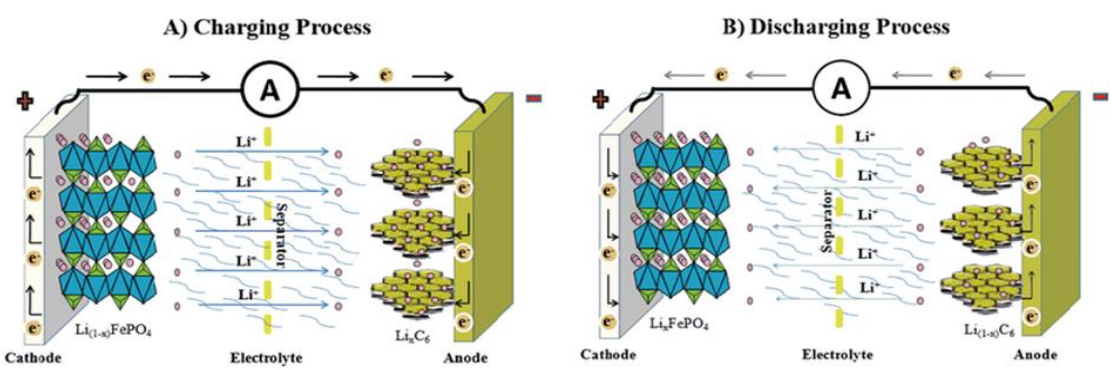

Figure 2-4: Charging and discharging of LFP battery [3].

2.1.2. Lithium-ion chemistries

Table 2-1 shows a comparison of the three most widely used LIB chemistries for grid-connected LIB systems and the major manufactures. Other LIB chemistries such as LCO, LMO and NCA are generally not used for grid electricity storage and are therefore not included in the table. The numbers in the table are taken from cell manufactures, product or system suppliers. NMC is the most widely used of the three chemistries due to the increased production volume and lower prices lead by the automotive sector. The NMC battery has a

high energy density but uses cobalt. The environmental challenges in using cobalt are described in the section: “Environment”.

The LFP battery do not use cobalt in the cathode, but are not as widely used as NMC, and are therefore generally higher priced, primarily due to the lower production volumes.

Both NMC and LFP batteries have graphite anodes. The main cause for degradation of NMC and LFP LIBs is graphite exfoliation and electrolyte degradation which in particular occur during deep cycling when the SOC is decreased below 10%.

LTO (Lithium Titanate Oxide) LIBs are the most expensive cell chemistry of the three. In LTOs the graphite anode is replaced with a Lithium Titanate anode. The cathode of a LTO battery can be NMC, LFP or other battery cathode chemistries. LTO batteries stand out for their high-power density and find widespread application in transportation and energy storage systems. Unlike conventional lithium-ion batteries, LTO batteries utilize a unique anode material—lithium titanate nanocrystals ($Li_4Ti_5O_{12}$). These nanocrystals offer an effective surface area approximately 30 times larger than traditional carbon-based anodes. Notably, LTO batteries excel in rapid charging, making them suitable for scenarios where quick energy replenishment is crucial. However, their energy density remains lower compared to other lithium-ion variants. The LTO battery is characterized by long calendar lifetime and high number of cycles. Table 2-1 gives the comparison of widely used LIB chemistries.

Table 2-1: A comparison of widely used LIB chemistries.

Short name	Name	Anode	Cathode	Energy density Wh/kg	Cycles	Calendar life	Major manufactures	References
NMC	Lithium Nickel Manganese Cobalt Oxide	Graphite	Li $Ni_{0.6}Co_{0.2}Mn_{0.2}O_2$	120-300	3000-10000	10-20 years	Samsung SDI LG Chem SK Innovation Leclanche Kokam	[4], [5]
LFP	Lithium Iron Phosphate	Graphite	$LiFePO_4$	50-130	6000-8000	10-20 years	BYD/Fenecon Fronius/Sony*	[4]
LTO	Lithium Titanate Oxide	$LiTO_2$	$LiFePO_4$ or Li $Ni_{0.6}Co_{0.2}Mn_{0.2}O_2$	70-80	15000-20000	25 years	Leclanche Kokam Altairnano	[4], [6]

**Residential energy storage system. All other systems are multi-MWh size.*

2.1.3. Lithium-ion battery packaging

The most common packaging styles for LIB cells are presented in Figure 2-5 (a)-(d). Figure 2-5 (a) shows a schematic drawing of a cylindrical LIB cell, cylindrical cells find widespread applications ranging from laptops and power tools to Tesla's battery packs. Figure 2-5 (b) outlines a coin LIB cell Coin cells are usually used as primary cells in portable consumer electronics, watches and hearing aids. Since they are not used for secondary cells (rechargeable) in grid-connected LIB Battery Energy Storage Systems they are not described further in this text. Figure 2-5 (c) displays a schematic drawing of a prismatic LIB cell, which are often used in industrial applications and grid-connected LIB Battery Energy Storage Systems. Figure 2-5 (d) shows a schematic drawing of a pouch LIB cell, which are also used in electric vehicles such as the Nissan Leaf. Figure 2-6 (a)-(d) shows examples of various commercial LIB. Figure 2-6 (a) shows Tesla's 21700 cylindrical LIB cell which is 21 mm in diameter and 70 mm in length. The cell is produced in Tesla's Gigafactory 1 for Tesla Model 3 [7]. The Samsung SDI prismatic LIB cell is shown in Figure 2-6 (b), this cell type is used in the BMW i3 [8]. Figure 2-6 (c) shows an LG Chem pouch NMC LIB cell used in LG Chem's grid-connected LIB Battery Energy Storage Systems [9].

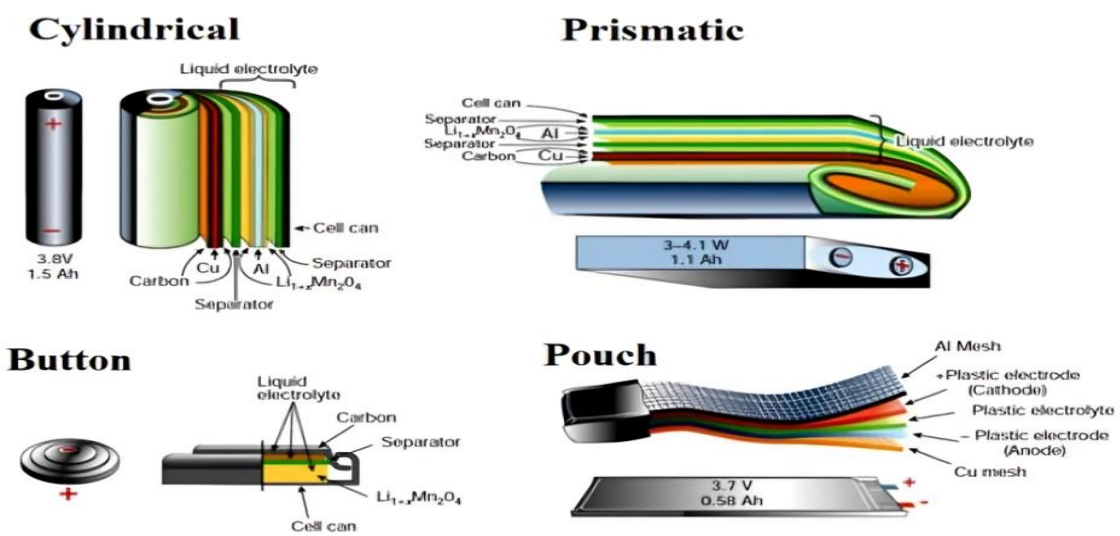

Figure 2-5: Schematic drawing showing the shape, packaging and components of various Li-ion battery configurations [10]. (a) Cylindrical; (b) Button; (c) prismatic; and (d) pouch.



Figure 2-6: Examples of LIB cells. (a) Tesla 21700 cylindrical NMC LIB cell [11]. (b) Samsung SDI prismatic LIB cells [12]. (c) LG Chem pouch NMC LiB cell [13].

2.1.4. Components in a lithium-ion battery energy storage system

Figure 2-7 provides an overview of the components in a LIB storage system with interface to the power grid. In LIB storage systems, battery cells are grouped together to form modules which are then grouped together

to form packs. The LIB storage system includes Thermal Management System (TMS) and Energy storage Management System (EMS). A Thermal Management System (TMS) regulates the temperature for the battery and storage system. The TMS depends on the environmental conditions, e.g. whether the system is placed indoor or outdoor. Further, an Energy Management System (EMS) regulates the charging and discharging of the grid-connected LIB storage. The power electronics system can have either one or more voltage inverter units (DC/AC link) and a transformer coupling element based on the preferred application. The system can also be integrated into higher grid voltage levels.

The grid integration provides services to the grid such as increased reliability, load shifting, frequency regulation etc. The services are described further below in section 2.4 Regulation ability and other system services. Value generation and profit is created by selling the services to grid Transmission System Operators (TSOs) in Ancillary services market. Battery capacity may be sold to the TSOs in full or partially, allowing for alternate use of the remaining capacity, for example local load management, energy trading or DSO services. Appropriate sizing of the battery and power conversion systems is essential to maximize the revenue. Technical and economic aspects of a battery storage system, system coupling, and grid integration are summarized in Table 2-2.

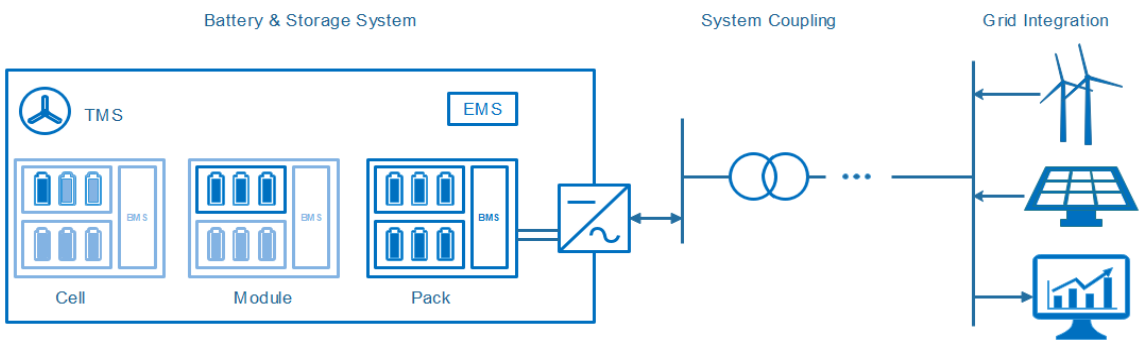

Figure 2-7: Schematic drawing of a battery storage system, power system coupling and grid interface components. [14]. TMS: Thermal management system, EMS: Energy management system, BMS: Battery management system.

Table 2-2: Formalized overview of the battery storage system, power system and grid interface components considering both technical and economic aspects. Modified from [14].

Parameters	Battery & Storage System	System Coupling	Grid Integration
Technical	Battery System (Cell, Module, Pack) Battery Management System (BMS) Energy Management System (EMS) Thermal Management System (TMS)	Power Electronics (AC/DC) & Transformer Environmental Conditions	Application Specific Profile Local Connection / Grid Level of Integration Dispatching according to operator.
Economic	CAPEX: Battery system and sizing OPEX: Degradation and Efficiency Operation Control Strategy	CAPEX: Power Electronics/ Placement of System OPEX: Conversion Efficiency	CAPEX: Regulatory Framework OPEX: Regulatory Framework Profit / Savings via Application

2.2. Input/Output

Input and output are both electricity. Electricity is converted to electrochemical energy during charge and converted back to electricity during discharge in the reaction process as described earlier.

2.3. Energy efficiency and losses

The losses in a LIB can be divided in operational and standby losses. The operational losses are first described, then the standby losses. Finally, the energy efficiency is discussed.

2.3.1. Operational losses

The operational losses occur when energy is discharged or charged to/from the grid. It includes the conversion losses in the battery and the power electronics.

When the LIB is not operated its voltage U equals the *EMF*. However, during discharge or charge the battery voltage U change due to current I passing the internal resistance R_i in the LIB. The voltage change ΔU can be described using Ohms law

$$\Delta U = U - EMF = R_i I \quad (1)$$

and the loss in the internal resistance is defined as

$$P_{loss} = \Delta U I = R_i I^2 \quad (2)$$

Equation (2) explains how the loss increases with increasing current.

The LIB provides a DC current during discharge and needs a DC current input for charging. Before the electricity is sent to the grid the inverter converts the DC current to AC. The inverter loss typically increases gradually from around 1% to 2% when increasing the relative conversion power from 0% to 100% [15].

2.3.2. Standby losses

Unwanted chemical reactions[3] cause internal current leakage in the LIB. The current leakage leads to a gradual self-discharge during standby. The self-discharge rate increases with temperature and the graph below shows the remaining charge capacity as function of time and temperature for a LIB. The discharge rate is the slope of the curve and is around 0.1% per day at ambient temperature. Figure 2-8 shows the remaining charge capacity for a typical LIB.

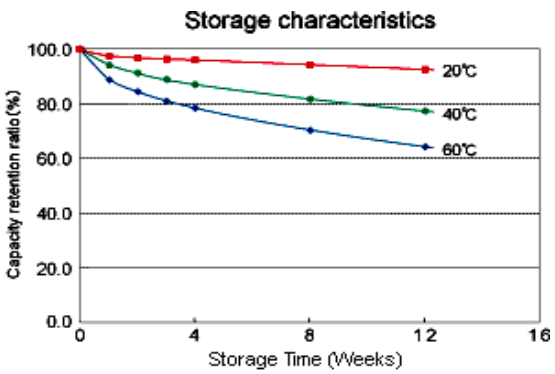

Figure 2-8: Remaining charge capacity for a typical LIB as function of storage time [16].

Besides the self-discharge in the cell, a LIB electricity storage system requires power to operate the auxiliary balance of plant (BOP) components. Figure 2-7 outlines the BOP components which include the inverter, BMS (Battery Management System), EMS (Energy Management System) and TMS (Thermal Management System). The relative energy loss to the BOP components depends on the application, and a careful operation strategy is important to minimize their power consumption [15]. The standby loss E_{stb} is the sum of the energy losses during standby due to self-discharge and power consumption in the BOP components.

2.3.3. Energy Efficiency

The conversion roundtrip efficiency of the LIB cell is the discharged energy divided with the charged energy. The battery conversion efficiency decreases with increasing current since the P_{loss} increases. An example of a LIB cell conversion efficiency is shown in Figure 2-9. The C-rate is the inverse of the time it takes to discharge a fully charged battery. At a C-rate of 2 it takes ½ hour and at a C-rate of 6 it takes 10 minutes.

[3] In LIB sometimes, unwanted side reactions can occur due to impurities, defects, or degradation of the battery components over time. These unwanted chemical reactions can lead to the formation of conductive pathways within the battery, which allow electrons to bypass the intended circuit, causing internal current leakage

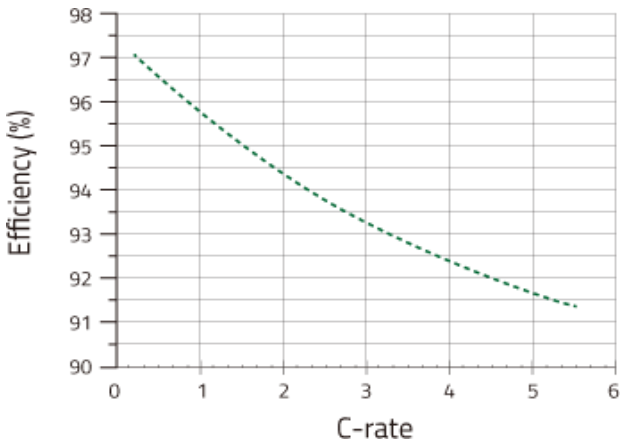

Figure 2-9: Conversion round trip efficiency vs. C-rate for one of Kokam's NMC-based lithium polymer batteries [17].

The system conversion roundtrip efficiency $\eta_{conversion}$ considers losses which occur on the conversion path from the energy charged $E_{Ch\,\mathrm{arg}\,e,\,AC}$ and the energy discharged $E_{Disch\,\mathrm{arg}\,e,\,AC}$ from/to the grid. It includes the conversion losses in the battery and power electronics and can be written as

$$\eta_{Conversion} = \frac{E_{Disch\,\mathrm{arg}\,e,AC}}{E_{Ch\,\mathrm{arg}\,e,AC}} \qquad (3)$$

The total roundtrip efficiency $\eta_{Total\,1}$ further includes the standby losses:

$$\eta_{Total} = \frac{E_{Disch\,\mathrm{arg}\,e,AC}}{E_{Ch\,\mathrm{arg}\,e,AC} + E_{stb}} \qquad (4)$$

Here E_{stb} denotes the energy required from the grid to continuously operate BOP and maintain state of charge. The various types of losses make η_{Total} heavily dependent on the application. The total roundtrip efficiency for a system is around 80 % at the lower end [19]. Lazard uses an estimate of 85% [20]. To summarize, the total roundtrip loss typically consists of 2-5% related to the cell, 2-4% to the power electronics and the rest to standby losses.

2.4. Regulation ability and other system services

Grid-connected LIBs can absorb and release electrical energy fast. The response time of grid-connected LIBs are strongly dependent on control components, namely the EMS, BMS and PCS (Power conversion system).

The competitive installation cost (outlined below) makes grid-connected LIB BESS (Battery Energy Storage System) suitable for a broad range of applications [21] such as peak load shaving where the BESS provides or receives energy to reduce peaking in a power system. In relation to this BESS can promote renewable integration, e.g. time or load shifting of photovoltaic power from day to night. Further the BESS can provide transmission congestion relief where locally deployed BESS reduces the load in the transmission and distribution system. In this way the BESS can help defer expensive upgrades of the transmission and distribution network.

The fast response time enables the use of BESS for a broad range of primary control provisions. These include Frequency regulation where the BESS are used to alleviate deviations in the AC frequency. Today, frequency regulation is the main application of stationary BESS systems deployed worldwide. The BESS can also be used to improve network reliability by reacting immediately after a contingency. Here the BESS can help maintaining stability in the power system until the operator has re-dispatched generation. Moreover, the

BESS can effectively be used for black-starting distribution grids and LIB-BESS systems are suitable for enhancing the power quality and reducing voltage deviations in distribution networks. The BESS can further be used to provide spinning reserves and regulate active and reactive power thereby improving the network voltage profile. This can improve the integration of renewable energy.

2.5. Typical characteristics and capacities

The frame or shelf that holds the batteries is called a rack, i.e. the battery pack (Figure 2-7) without the BMS. The energy per rack is typically 60-166 kWh [5], [22].

- The size is e.g. 415mm x 1067 mm x 2124 mm (W x D x H) for a 111kWh rack from Samsung SDI [5] and 520 mm x 930 mm x 2200 mm (W x D x H) for a 166.4 kWh rack from LG Chem [22]. Both companies use the NMC chemistry.
- The weight of the Samsung SDI rack is 1170 kg, and the C-rate is 0.5 during charge and up to 6 during discharge. For the LG Chem system the weight is 1314 kg and C-rate for the LG Chem systems ranges from around 0.3 to +1 but is not specified in detail.
- The energy density of 118 kWh/m^3 and 0.095 kWh/kg for the Samsung SDI system and 156 kWh/m^3 and 0.127 kWh/kg for the LG chem system

For the Samsung SDI system the power density in charge-mode is 50 kW/m^3 and 0.047 kW/kg. In discharge-mode it is 708 kW/m^3 and 0.569 kW/kg. For LFP Delta ESBU model series the cabinet installed capacity is 315.4 kwh and the size for 10 such cabinet is 7400 mm x 3530 mm x 2440 mm and the weight for this system is 39,500 kg. This module consists of LFP 280 Ah cells [23].

2.6. Typical storage period

Several aspects of the LIB technology put an upper limit to the feasible storage period. The self-discharge rate makes storage periods of several months unfeasible. The BOP power for standby operation adds parasitic losses to the system which further limits the feasible standby time. Unwanted chemical reactions in the LIB gradually degrade the battery and limit the calendar lifetime. This calls for shorter storage periods in order to obtain enough cycles to reach positive revenue.

For LIBs the total number of full charge-discharge cycles within the battery lifetime is limited between a few thousands up to some ten-thousands. The exact number depends on the chemistry, manufacturing method, design and operating conditions such as temperature, C-rate and calendar time. This impacts the type of suitable applications LIB systems have been deployed to provide frequency response with a response time ranging from seconds to minutes [24], and the systems are increasingly used for renewables time shifting with typical storage periods of a few hours [15], [24].

2.7. Space requirement

2.7.1. NMC battery

The racks and battery packs are typically assembled in containers and the energy per 40 feet container is 4 – 6 MWh for NMC batteries [5], [22]. The footprint of a 40-feet container is 29.7 m^2. This gives a space requirement around 5-7.5 m^2/MWh.

2.7.2. LFP battery

For LFP battery the energy density is 120 Wh/kg, weight of the battery pack required for 1 MWh is 8333 kg and the corresponding space requirement is 18.12 m^2 [23]. Using the space required for LFP as a reference, the corresponding area for NMC with an energy density of 220 Wh/kg is 9.7 m^2.

2.8. Advantages/disadvantages

Within the last decade the commercial interest for electricity storage using LIB systems has increased dramatically. The production volume is still limited and there is a promising potential for cost reductions through upscaling. The technology is stand-alone and requires a minimum of service after the initial installation. The following Table 2-3 and Table 2-4 summarize the advantages and disadvantages of lithium-ion batteries.

Table 2-3: Advantages and disadvantages of NMC batteries [25].

Advantages	Disadvantages
High energy density (> 200 Wh/kg)	Higher cost
Rapid charging and discharging (C/2 to C/3)	Lower thermal stability relative to LFP batteries
Versatile applications (EVs, portable electronics, grid storage)	Smaller lifespan
Good power-to-weight ratio	Limited tolerance for high-temperature environments
Improved cycle life compared to some other Li-ion chemistries	Environmental concerns over the mining of cobalt (in some NMC formulations)

Table 2-4: Advantages and disadvantages of LFP batteries [25].

Advantages	Disadvantages
High thermal stability	Lower energy density compared to NMC batteries
Cost-effective	Potential space requirements (not an issue in grid applications)
Long lifespan (3000-10,000 cycles)	Slower rate of energy release
Low maintenance	Heavier weight compared to NMC batteries
Improved safety characteristics	Limited high-rate charge and discharge capabilities

2.9. Environmental impact

Recent analysis shows that average global warming potential (GWP) from lithium-ion NMC batteries is 17.63 kg CO_2 eq/kg. These emissions mainly come from the mining of the materials, the refinement of these materials, and the manufacturing of the batteries themselves. This GWP varies depending on where in the world the batteries are produced, mainly due to how clean the electricity grid is in the local area. Other aspects either contribute low amounts to the total GWP caused by NMC batteries or they do not vary geographically. [26], [27]

The LIB cathode material NMC contains toxic cobalt and nickel oxides. About 60% of the global production of cobalt comes from DR Congo and the environmental health risks and work conditions in relation to the cobalt mining raises ethical concerns [28]. However, more recent lithium-ion chemistries, namely LFPs, remove the need for cobalt, eliminating one of the most problematic aspects of NMC production. It has also been shown that LFPs have a lower GWP by up to 50%. [26]

2.10. Research and development perspectives

Currently a wide range of government and industry-sponsored LIB material, cell, and system level research is taking place. Some of the ongoing material research to further increase the energy density of LIB cells includes high-voltage electrolytes allowing charging voltages of up to 5 volts [29] and silicon nanoparticle-based anodes to boost the charge capacity [30]. Several research and development activities focus on improving the cycle lifetime of LMO cells [31], [32], [33].

Some of the most promising post Li-ion technologies include Lithium Sulphur batteries that use Sulphur as an active material. Sulphur is abundantly available at reasonable price and allows for very high energy densities of up to 400 Wh/kg. Also, Lithium air batteries have received considerable attention. Since one of the active materials, oxygen, can be drawn from the ambient air, the lithium-air battery features the highest potential energy and power density of all battery storage systems. Due to the existing challenges with electrode passivation and low tolerance to humidity, large-scale commercialization of the lithium-air battery is not expected within the next years.

Several non-lithium-based battery chemistries are being investigated. Aluminium Sulphur batteries may reach up to 1000 Wh/kg with relatively abundant electrode materials but are still in the very early development phase [34].

Besides the materials research, improved cell design, BMS, TMS and EMS technology and operation strategy can improve storage efficiency considerably [15].

Although LIB systems for electricity storage are now commercially available, the R&D is still in its relatively early phase and is expected to contribute to future cost reductions and efficiency improvements.

2.11. Examples of market-standard technology

Grid scale turn-key LIB systems are commercially available from a wide range of suppliers. Referenced examples are shown in Table 2-5. Two larger grid-connected LIB systems are installed in Denmark: **A)** In Nordhavn, Copenhagen, Denmark a 630kW/460kWh was installed by ABB for Radius Elnet and Ørsted in 2017. This set the scene for Ørsted's first steps into commercial battery storage. For Ørsted the following energy storage projects are under development: a 20MW battery storage near Liverpool in UK and a 1 MW storage pilot project in Taiwan [35]. Lem Kær Wind Farm was Vestas' pilot project for energy storage which participates in the DK frequency regulation market. Vestas is working on Kennedy Power Plant that integrates wind and solar with grid-scale energy storage and will feature a 2MW / 4MWh grid-scale LIB storage system to provide ancillary services, test energy arbitrage and reduce curtailment.

Globally the two largest grid-scale LIB storage systems are the Mira Loma Substation in California which features 20MW/80MWh using 400 Tesla Powerpack 2 [38,39] and the Neoen's Hornsdale Wind Farm which features 100MW/129MWh [36], both systems provide peak shaving.

The Laurel Mountain, West Virginia, USA grid-scale LIB storage system at 32MW/8MWh [41] is designed for frequency regulation and with high power to energy ratio compared to the Tesla grid-scale LIB storage systems which are designed for peak shaving with a lower power to energy ratio.

Table 2-5: Examples of market-standard technology for grid-connected LIB systems.

Image	Location	Primary usage	Year	Power capacity	Techn. provider	Ref.
	Energylab Nordhavn, Copenhagen, Denmark	Frequency Regulation Peak Shaving Voltage Regulation Harmonic Filtering	2017	630 kW 460 kWh NMC	ABB for Radius Elnet / Ørsted	[37]
	Lem Kær Wind Farm, Denmark	Frequency regulation	2014	400kW LFP and 1.2MW LTO	Altairnano and A123 for Vestas	[38]
	Mira Loma Substation, California, USA	Peak Shaving	2016	20 MW 80 MWh	Tesla	[39], [40]
	Neoen's Hornsdale Wind Farm, South Australia	Peak Shaving	2017	100 MW 129 MWh	Tesla	[36]
	Laurel Mountain, Belington, West Virginia, USA	Frequency Regulation and Renewable Energy Integration	2011	32 MW 8 MWh	AES and A123	[41]

Examples of pilot projects of NMC and LFP technology in India [42] are shown in Table 2-6.

Table 2-6: Examples of market-standard technology for grid-connected LIB systems in India.

Image	Location	Manufacturer	Rating	Type	Applications
	Delhi	Assembly – Tata, AES Mitsubishi Battery – LG Chemicals	10 MW/ 10MWh	NMC	DSM, Frequency regulation, Peak shaving and Reactive Power Control
	Puducherry	PGCIL	500kW/250 kWh	LFP	Energy time shift, Frequency regulation
	Hyderabad	BHEL	500 kWh	LFP	Ramp rate control, Capacity firming
	Delhi	BHEL	415 kW /410 kWh	LFP, NMC and LTO	Peak shaving (cat.-A), Reliability improvement (cat.-B), Energy time shift (cat.-C)

Descriptions of additional projects are presented below.

2.11.1. TATA AES MITUSBHI 10 MW/10 MWH PROJECT (NMC)



Figure 2-10: TATA Li-ion (NMC) Plant in Delhi.

AES India, in collaboration with Mitsubishi Corporation, has commissioned a 10 MW/10 MWh Grid-connected Battery Energy Storage System in Delhi, for Tata Power Delhi Distribution Limited. The project employs advanced Lithium Nickel Manganese Cobalt oxide (NMC) battery technology from LG Chemical. It features four 2.5 MVA BESS transformers, totalling eight cores, with 31 racks per core for battery nodes. Each node has a capacity of 85 kWh, and individual battery fans maintain optimal temperature. The Battery Management System (BMS) ensures state of charge (SOC) within a range of 45–55%. The system's auxiliary energy consumption is 1–2% of battery capacity. This project has been completed in two years [43], [42].

The primary application is deviation settlement mechanism (DSM) due to substantial penalties incurred by the utility. However, the system is currently being tested to determine its most effective applications, which include frequency regulation, energy arbitrage, deviation settlement mechanism (DSM), peak shaving, and reactive power control among others.

The project, operating since April 2019 with a cost of 473 million INR (excluding taxes), allocates only 30% of the budget to batteries. Most of the capital is directed towards power-conditioning units, EMS, isolation transformers, and construction. Inverters account for 10–15% of the cost, while communication and electronic devices constitute a significant portion. [42]

Table 2-7: Technical specifications of NMC battery.

Parameter	Details
Battery Module Capacity	6.5 kWh
Voltage Rating of Battery Module	51.7 V
Modules per Node	14 (Connected in series)
Node Capacity	91 kWh
Battery Racks	31 per core
Battery Cooling System	Individual fans for each module (Activated above 40°C)
State of Charge (SOC) Range	10% to 99%
C-Rate for Battery	1 C
Auxiliary Energy Consumption	1–2% of battery capacity

2.11.2. BSES Rajdhani Power Limited (BRPL) – 20 MW / 40 MWh Standalone Battery Energy Storage System (BESS) Project

BSES Rajdhani Power Limited (BRPL) has commissioned a 20 MW / 40 MWh grid-connected standalone Battery Energy Storage System at its Kilokari substation in New Delhi. The project was developed under the support framework of the Global Energy Alliance for People and Planet (GEAPP) and executed through a public–private partnership involving BRPL, IndiGrid, and AmpereHour Energy. The system was commissioned within a 20-month implementation period. [44]

Table 2-8: Project overview [44].

Parameter	Details
Location	Kilokari Substation, New Delhi
Power Rating	20 MW
Energy Capacity	40 MWh
Implementing Agency	BSES Rajdhani Power Limited (BRPL)
Partners	GEAPP, IndiGrid, AmpereHour Energy
Commissioning Timeframe	20 months
Funding / Support	Global Energy Alliance for People and Planet (GEAPP)

The storage system supports multiple operational functions within BRPL's distribution network, including:

- Managing peak-load demand and reducing transformer overloading;
- Supporting renewable-energy integration and short-term energy balancing;
- Providing frequency and voltage control to enhance grid stability;
- Offering backup and reliability support for connected feeders during contingency events.

The BESS installation comprises modular containerized units with integrated power conversion systems, protection equipment, and an energy management system (EMS) interfaced with BRPL's supervisory control and data acquisition (SCADA) platform. The system's configuration allows flexible operation under both grid-support and renewable-integration modes.

This project is part of a broader initiative supported by GEAPP to demonstrate commercially viable storage solutions for distribution-level operations in India. The collaborative procurement and financing approach is intended to inform future large-scale deployments and policy frameworks for storage integration at the utility level.

2.11.3. BHEL 1 MWH PROJECT, HYDERABAD (LFP)

BHEL deployed 1 MWh of containerized BESS in three segments with different battery chemistry for ramp-rate control and capacity-firming applications. Various chemistries are selected to analyse their performance. Additionally, the system operates for capacity firming with a set power flow limit at interconnection points. [42].

The system consists of 500 kWh lithium–iron phosphate, 300 kWh advanced lead-acid, and 200 kWh flow batteries, integrated with a 500 kWp solar PV plant at a 6.6 kV AC bus. Three separate power-conditioning systems (500 kW, 100 kW, and 50 kW) are used.

The idea behind the selection of different battery chemistries is to analyze the performance of distinct chemistries since each battery technology exhibit some merits and demerits over other technologies. The system is designed for renewable integration; thus, the BESSs are integrated with a 500-kWp solar PV installed at BHEL corporate R&D, Hyderabad. Since the system is configured to operate in ramp-rate control mode, a predefined ramp-rate limit of 10% per minute of capacity (that is, ± 50 kW/minute) has been set. Accordingly, the control commands for charge/discharge operation are prompted by central EMS, if any change in generation (more/less than the predefined limit) from the solar PV plant is observed. Besides this, the system is configured to operate for capacity firming, thus a predefined limit for power flow can be ensured at common interconnection points irrespective of solar generation patterns. Consequently, the power flow (as a set point for BESS operation) at 6.6 kV bus has been set at 250 kW from 07:00 AM to 06:00 PM. The battery will be charged when solar PV generation is more than 250 kW while discharging of BESS takes place in case generation is lesser than 250 kW, thereby a constant power will be supplied to the grid during this period from the system (either from solar PV or through BESS).

2.12. Projection of performance and cost

The projection of cost has been conducted using the learning rate approach. Projections for installed capacity are sourced from the World Energy Outlook 2024 [45], while current globally installed capacity figures are derived from BNEF's 1H 2024 Energy Storage Market Outlook [46]. Learning rates are based on data from BNEF's Energy Storage System Cost Survey 2023 [47] and the IEA's Batteries and Secure Energy Transitions, 2024 [48], in accordance with the methodology outlined in the Colombian Technology Catalogue for Power Generation and Storage Technologies 2025 [49]. No cost reductions are anticipated between 2050 and 2070,

as batteries are assumed to have reached maturity, and further significant technological advancements are not expected. For details regarding learning rate approach please consult the Appendix.

Table 2-9: Component-wise learning rates for Lithium-ion batteries.

Technology	Component	Learning rate	Source
Lithium-ion battery energy storage	CAPEX - energy component (cr. INR/MWh)	17 %	[47]
	CAPEX - capacity component (cr. INR/MW)	10 %	[48]
	CAPEX - other project costs (cr. INR/MWh)	10 %	[48]
	Fixed O&M (cr. INR/MW/year)	10 %	[48]
	Variable O&M (INR/MWh)	10 %	[48]

Table 2-10: Cumulative deployment capacities assumptions.

	2024	2030	2040	2050
High-cost uncertainty (based on Net Zero Emissions by 2050 Scenario)	156 GW	853	2339	3438
Reference cost estimate (based on Announced Pledges Scenario)	156 GW	1015	2939	4386
Low-cost estimate (based on Stated Policies Scenario)	156 GW	1260	3802	5512
Source	[46]	[45]	[45]	[45]

2.13. Uncertainty

The cost projections imply a broad range of uncertainties. Both the learning rate and projected installed capacity developments are uncertain. Here, different assumptions for capacity developments are considered following the three scenarios of the WEO 2024: Stated Policies, Announced Pledges, and Net-zero by 2050 [45].

All other uncertainties, i.e. current costs, existing technical parameters, and projected technical developments—are based on a review of the literature and input from stakeholders.

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2.15. Datasheet

Technology	Battery storage system (LFP Lithium-ion)										
	2024	2030	2040	2050	2070	Uncertainty (2024)		Uncertainty (2070)		Note	Ref
						Lower	Upper	Lower	Upper		
Energy/technical data											
Form of energy stored	Electricity										
Application	System, power- and energy-intensive										
Generating capacity for one unit (MW)	10	10	10	10	10	1	10	1	10	A	9, 15
Storage capacity (MWh)	40	40	40	40	40	2	40	40	60	B, K	6, 15, 16
Depth of Discharge (%)	85	85	90	90	90	70	100	80	100	C	3, 15, 17
Round trip efficiency (%AC)	88	89	92	92	92	83	92	91	93		10, 15, 2, 5, 11
Round trip efficiency (%DC)	93	94	96	96	96	90	97	95	97		17, 15, 11, 5
- Charging efficiency (%)	96	97	98	98	98	95	98	97	98		11, 15, 17
- Discharge efficiency (%)	96	97	98	98	98	95	98	97	98		11, 15, 17
Energy loss during storage (%/day)	0.09	0.09	0.09	0.09	0.09						18, 11
Forced outage (%)	1.0	0.9	0.8	0.7	0.7	0.8	1.2	0.4	0.8		5
Planned outage (weeks per year)	1	0.5	0.5	0.5	0.5	0.2	2	0.1	0.6		5, 17
Technical lifetime (years)	15	20	20	25	25	10	20	20	30		3, 11, 15, 17
Construction time (years)	1	1	0.5	0.25	0.25	0.5	2	0.2	0.5		5, 15, 17
Lifetime (battery cycles)	5000	6000	8000	10000	10000	4000	6000	8000	11000		3, 17, 31, 32
Discharge time (h)	4	4	4	4	4	2	4	4	6	B, K	6, 15, 16
Regulation ability											
Primary load support (% per 30 seconds)	100	100	100	100	100						5
Secondary load support (% per minute)	100	100	100	100	100						5
Minimum load (% of full load)	0	0	0	0	0						5
Financial data (in 2023₹)											
Capital cost (cr. ₹/MWh)	1.47	0.97	0.77	0.70	0.70	1.22	1.72	0.67	0.74	H	17, 30
- energy component (cr. ₹/MWh)	0.93	0.56	0.42	0.38	0.38	0.77	1.09	0.36	0.41	E	17, 30 , 15
- capacity component (cr. ₹/MW)	0.38	0.28	0.24	0.23	0.23	0.31	0.44	0.22	0.24	F	17, 30 , 15
- other project costs (cr. ₹/MWh)	0.44	0.33	0.28	0.27	0.27	0.37	0.52	0.26	0.28	G	17, 30 , 15
Fixed O&M (cr. ₹/MW/year)	0.18	0.13	0.11	0.11	0.11	0.15	0.35	0.10	0.11	L	13, 17
Variable O&M per output (₹/MWh)	0.00	0.00	0.00	0.00	0.00	0.00	45.00	0.00	28.12	M	9, 13
Technology specific data											
Alternative Total investment cost (cr. ₹ per MW)	6.06	3.99	3.16	2.90	2.90	5.24	6.88	2.76	3.06	H	
Energy density (Wh/L)	324					261	350			N	1
Specific energy (Wh/kg)	156					133	172			N	1

Notes

A In the literature, a capacity of 10 MW is commonly taken as standard size.

B Recent tenders have predominantly featured 2-hour durations, but there is a growing shift toward 4-hour durations. Up to 6h can be expected in the future. 4h is a standard reference size in literature.

C At beginning of life, the Depth of Discharge is up to 100% while it decreases to 70% at the end of life

D Taken from test results of PSE Utility at the site Glacier with 4.4 MWh capacity in [7]

E Considering Storage Block cost + Storage Balance of System + System Integration

F Considering Power Equipment Cost + Controls and Communication + Grid Integration

G Considering Project Development + Engineering, Procurement, and Construction Cost (EPC)

H Calculated based on reference size and component costs.

K Storage capacity indicates the size for which the cost data has been compiled. Discharge time indicates the typical size in Indian projects.

L Lower and upper uncertainty are assumed to be 2.5% and 6 % of CAPEX in cr INR/MW, respectively

M For the point estimate, all O&M costs are assumed to be represented in Fixed O&M, following [13]

N cell level; derived from industry data published in [1], supplementary data

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Technology	Battery storage system (NMC Lithium-ion)										
	2024	2030	2040	2050	2070	Uncertainty (2024)		Uncertainty (2070)		Note	Ref
						Lower	Upper	Lower	Upper		
Energy/technical data											
Form of energy stored	Electricity										
Application	System, power- and energy-intensive										
Generating capacity for one unit (MW)	10	10	10	10	10	1	10	1	10	A	4, 8
Storage capacity (MWh)	40	40	40	40	40	2	40	40	60	B, C	9, 25
Depth of Discharge (%)	90	90	90	90	90	80	100	80	100	D	1, 8, 24
Round trip efficiency (%AC)	88	89	92	92	92	83	91	91	93		3, 8
Round trip efficiency (%DC)	93	94	96	96	96	90	95	95	97		3, 8
- Charging efficiency (%)	96	97	98	98	98	95	98	97	98		3, 8
- Discharge efficiency (%)	96	97	98	98	98	95	97	97	98		3, 8
Energy loss during storage (%/day)	0.08	0.08	0.08	0.08	0.08					E	2
Forced outage (%)	1.0	0.9	0.8	0.7	0.7	0.8	1.2	0.4	0.8	R	1
Planned outage (weeks per year)	1	0.5	0.5	0.5	0.5	0.2	2	0.1	0.6	R	1
Technical lifetime (years)	15	20	20	25	25	10	20	20	30		3, 8, 10
Construction time (years)	1	1	0.5	0.25	0.25	0.5	2	0.2	0.5	R	1, 8
Lifetime (battery cycles)	3000	4000	6000	7000	7000	1500	4000	6000	8000		8, 11, 29, 30
Discharge time (h)	4	4	4	4	4	2	4	4	6	G	8, 9, 25
Regulation ability											
Primary load support (% per 30 seconds)	100	100	100	100	100						1
Secondary load support (% per minute)	100	100	100	100	100						1
Minimum load (% of full load)	0	0	0	0	0						1
Financial data (in 2023₹)											
Capital cost (cr. ₹/MWh)	1.67	1.10	0.87	0.80	0.80	1.38	1.95	0.76	0.84	H, N	27
- energy component (cr. ₹/MWh)	1.06	0.64	0.48	0.43	0.43	0.88	1.24	0.41	0.46	I	27, 8
- capacity component (cr. ₹/MW)	0.43	0.32	0.27	0.26	0.26	0.36	0.50	0.25	0.27	J	27, 8
- other project costs (cr. ₹/MW)	0.50	0.38	0.32	0.30	0.30	0.42	0.59	0.29	0.31	K	27, 8
Fixed O&M (cr. ₹/MW/year)	0.20	0.15	0.13	0.12	0.12	0.17	0.40	0.12	0.12	O	
Variable O&M per output (₹/MWh)	0.00	0.00	0.00	0.00	0.00	0.00	45.00	0.00	28.12	P	
Technology specific data											
Alternative Total investment cost (cr. ₹ per MW)	6.87	4.52	3.59	3.29	3.29	5.94	7.80	3.13	3.47	H	
Energy density (Wh/L)	525					364	795			Q	31
Specific energy (Wh/kg)	259					190	395			Q	31

Notes

A In the literature, a capacity of 10 MW is commonly taken as standard size.

B Recent tenders have predominantly featured 2-hour durations, but there is a growing shift toward 4-hour durations. Up to 6h can be expected in the future. 4h is a standard reference size in literature.

C Storage capacity indicates the size for which the cost data has been compiled. Discharge time indicates the typical size in Indian projects.

D At beginning of life the Depth of Discharge is up to 100% while it decreases to 80% at the end of life

E The energy loss is obtained from [2] as 2.3 % per month and converted to %/day by division with 30

F Taken from test results of PSE Utility at the site Glacier with 4.4 MWh capacity in [7]

G Recent tenders have predominantly featured 2-hour durations, but there is a growing shift toward 4-hour durations. Up to 6h can be expected in the future. 4h is a standard reference size in literature.

H Calculated based on reference size and component costs.

I Considering Storage Block cost + Storage Balance of System + System Integration

J Considering Power Equipment Cost + Controls and Communication + Grid Integration

K Considering Project Development + Engineering, Procurement, and Construction Cost (EPC)

N Lower uncertainty is derived from LFP Capital cost uncertainty range, upper uncertainty is based on [12] and adjusted with [13], see note M

O Lower and upper uncertainty are assumed to be 2.5% and 6 % of CAPEX in cr R/MW, respectively, following LFP assumptions

P For the point estimate, all O&M costs are assumed to be represented in Fixed O&M, following LFP assumptions and [6]

Q cell level; derived from industry data published in [31], supplementary data

R Following LFP assumptions

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3. Sodium-ion Batteries

3.1. Brief technology description

While the first Na-S systems existed in the 1970s, modern sodium-ion battery (SIB) systems were first developed in the late 1980s. However, it is only recently that SIB technology has become commercially viable. Since 2009, the number of publications related to Na-based batteries has grown significantly and over the last 20 years, more than 50 % of the patented research activity has been in sodium-ion batteries. Ions are electrically charged atoms that have gained or lost electrons. Various appropriate cathode materials have been found for SIBs and hence most recent research activities have been devoted to discovering high-performance anodes that have reversible high energy density and structural stability. In India, companies are demonstrating their prototypes. [1], [2] The secondary (rechargeable) SIBs have similar battery components and energy storage mechanisms as lithium-ion batteries (LIBs), except mainly for the electrolytes. Sodium-based electrolyte and some cathode materials are cheaper than their lithium analogues. [3] SIBs have therefore emerged as a promising alternative to commercial LIBs due to the low cost, abundance, and accessibility of Na resources and similar properties of the Li and Na elements.

Working Principle of Sodium-ion Battery

SIB is an electricity storage device and like all batteries, it stores electricity as chemical energy. It is based on electrochemical (redox) reactions that involve an exchange of electrons and ions. These reactions occur at the electrodes and the electrolyte facilitates the transport of ions from one electrode to the other, while the external circuit allows for the transfer of electrons.

The cathode (by convention) in a SIB is often composed of sodium-containing layered materials (usually transition metal oxides), and the anode (by convention) is made mainly of carbon-based materials (usually hard carbon) and less often based on metals (Ti and P) and alloys. Note: In rechargeable batteries like SIBs, the functional roles of the anode and cathode reverse during charging; however, their naming convention refers to their roles during discharge. The electrodes are separated by a porous material called the separator which is selectively permeable for ions and restricts electron flow between the electrodes. This separation of electrons and ions as they flow between the electrodes of the battery is key to the function of a battery. The electrodes and the separator can either be immersed in a liquid electrolyte that can be made up of sodium salts dissolved in an aqueous or an organic solution or have a solid electrolyte.

An example of the reactions that occur at the electrodes in a SIB during discharge is as follows:

Anode: $Na_xC \rightarrow C + Na^+ + e^-$

Cathode: $NaFePO_4 + Na_x^+ + e^- \rightarrow Na_{1+x}FePO_4$

Overall cell reaction: $Na_xC + NaFePO_4 \rightarrow C + Na_{1+x}FePO_4$

During discharge, the Na^+ travels from the anode to the cathode through the electrolyte and the electrons travel in the same direction through the external electrical circuit. During charge, Na^+ and the electrons travel in the opposite direction (from cathode to anode). Under normal charge and discharge conditions, the introduction and removal of sodium ions between the positive and negative electrodes does not damage the basic chemical structure of the electrode material. Sodium maintains a stable ionic form throughout the charge and discharge cycle. [4]

There are two current collectors in the battery, one on the positive and one on the negative electrode. They allow electrons to be supplied to and from the battery.

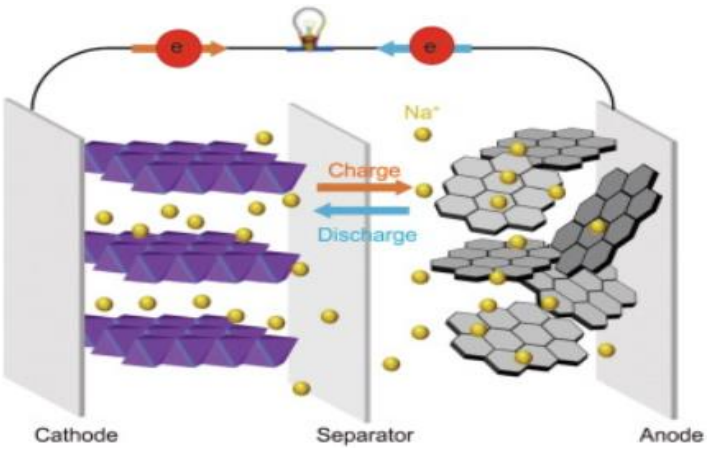

Figure 3-1: Working Diagram of sodium-ion battery [5].

3.2. Input/Output

Input and output are both electricity. Electricity is converted to chemical energy during charge through the storage of electrons in the battery's active materials. These electrons are released on discharge and the chemical energy is converted back to electricity.

3.3. Energy efficiency and losses

The first loss in capacity for SIBs is through SEI formation which happens during the initial cycle and a capacity of 91% to 88.5% of the original capacity is reported by various manufacturers. [6]

SIBs have shown a DC round-trip efficiency of 86% with values ranging between 80% and 92% (see datasheet).

The AC-DC conversion and energy demand from the control electronics are expected to be the same as for LIBs as the same devices can be used for the conversion. Hence a similar additional loss from conversion results in an AC-AC round trip efficiency of 79% (see datasheet).

3.3.1. Self-discharge

Sodium-ion Batteries have a low self-discharge rate, generally around 0.1% per day. [7] Therefore, even if sodium-ion batteries are left idle for an extended period, they can still retain a high capacity.

Self-discharge in sodium-ion batteries refers to the gradual loss of charge that occurs even when the battery is not connected to a load. This is a common phenomenon in all types of rechargeable batteries, including sodium-ion (Na-ion) batteries. Self-discharge can reduce the overall efficiency and lifespan of the battery.

3.4. Regulation ability and other system services

SIBs like LIB installations are very flexible in terms of power/energy capacity and time of discharge. This type of battery has a response time in the order of milliseconds (determined by the inverter), which makes it suitable for a wide range of applications, including power quality. However, the slower transport of Na+ ions compared to Li+ means that there is a higher capacity loss associated with higher C rates in SIBs compared to LIBs. [8]

3.5. Typical characteristics and capacities

Sodium-ion batteries are undergoing a critical period of commercialization as industries from automotive to energy storage bet big on the technology. Established battery manufacturers and newcomers are jostling to get the batteries commercialized and for them to be a viable alternative to lithium-ion. With the TRL of 7 (meaning a prototype demonstration in operation), [9] Sodium-ion battery shows great potential for electric mobility and stationary storage. Sodium-ion batteries offer enhanced safety, lower raw material costs, and a more environmentally friendly footprint compared to lithium-ion batteries. A few companies have come up with commercial batteries but at present, only one large-scale project is ongoing in China that uses batteries by HiNa Battery Technology Co., Ltd. As of now, 50% of the project's capacity is online. [10]

Table 3-1: Typical characteristics and capacities.

Location	**Qianjiang Hubei Province, China**
	
Storage capacity	200 MWh
Power capacity	100 MW
Energy density	145 Wh/kg
Lifecycle	4500 cycles

It is difficult to quantify the energy storage capacity, input and output power and specific energy density of the cells in general as the commercialization of these types of batteries is in their infancy. Below are the parameters for various commercial batteries at smaller scales.

3.6. Typical storage period

The typical storage period depends on the operation and it ranges from a few minutes to about 6 hours. Since the energy and power components of the battery are coupled, these batteries are not usually used for long-duration storage.

3.7. Space Requirement

The space requirement is assumed to be the same as for LFP grid-scale storage facilities, which is 5 – 7.5 m^2/MWh (see Lithium-ion Battery chapter).

3.8. Advantages/disadvantages

Sodium resources are more abundant and globally distributed. The cost of sodium-ion batteries has the potential to be much lower than Lithium-ion batteries due to the abundance of sodium resources and the lower cost of materials. [13]

Sodium-ion batteries (SIBs) have lower energy density than lithium-ion batteries, meaning they store less energy per unit weight compared to lithium-ion batteries (LIBs), making them more difficult to use for applications requiring high energy density such as electric vehicles. Additionally, SIBs tend to have a shorter cycle life compared to LIBs as they undergo fewer charge-discharge cycles before their capacity degrades significantly, limiting their long-term use in high-demand applications. That being said, SIBs are quickly closing the gap to lithium-ion batteries on both of these fronts, and if they can be produced at lower costs than LFPs (especially if there is another lithium price shock), it's possible they could see large scale adoption in a number of industries including electric vehicles. [14] [15]

This includes the supply chain for raw materials, where sodium extraction and refinement processes are not yet optimized, the manufacturing processes, which are still evolving to match the efficiency and scalability of LIB production, and the recycling infrastructure, which remains underdeveloped, lacking established methods for the recovery and reuse of sodium-ion battery components at the same level as the well-established LIB recycling systems. However, SIBs are similar enough to LFPs from a manufacturing point of view that it is believed that SIBs can use the existing manufacturing capacity that already exists for LFPs if they become widely popular.

Among the myriad battery technologies, sodium-ion and lithium-ion batteries are two of the most promising. Each has unique strengths and weaknesses. Advantages and disadvantages of sodium-ion battery concerning Li-ion battery can be seen in the table below.

Table 3-2: Advantages and the description of sodium-ion battery [1], [2], [13], [14], [16], [17].

Advantages	Description
Cost-effectiveness	Sodium-ion batteries are cost-effective due to the affordability and wide availability of sodium.
Gravimetric energy density	Despite being less expensive, sodium-ion batteries provide high energy storage capacity, delivering significant amounts of electrical energy. The SIB gravimetric energy density is currently around 130 Wh/kg to 160 Wh/kg, but is expected to top 200 Wh/kg in the future.
Raw material abundance	Sodium is over 1000 times more abundant than lithium and more evenly distributed worldwide.
Safety	Sodium-ion cells are expected to have better thermal performance than Li-ion batteries, which would either make them safer or cheaper to cool.
Performance in cold	Sodium-ion batteries tend to perform better in cold temperatures compared to lithium-ion batteries. Sodium-ion battery temperature range -20°C to 60°C.
Environmental impact	Sodium-ion batteries have a smaller ecological footprint. Sodium extraction is less harmful to the environment than lithium mining, and sodium-ion batteries are more accessible to recycle.

Table 3-3: Disadvantages and description of sodium-ion battery [18], [19], [20].

Disadvantages	Description
Low volumetric energy density	Sodium-ion cells have lower energy densities than lithium-ion. This is due to sodium being significantly heavier and larger than lithium, as well as Na+/Na having a higher reduction potential than Li+/Li.
Cycle life	Improving quickly, but still lags behind LFPs specifically.
Commercial availability	Still an emerging technology with limited availability whereas Lithium-ion batteries are widely available and used in many applications.

3.9. Environmental impact

Sodium-ion batteries offer a versatile and economically viable option by relying on an alkaline metal which is abundant on Earth. They are less toxic than other popular batteries, as they do not require lithium, cobalt, copper, or nickel and can release polluting gases in the event of a fire.

Battery manufacturing in general is an energy-intensive process that involves the extraction of raw materials, their processing into battery components, assembly, and finally, recycling or disposal at the end of the battery's life. Each stage has potential environmental impacts, from greenhouse gas emissions to water usage and ecological disruption.

One of the fundamental differences between Na-ion and other batteries lies in the materials used. Sodium, the key element in Na^+-ion batteries, is abundantly available and can be extracted from seawater and other saline sources. This abundance not only makes sodium more accessible but also reduces the ecological and social impacts associated with mining activities.

The environmental benefits of Na-ion batteries extend into their manufacturing process. The production of Na-ion batteries potentially requires lower temperatures and less energy compared to the complex processes needed for other batteries. This reduced energy demand translates into lower carbon emissions, if the energy comes from fossil fuels. As the manufacturing process of Na-ion batteries becomes more streamlined, its environmental advantage over Li-ion batteries is expected to grow.

Moreover, the scalability of Na^+-ion technology is promising. With sodium's abundance and the possibility of utilizing existing Li-ion manufacturing infrastructure, Na-ion batteries have the potential to achieve economies of scale that further reduce their environmental impact and cost.

As Na-ion battery technology matures, improvements in energy density and efficiency could make them a more compelling choice for a wide range of applications, balancing performance with environmental sustainability. [21]

3.10. Research and development perspectives

Titanium oxides

The anode material of SIBs, titanium oxides have the advantages of being rich, safe, and environmentally friendly. Rich refers to the abundance of titanium oxides as a natural resource. It means that titanium oxides are plentiful and easily accessible, making them a cost-effective choice for use as an anode material in SIBs.

Among them, TiO_2 is usually used as an anode for SIBs. At present, many researchers have put forward many improvement measures to remedy the shortcomings of TiO_2 as an anode material for SIBs. It is mainly modified by doping with nitrogen, sulphur, fluorine and phosphorus, as well as by combining with carbon materials to form nanoarrays and heterostructures.

According to different crystal structures, TiO_2 can be divided into rutile, anatase and bronze. However, its poor electron conductivity and low diffusion rate of Na^+ ions lead to the unsatisfactory electrochemical performance of TiO_2. [22]

A U.S. based company recently announced that they achieved the first-ever commercial-scale production of a sodium-ion battery. These batteries offer higher power density, higher cycles, and unique safety characteristics over other battery technologies. [23]

One of the leading Chinese companies unveiled its first-generation SIB in 2021, featuring an impressive energy density of 160 Wh/kg. This achievement positioned them as frontrunners in the commercialization of SIBs, a field still in its early stages. They haven't settled on this initial success. They are actively developing next-generation SIBs with an energy density exceeding 200 Wh/kg, a significant leap closer to competing with the current range of lithium-ion batteries. [24] [25] [26]

Recognizing the strengths of both technologies, the company is also pioneering the integration of SIBs and lithium-ion batteries. Their AB battery system technology allows for a mix of both types in a single battery pack, potentially optimizing cost, performance, and sustainability.

Another Chinese company started the first phase of 100 MW/ 200 MWh project in Qianjiang, Hubei Province. The company announced that they connected to the grid a 50 MW/ 100 MWh storage system, making it the world's largest operating sodium-ion battery energy storage system [27].

Companies are focused on creating sodium-ion batteries that are affordable, long-lasting, safe, and have a high-energy density as they are capable of providing the necessary materials for both the positive and negative electrodes, as well as the electrolytes. Although it primarily aims to use sodium-ion batteries for energy storage systems, it also explores potential applications in various areas such as electric bicycles, low-speed electric vehicles, communication base stations, data centres, home energy storage, and large-scale energy storage. [28]

3.11. Examples of market-standard technology

U.S. based company Natron Energy achieves first-ever commercial scale production of sodium-ion battery in the USA. Natron Energy is manufacturing a cabinet of sodium-ion batteries called BlueRack Critical Power Battery Cabinet. [12]



Figure 3-2: 100 MW/200 MWh Sodium-ion energy storage station Datang Hubei China [29].

In Qianjian, Hubei province, the Datang Hubei 100 MW/200 MWh sodium-ion new energy storage power station science and technology innovation demonstration project is under construction. The first phase was completed and put into operation, with a production scale of 50 MW/100 MWh. This is currently the world's largest sodium-ion battery energy storage project, marking a new stage in the commercial operation of sodium-ion battery energy storage. [30] The energy storage system consists of 42 sets of energy storage battery compartments and 21 sets of booster converters, it uses 185 ampere-hour large-capacity sodium-ion batteries supplied by HiNa Battery Technology and is equipped with a 110 kV transformer station. After being put into operation, a single charge can store 100 MWh of electricity, release electric energy during the peak period of the power grid, meet the electricity demand of about 12,000 households for a day, and reduce carbon dioxide emissions by 13,000 tons per year. The project is developed and managed by Datang Hubei Energy Development. [30] [11]

3.12. Projection of performance and cost

SIBs have been developed by drawing parallels with LiB technologies, due to their similar underlying system architectures. As SIBs share many design characteristics with LiBs—here lithium iron phosphate (LFP) batteries are chosen—it is reasonable to assume that most cost components will follow similar development trajectories. The primary distinction lies in the energy component, where SIBs differ in material composition of the battery cells.

The capital expenditure (CAPEX) associated with the energy component of SIBs is projected based on trends identified in Yao et al. [13], which provide insights specific to sodium-ion technologies. CAPEX for the capacity component and other system-related costs are assumed to follow the same trend of LFP batteries which have been identified in the LiB chapter. This assumption reflects the close technological similarity and manufacturing overlap between the two chemistries. Operational expenditures, both fixed and variable, are also aligned with LFP battery trends. No cost reductions are anticipated between 2050 and 2070, as batteries are assumed to have reached maturity, and further significant technological advancements are not expected.

3.13. Uncertainty

The uncertainties are based on data collected from the literature, and projected uncertainty ranges follow trends observed in LFP technologies.

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3.15. Datasheet

Technology	Na-ion battery										
	2024	2030	2040	2050	2070	Uncertainty (2024)		Uncertainty (2070)		Note	Ref
						Lower	Upper	Lower	Upper		
Energy/technical data											
Form of energy stored	Electricity										
Application	System, power- and energy-intensive										
Generating capacity for one unit (MW)	10	10	10	10	10	1	100	1	100	A	4, 14
Storage capacity (MWh)	40	40	40	40	40	5	100	5	100	A, B	1,4, 14, 15, 16
Depth of Discharge (%)	90	90	90	90	90	80	100	80	100		1, 2, 16
Round trip efficiency (%AC)	79	82	83	85	85	74	85			C	9
Round trip efficiency (%DC)	86	88	90	92	92	80	92				1, 2, 4, 15, 16
- Charge efficiency (%)	93	94	95	96	96	89	96			D	
- Discharge efficiency (%)	93	94	95	96	96	89	96			D	
Energy losses during storage (%/day)	0.10	0.10	0.10	0.10	0.10	0.09	0.11	0.08	0.12		16
Forced outage (%)											
Planned outage (weeks per year)											
Technical lifetime (years)	13	15	20	20	20	10	15	15	25		4, 15, 16
Construction time (years)	1	1	0.5	0.25	0.25	0.5	2	0.2	0.5	A	
Lifetime (battery cycles)	4000	4000	5000	6000	6000	1000	6000	6000	8000		1, 4, 5, 12, 15, 16
Discharge time (h)	4	4	4	4	4	0.5	10	2	10	A, B	1,4, 14
Regulation ability											
Primary load support (% per 30 seconds)											
Secondary load support (% per minute)											
Minimum load (% of full load)											
Financial data (in 2023₹)											
Capital cost (cr. ₹/MWh)	1.98	1.32	0.89	0.74	0.74	1.21	2.50	0.68	0.81	E, F, J	8, 15, 16, 3
- energy component (cr. ₹/MWh)	1.33	0.82	0.47	0.35	0.35	0.81	1.68	0.30	0.40	G	4, 3
- capacity component (cr. ₹/MW)	0.65	0.49	0.42	0.39	0.39	0.40	0.21	0.38	0.41	H	4
- other project costs (cr. ₹/MWh)	0.49	0.37	0.31	0.30	0.30	0.30	0.62	0.29	0.31	I	4
Fixed O&M (cr. ₹/MW/year)	0.24	0.18	0.15	0.14	0.14	0.08	0.48	0.14	0.15	K,M,N	4
Variable O&M per output (₹/MWh)	43.00	32.00	27.00	26.00	26.00	0.00	47.00	0.00	31.00	L,N	4
Technology specific data											
Alternative total investment cost (cr. ₹ per MW)	7.94	5.26	3.57	2.97	2.97	4.84	9.38	2.71	3.25	E	
Energy density (Wh/L)	313					250	375				2, 6, 7
Specific energy (Wh/kg)	135					100	170				1, 5, 6, 7, 16

Notes

A Assumed to be the same as LFP

B Storage capacity indicates the size for which the cost data has been compiled. Discharge time indicates the typical size in Indian projects.

C Same losses from DC RTE to AC RTE as LFP batteries as the power electronics used are assumed to be identical, i.e. (0.98)^2 RTE for inverter and transformer each, based on [9]

D Derived as square root of DC efficiency

E Calculated based on reference size and component costs. Although a promising technology with low purported costs, current commercial development is limited.

F High uncertainty due to low commercial maturity but is expected to become cost competitive with LiB in the future

G Considering Storage Block cost + Storage Balance of System + System Integration (table 2) [4]

H Considering Power Equipment Cost + Controls and Communication + Grid Integration (table 2) [4]

I Considering Project Development + Engineering, Procurement, and Construction Cost (EPC) (table 2) [4]

J Upper uncertainty based on [4] , cost contributions derived from [4], lower uncertainty based on [15]. Point estimate derived by weighing [4] with 2 and [15] with 1

K Lower uncertainty based on [4], upper uncertainty same as LFP: 6% of CAPEX

L higher uncertainty based on Table 2 in [4], lower uncertainty set to zero

M Fixed O&M is set to 3 % of the CAPEX (in (cr. ₹ per MW)) in 2024 reduced to 2% in 2050 - the percentage is lower than expected for LIB because energy storage per output power is higher. And According to [4] the fixed O&M is lower, it is app 0.078 cr ₹/MW/yr in 2024 prices.

N O&M are expected to be reduced by respectively: 2024-2030: 25%, 2030-2040 15%, 2040-2050 6% and 2050-2070 0%.

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4. Pumped Storage Project

4.1. Brief technology description

Pumped Storage Project (PSP) operates by storing electricity as gravitational potential energy through pumping water from a lower reservoir to an upper reservoir. Globally, with a total installed capacity of over 189 GW as of end 2024, more than 90 percent of grid-scale energy is stored using PSP. It is a mature and reliable technology capable of storing energy for daily or weekly cycles and up to months, as well as seasonal applications, depending on project scale and configurations. PSP has been built on a larger scale (GWs) since the beginning of the 1970's and it has continuously evolved to suit the needs of changing power systems, providing a suite of essential flexibility services to support the changing needs of power systems [1].

A PSP consists of two or more water reservoirs (natural or artificial lakes/dams), tunnels that convey water from one reservoir to another, a reversible pump turbine, a motor generator, transformers, and transmission connection. The discharging of the PSP is like the hydropower concept, exploiting the head difference between two water reservoirs, whether natural or artificially created through dams and weirs. In a PSP, the potential energy is converted into rotational kinetic energy, which spins the blades of a turbine connected to a generator. During the charging of PSP, water is pumped from a lower reservoir to the dams at higher elevations.

The amount of stored electricity is proportional to the product of the volume of water and head (elevation between the upper reservoir and power plant). For example, storing 1,000 MWh requires an elevation of 300 m and a water volume of about 1.4 million m^3. [2]

PSP systems can have one or more reservoirs with potential energy heads to supply water during energy generation. PSP plays a critical role in the electrical system by regulating the flow of water between these reservoirs, enabling energy storage & generation and regulating electricity supply and demand at peak times. During surplus electricity availability or when electricity prices are low, water is pumped from the lower reservoir to the higher reservoir and energy is stored in the form of potential energy. Conversely, during peak demand when electricity prices are high, water is released from the higher reservoir to the lower reservoir to generate electricity via turbines.

PSP systems capitalize on price fluctuations in electricity markets, purchasing power during low-demand periods and selling it during high-demand times. This strategy is known as arbitrage.

There are three principal categories of PSP plants [3]:

- **On-stream PSP**: Both reservoirs are located on any river/ stream/ nallah.
- **Off-stream Open-loop PSP:** One reservoir is located on river/ stream/ nallah. Other reservoir (off-stream reservoir) is not located on any river/ perennial stream/ perennial nallah as shown in Figure 4-1.
- **Off-stream Closed-loop PSP:** None of the reservoirs is located on any river/ perennial stream/ perennial nallah as shown in Figure 4-2.

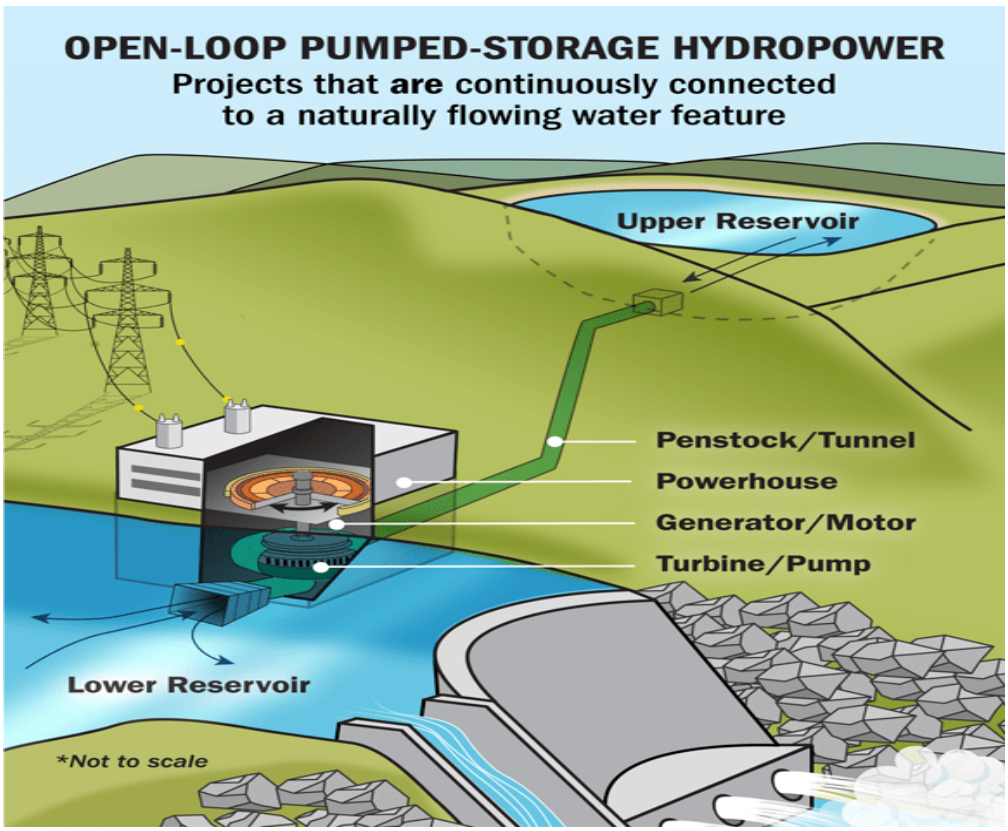


Figure 4-1: Off-stream Open-Loop Pumped Storage project [4].

Off-stream Open-loop PSP: The implementation of a new Off-stream open loop PSP, which integrates both dams and a hydropower plant with a reservoir, entails significant capital expenditures and a lengthy construction period. However, it is essential to recognize that this hybrid plant offers not only storage capacity but also adds to the electricity generating capacity, due to its dual functionality as both a hydropower plant and a Pumped Storage Project system. When retrofitting an existing hydropower plant to include PSP capabilities, the investment per installed MW is notably reduced, and the construction time ranges between 2 and 3 years. Moreover, the costs of PSP integrated into existing hydro projects, where one or both reservoirs are already present and Off-stream PSP , are substantially lower [5].

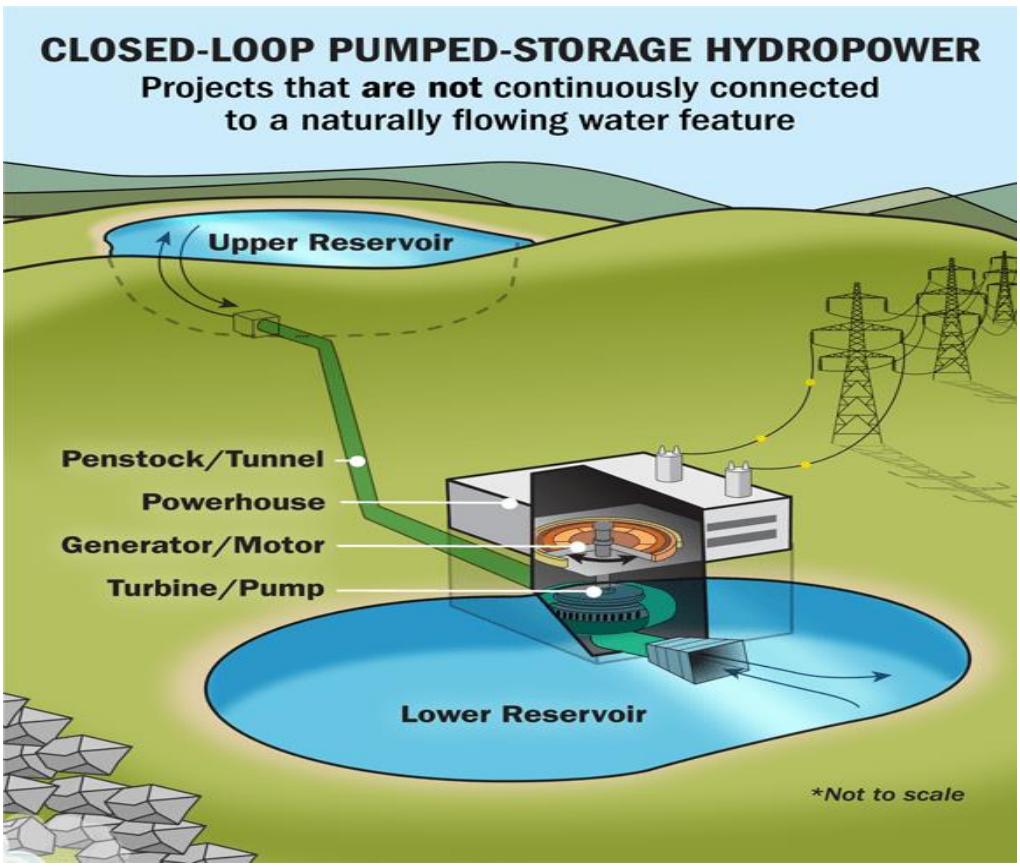


Figure 4-2: Off-stream Closed-Loop Pumped-Storage Project [4].

Off-stream Closed-loop PSP: Off-stream Closed-loop PSPs diverge from Off-stream open-loop PSPs by operating independently of continuous water sources. These projects produce power only from water previously pumped to an upper reservoir, and there is no significant natural inflow of water. The top and lower reservoirs in this kind of plant are situated "off-stream." This strategy has the benefit of limited interacting with aquatic species and lessens its negative effects on the ecosystem. Therefore, the environmental approvals and review procedures are minimized or avoided in the Off-stream closed-loop architecture. The Off-stream closed-loop PSP needs a water source that can supply the initial charge and makeup water to compensate for the losses from seepage and evaporation. The schematic for Off-stream closed-loop PSP is shown in Figure 4-2.

4.2. Input/Output

Input is electricity which is used to pump the water from the lower reservoir to the upper reservoir to store the energy in the form of potential energy of water.

Output is electricity as when the water in the upper reservoir it is released to the lower reservoir the potential energy of the water is converted to electricity using the turbines.

4.3. Energy efficiency and losses

The cycle (roundtrip) efficiency is typically in the range of 70% to 80%, meaning most of the energy used during pumping (charging) is returned to the grid in turbine mode (discharging). The losses are mostly due to the losses in the process of pumping water up into the reservoirs and generation losses [6].

4.4. Regulation ability and other system services

The primary purpose of PSP is to provide time-shifting for the electricity system by storing excess energy during low-demand periods and releasing it during high-demand periods. However, PSP can also provide ancillary service functions, such as frequency regulation in the generation mode. A variable-speed system design allows for providing ancillary service capability as well as increasing overall plant efficiency. PSP offers the following regulation abilities [7].

Response time
PSP can reach full load in a few minutes from turbine stand-still, or less than 60 seconds from turbine spinning state. Advanced installations can be even quicker. For example, units at Dinorwig pumped storage station (in England & Wales) can be pre-synchronized to the grid and kept spinning in air and ramped from this ready-state to full load in 12 seconds. It is also worth noting that variable-speed turbine-generator systems can now enable PSP for enhanced responses in case of frequency deviations and grid faults. [8]

Inertia
PSP offers instantaneous support to grid frequency variations, through its large rotating mass. The high kinetic energy stored in the rotating turbine offers rotating mechanical inertia, and is provided via synchronous electrical machines directly connected to the power grid. In contrast, electronic-interfaced energy sources, such as batteries, can provide synthetic inertia which is almost instantaneous. [8]

Black start
PSP can provide black start capability, if there is water in the upper reservoir of PSP ready for generation, it can be used for energizing the grid in case of cascade tripping. [9]

Voltage Support
PSP can also provide voltage support services by rendering reactive power production and absorption. An imbalance in the supply and demand of reactive power can cause voltage to rise or drop across the power system. In both pumping and generation modes, voltage control is performed through the voltage regulator which is part of the excitation system. The machine voltage can be adjusted by changing the field current via the excitation system. PSP can be operated in lead or lag modes to meet the requirement of reactive power of the grid. PSP can also be operated in synchronous condenser mode to improve the system power factor and provide inertia. [9]

4.5. Typical characteristics and capacities

Typical characteristics according to [10] are:

- Energy storage capacity, in MWh: amount of energy that can be stored in PSP that is 8000 MWh for a standard example
- Input and output capacities, in MW: the rate at which the energy can either charge or discharge that is 250 MW for a standard example
- Energy density and specific energy, in Wh/m^3: for a typical PSP with 100 meters of elevation of a higher reservoir from the lower reservoir and a reservoir volume of 10,000 cubic meters, energy density is 981 kJ/m^3 which translates to 273 Wh/m^3

In general, PSP achieves economies of scale for high energy storage capacity and long duration energy storage. PSP capacities in India vary based on geographic factors, ranging from a few megawatts to gigawatts (GW). Currently, in India, operational PSP capacities range from 12 MW (Ujani, Maharashtra) to 1,680 MW (Pinnapuram PSP, AP), with the first PSP plant, Nagarjuna Sagar in Telangana, boasting an operational capacity of 705 MW since its construction in 1970 [11]. The capacities are heavily influenced by land

availability, elevation differences and other location-specific factors. As on March 2026, India has an aggregated capacity of 7.17 GW from 11 operational PSP projects, with additional projects under construction with a capacity of 16.12 GW. Furthermore, there are 71 projects in the pipeline, with a combined capacity of about 100 GW, indicating a significant growth potential in the PSP sector [12].

In addition to large variations in capacities, PSP is also diverse regarding characteristics such as the discharge time (at max capacity), which ranges from several hours to a few days.

4.6. Typical storage period

The typical storage period for a PSP system is 6-7 hours [13], this duration refers to the time during which the system can continuously discharge electricity at maximum discharge capacity. Compared with battery systems, PSP typically has much higher installed power (MW) and stored energy (MWh) capacity due to economies of scale. With low energy storage capacity costs, PSP excels at long-duration energy storage, which can be utilised during long periods of a supply profile change, such as the seasonality of wind and solar generation in high renewables systems.

4.7. Space requirements

For an off-river pumped hydro system with a 400-meter head, 90% generation efficiency, 85% usable water volume, and an average water depth of 20 meters, the land area needed for both the upper and lower reservoirs to store one gigawatt-hour (GWh) of energy is approximately 12 hectares [5].

4.8. Advantages/disadvantages

PSP has a large energy storage capacity as compared to other storages e.g. various batteries.

Advantages and disadvantages of the On stream, Off-stream open loop and Off-stream closed loop sub technologies of PSP are given in Table 4-1, Table 4-2 and Table 4-3 [14] [15].

Table 4-1: Advantages and disadvantages of On-stream PSP.

On-stream PSP	
Advantages	**Disadvantages**
Utilizes natural water bodies for energy storage.	Relies on specific geographical features
Easily constructed on existing hydropower plant	Sensitive to changes in water availability
Generally lower construction costs, if constructed on the already existing hydroelectric dams	Less availability of sites
Zero or minimal relocation of the local community	May affect aquatic ecosystems and fish habitats
Fast response times for grid stabilization.	Away from local roads/transportation
Enhances grid stability and reliability.	
High-efficiency in energy conversion	
Recharges Ground water	

Table 4-2: Advantages and disadvantages of Off-stream open loop PSP.

Off-stream Open-Loop PSP	
Advantages	**Disadvantages**
Utilizes one reservoir from natural water bodies/existing reservoir for energy storage.	Relies on specific geographical features.
Easily constructed on existing hydropower plant	Requires relocation of the local community, thus it may be subject to hurdles and protests
Generally lower construction costs	Sensitive to changes in water level in existing reservoir.
Lesser clearances required from statutory bodies	Requires a large land area for reservoirs.
Fast response times for grid stabilization.	
Enhances grid stability and reliability.	
High efficiency in energy conversion.	
Recharges Ground water	

Table 4-3: Advantages and disadvantages of Off-stream closed loop PSP.

Off-stream Closed-Loop PSP	
Advantages	**Disadvantages**
Can be implemented in areas without natural water bodies.	Capital cost may still be high as creation of two new reservoirs is involved
Reduced impact compared to conventional dams.	
Easy site selection and may be away from forest and river system.	
Can respond quickly to changing demand.	
Contributes to grid stability.	
Lesser clearances required from statutory bodies	
Recharges Ground water	
Not affected by hydrology/water availability during operation	
minimal relocation of the local community	

4.9. Environmental impact

The PSP technology, while not generating any detrimental emissions, exerts a notable influence on water ecology, particularly in the context of river dams. This impact on river dams stems from various aspects of PSP operation and its interaction with aquatic ecosystems are given in Table 4-4 [15]. The environmental concerns for Off-stream closed loop are given in Table 4-5 [15].

Table 4-4: Environmental concerns of On Stream and Off-stream Open Loop PSP [15].

Concerns	Points
Surface Water	Erosion, sedimentation, water quality impact - Altered temperature, oxygen levels, circulation
Groundwater	Limited impact except during construction/seepage - Possible water movement, rising levels, structural effects
Aquatic Ecology	Widespread, lasting impact on aquatic life - Altered habitat, fish impingement, species transfer
Geology and Soils	Runoff, erosion, and sedimentation from excavation - Shoreline erosion, sedimentation increase
Terrestrial Ecology	Clearing of vast habitat, impact on species
Land Use	Clearing land, affecting land uses
Visual Resources	Impact on viewsheds from above-ground facilities - Limited mitigation due to siting constraints
Cultural Resources	Clearing land, affecting known/undiscovered resources

Table 4-5: Environmental concerns of Off-stream Closed Loop PSP [15].

Concerns	Points
Surface Water	Lower impact on quality/quantity compared to Off-stream open-loop - Possible impact using surface water for refill/replacement
Groundwater	Potential quality/quantity impact based on fill[4] source - Circulation, chemistry changes, large pumping for filling
Aquatic Ecology	Avoids many impacts due to off-stream location - Possible impact from pumping groundwater for dewatering
Geology and Soils	Similar impacts to Off-stream open-loop for above-ground reservoirs - Additional spoil, potential land subsidence for underground

[4] Fill source refers here to the source from which groundwater was taken to fill the upper and lower reservoirs

Concerns	Points
Terrestrial Ecology	Relatively lower impacts, habitat clearing for pipeline - Much smaller impacts for underground projects
Land Use	Relatively lower impacts, fewer siting constraints - Potential proximity to resources/demand centres
Visual Resources	Relatively lower impacts for above-ground facilities - Much smaller impacts for underground projects
Cultural Resources	Relatively lower impacts, potential from underground pipeline - Potential impact from underground pipeline on cultural resources

4.10. Research and development perspectives

Although pumped storage hydropower has been around for many years, the technology is still evolving with the introduction of power electronic controllers. At present, many new PSP concepts and technologies are being proposed or actively researched and these include, small-scale systems with corrugated steel and floating membranes, submersible pump-turbines with motor generators, geomechanically setups, hybrids with wind plants and floating photovoltaic, integrated desalination plants, tunnel-boring machine-excavated underground storage, mine-based PSP, open-pit mine PSP, modular Off-stream closed-loop scalable systems, pressurized vessel setups, thermal underground configurations, and high-density fluid PSP [16].

4.11. Examples of market-standard technology

Various developed PSP plants in India are as follows:

1. Tehri Pumped Storage Project

Tehri PSP comprises of four reversible pump turbines of 250 MW each. The operations are based on the concept of recycling of water discharged between the upper to lower reservoir. The Tehri Dam reservoir shall function as the upper reservoir and Koteshwar reservoir as the lower balancing reservoir. The plant generates 1,000 MW peaking power. Considering multiple pumping cycles (11/12 hours of pumping), 3075 MU energy shall be consumed in pumping mode, whereas 2442 MU energy shall be generated in turbine mode. The estimated capital cost of construction of Tehri PSP is INR 8339.26 Crore (February 2025 price level).

2. Srisailam PSP Plant

The Srisailam Hydro Electric Project is constructed across the river Krishna, which is one of the major rivers of Peninsular India, and a Power Station on the right side of the Dam. The project site “Sunni Penta” of Kurnool District is 220 km from Hyderabad. The project was executed in two stages. The first stage included construction of the dam, water conductor system, powerhouse and installation of four 110 MW Hydro Generating Equipment. The second stage added three more generating units of 110 MW capacity [18].

In addition, the Srisailam Left Bank Power House (SLBPH)**,** which functions as a pumped storage plant**,** was later developed to optimize water utilization and energy generation. The SLBPH has a total installed capacity of 900 MW (6 × 150 MW) and operates in both pumping and generating modes, supporting grid stability and meeting peak power demands. [12]

3. Purulia Pumped Storage Project Project

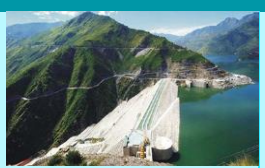
The main structures involved in the project are two Rockfill dams (Upper and Lower Dam) with central clay cores for upper and lower reservoirs with a live storage of 13 MCM each, twin water conductor, an underground power house (157 m long, 22.5 m width, 48.7 m height) to accommodate four reversible pump turbines (vertical Francis, rated head 177 m, maximum power discharge: 150 m^3/sec) of 225 MW each, an underground transformer (Four nos. with capacity 16.5 kV/400 kV 280 MVA each), cavern (119 m long, 17 m width, 17 m height), an access tunnel to powerhouse and 400 kV gas insulated substation linked through a cable tunnel. Two 400 kV double circuit transmission lines connecting Durgapur Sub-station and Arambagh Sub-station with Purulia PSP project have been developed to transmit and receive power. PSP has four types of operation modes; Generation, Pumping, Synchronous Condenser and Line Charging (up to 400 kV Bus) mode [18].

4. Pinnapuram Integrated Renewable Energy Project (IREP)

Pinnapuram IREP has been conceived as the world's first and largest gigawatt scale integrated project with solar, wind and pumped storage components that can supply schedulable power on demand which is dispatchable and schedulable renewable energy to the consumers across India. The project has been commissioned. The government of Andhra Pradesh has also allocated 1 thousand million cubic feet (TMC) of water for establishing the 1680 MW (240x6+120x2) Pumped Storage component with a 6 -hour storage capacity. The Standalone pumped storage component of Pinnapuram IREP is located in Kurnool District of Andhra Pradesh. Pinnapuram IREP comprises of two reservoirs constructed in existing natural depressions with low-height embankments of average height of 12-14 m (with a maximum height of 40 m) to create the desired storage capacity. Due to standalone nature, both the reservoirs are located away from all existing natural water systems and have no/negligible catchment area. Water will be lifted one time from the existing Gorakallu Reservoir irrigation system and will be stored in the reservoirs and used cyclically for energy storage charging and discharging. Evaporation losses, if any, will be recouped periodically. This Project envisages non-consumptive re-utilization of 1 TMC of water for recirculation among two proposed reservoirs [19].

Table 4-6 gives a brief idea of PSP plants location, type, capacity, operator and year of commissioning.

Table 4-6: Indian Examples of Pumped Storage Project.

No	Image	Location	Type	Capacity	Operator	Year of commiss-ioning	Reference
1		Tehri, Uttarakhand	On Stream PSP	1000 MW	THDC	2025	[17]
2		SRISAILAM, Telangana	On Stream PSP	900 MW	TSGENCO	2021	[7]
3		Purulia, West Bengal	Off-stream Open loop PSP	900 MW	WBSEDCL	2007	[18]
4		Pinnapuram, Andhra Pradesh	Off-stream Closed loop PSP	1680 MW	Greenko	2025	[19]

4.12. Projection of performance and cost

Costs for pumped storage plants are by nature difficult to assess and are site specific given the different conditions of each plant in terms of topography, climate, etc. Cost and performance variations are therefore large for this type of technology. The cost estimates have been assumed according to currently under-construction plants in India while remaining data parameters are consistent with existing plants that are already in operation (see datasheet for sources).

Cost reductions in energy technologies are typically driven by technological advancements, economies of scale, and improved manufacturing processes. However, Pumped Storage Project (PSP) is already a highly mature technology, with limited room for further technological innovation. Most of the achievable efficiencies and design improvements have already been realized. As a result, no significant future cost reductions are expected for Pumped Storage Project, and cost assumptions remain stable moving forward.

4.13. Uncertainty

Uncertainties are defined by the range between the minimum and maximum cost values identified in the data collection given in the datasheets.

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4.15. Datasheet

Technology	Hydro power plants, Pumped storage on-river										
	2024	2030	2040	2050	2070	Uncertainty (2024)		Uncertainty (2070)		Note	Ref
						Lower	Upper	Lower	Upper		
Energy/technical data											
Form of energy stored	Electricity										
Application	System										
Generating capacity for one unit (MW)	250	250	250	250	250	100	500	100	500	A	1, 12, 13, 14
Storage capacity for one unit (MWh)	1500	1500	2000	2000	2000	600	3000	600	3000		1, 12, 13, 14, 30
Electricity efficiency, net (%), name plate	80	80	80	80	80	70	85	70	85		9, 15, 16, 32
Electricity efficiency, net (%), annual average	80	80	80	80	80	70	85	70	85		9, 15, 16, 32
Energy loss during storage (%/day)										B	20
Forced outage (%)	1	1	1	1	1	0.8	4	0.6	3	C	3, 33
Planned outage (weeks per year)	2.5	2.5	2.5	2.5	2.5	2.0	6	2.0	4	D	4, 33
Technical lifetime (years)	50	50	50	50	50	40	60	40	90		9, 10, 21, 29, 32
Construction time (years)	4.75	4.75	4	4	4	4.5	5	3	5		7, 9, 21
Discharge time (h)	6	6	8	8	8	4	7	4	12	E, H	1, 12, 13, 14, 30, 32
Regulation ability											
Ramp Up Rate (% of Full Load/Minute)	75	75	75	75	75	50	100	50	100		6, 24, 29
Ramp Down Rate (% of Full Load/Minute)	75	75	75	75	75	50	100	50	100		6, 24, 29
Primary load support (% per 30 seconds)	45	45	45	45	45	30	60	0	30		22, 28
Secondary load support (% per minute)	75	75	75	75	75	50	100	50	100		6, 24, 29
Minimum load (% of full load)	0	0	0	0	0	0	35	0	35	K	6, 29
Financial data (in 2023₹)											
Capital Cost (cr. ₹/MW)	6.40	6.40	6.40	6.40	6.40	4.40	8.36	4.40	8.36	F, H	12, 13, 14, 31
- of which equipment (%)											
- of which installation/development (%)											
- of which is related to rent of land (%)											
- of which is related to other costs (i.e. compensation of neighbours, etc.) (%)											
Fixed O&M (cr. ₹/MW/year)	0.12	0.12	0.12	0.12	0.12	0.06	0.17	0.06	0.17	I	25, 29
Variable O&M per output (₹/MWh)	49	49	49	49	49	40	60	40	60		25
Technology specific data											
Alternative Total investment cost (cr. ₹ per MWh)										J	
Power Density (W/m3)	140	140	140	140	140	80	175	85	175	L	11
Energy density (Wh/m3)	1000	1000	1000	1000	1000	500	1500	500	1500	M	11
Specific energy (Wh/kg)											
Specific power (W/kg)											

Notes

A Representative discharge duration of 6h is taken

B Mostly negligible but in specific climates water evaporation could result in non-negligible energy losses

C [3]: forced outages in NJHPS were 2736 machine hours for total of 262800 working hours , which worked out to be 1.041 per cent

D Planned outage for maintenance (days) for Korian PSH plant[4] were 16.50 days in the year which works out as 2.4 weeks per year

E The Indian Ministry of Power promotes duration of more than 6 hours in a PSP Guideline [30]

F Lower uncertainty is based on the pre-feasibility and Environmental Impact Assessment reports of 3 planned on-river projects. However these seem overly optimistic as often cost overruns and delays occur. Upper uncertainty is based on [32] while the point estimate is close to Indian Stakeholder data

H very site specific

I lower uncertainty: 1-2% of CAPEX, upper bound: NREL ATB 2024 [25], point estimate: 2 % of CAPEX

J PSP costs mainly depend on the installed power capacity, hence no costs per energy capacity are given here

K Upper uncertainty taken from [6] is considered same as hydropower plants only limited data for PSP is available

L For PSP cases, with an energy density of 1000 Wh/m³ (corresponding to a head of roughly 350–400 m) combined with 7–8 hours of full-load discharge implies a volumetric power density in the range of approximately 130–150 W/m³. for the uncertanties other heads are assumed

M Energy density for pumped storage hydropower is strongly dependent on the hydraulic head between the upper and lower reservoirs. An energy density of 1000 Wh/m³ corresponds approximately to a medium-to-large head plant with an assumed head in the range of 350–400 m.

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Technology	Hydro power plants, Pumped storage off-river										
	2024	2030	2040	2050	2070	Uncertainty (2024)		Uncertainty (2070)		Note	Ref
						Lower	Upper	Lower	Upper		
Energy/technical data											
Form of energy stored	Electricity										
Application	System										
Generating capacity for one unit (MW)	200	200	200	200	200	100	500	100	500		1, 12, 13
Storage capacity for one unit (MWh)	1400	1400	1600	1600	1600	600	3000	600	3000	A	1, 12, 13, 30
Electricity efficiency, net (%), name plate	80	80	80	80	80	70	85	70	85		7, 10, 11, 32
Electricity efficiency, net (%), annual average	80	80	80	80	80	70	85	70	85		7, 10, 11, 32
Energy loss during storage (%/day)										B	20
Forced outage (%)	1	1	1	1	1	1	4	0.6	3	C	3, 33
Planned outage (weeks per year)	2.5	2.5	2.5	2.5	2.5	2.0	6	2.0	4	D	4, 33
Technical lifetime (years)	50	50	50	50	50	40	60	40	90		7, 8, 16, 32, 2
Construction time (years)	4.75	4.75	4	4	4	4.5	5	3	5	E	1, 16, 17
Discharge time (h)	7	7	8	8	8	6	8	6	12	F, I	1, 12, 13, 30, 32
Regulation ability											
Ramp Up Rate (% of Full Load/Minute)	75	75	75	75	75	50	100	50	100		28, 23, 2
Ramp Down Rate (% of Full Load/Minute)	75	75	75	75	75	50	100	50	100		28, 23, 2
Primary load support (% per 30 seconds)	45	45	45	45	45	30	60	30	60		21, 29
Secondary load support (% per minute)	75	75	75	75	75	50	100	50	100		28
Minimum load (% of full load)	0	0	0	0	0						2
Financial data (in 2023₹)											
Capital Cost (cr. ₹/MW)	6.30	6.30	6.30	6.30	6.30	4.30	8.36	4.30	8.36	G, I	12, 13, 31, 32
- of which equipment (%)											
- of which installation/development (%)											
- of which is related to rent of land (%)											
- of which is related to other costs (i.e. compensation of neighbours, etc.) (%)											
Fixed O&M (cr. ₹/MW/year)	0.12	0.12	0.12	0.12	0.12	0.06	0.17	0.06	0.17	J	2, 18
Variable O&M per output (₹/MWh)	49.00	49.00	49.00	49.00	49.00	40.00	60.00	40.00	60.00		18
Technology specific data											
Alternative Total investment cost (cr. ₹ per MWh)										K	
Power Density (W/m3)	140	140	140	140	140	80	175	85	175	L	9
Energy density (Wh/m3)	1000	1000	1000	1000	1000	500	1500	500	1500	M	9
Specific energy (Wh/kg)											
Specific power (W/kg)											

Notes

A Representative discharge duration of 7 h is taken

B Mostly negligible but in specific climates water evaporation could result in non-negligible energy losses

C [3]: forced outages in NJHPS were 2736 machine hours for total of 262800 working hours, which worked out to be 1.041 per cent

D Planned outage for maintenance (days) for Korian PSH plant[4] were 16.50 days in the year which works out as 2.4 weeks per year

E very site and project specific

F The Indian Ministry of Power promotes duration of more than 6 hours in a PSP Guideline [30], Range is based on pre-feasibility and Environmental Assessment reports

G Lower uncertainty is based on the pre-feasibility and Environmental Impact Assessment reports of 2 planned off-river projects. However, these seem overly optimistic as often cost overruns and delays occur. Upper uncertainty is based on [32] while the point estimate is close to Indian Stakeholder data

I very site specific

J lower uncertainty: 1% of CAPEX, upper bound: NREL ATB 2024 [18], point estimate: 2 % of CAPEX

K PSP costs mainly depend on the installed power capacity, hence no costs per energy capacity are given here

L For PSP cases, with an energy density of 1000 Wh/m³ (corresponding to a head of roughly 350–400 m) combined with 7–8 hours of full-load discharge implies a volumetric power density in the range of approximately 130–150 W/m³. for the uncertainties other heads are assumed

M Energy density for pumped storage hydropower is strongly dependent on the hydraulic head between the upper and lower reservoirs. An energy density of 1000 Wh/m³ corresponds approximately to a medium-to-large head plant with an assumed head in the range of 350–400 m.

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5. Vanadium Redox Flow Battery

5.1. Brief technology description

Flow batteries generally consist of a reaction cell stack where electrochemical reactions happen, storage tanks containing electrolytes (anolyte for the negative electrode and catholyte for the positive electrode), pipes connecting the tanks to the cell stack, and pumps to circulate the electrolytes through the system. A schematic of a traditional flow battery is shown in Figure 5-1. The region bordered by the grey electrodes is the reaction cell stack. Vanadium redox flow batteries (VRB) are the most common flow batteries and most promising application at grid scale as well as local user level. In this catalogue, the focus is on grid scale applications.

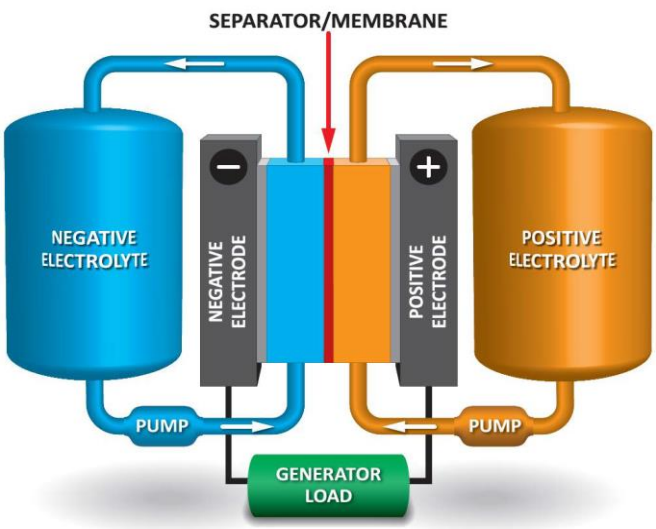

Figure 5-1: Schematic of flow battery [1].

In a VRB, the anolyte reactive species are V^{2+} and V^{3+} ions. The catholyte reactive species are VO_2^+ (V^{4+}) and VO^{2+} (V^{5+}) ions with the V atom in oxidation state +5 and +4, respectively[5]. Traditionally, the reactive species have been dissolved with concentrations of 1.5 - 2 M in aqueous sulfuric acid solutions with an acid concentration of 2-5 M [2].[6]

When pumped into the reaction cell, the anolyte and catholyte will be separated by a proton conducting (polymer) semi permeable membrane. An illustration of reaction cell components and a full reaction stack can be seen in Figure 5-2.

[5] These are the oxidation state of Vanadium.

[6] M is the Molarity, the number of moles of solute per liter of solution.

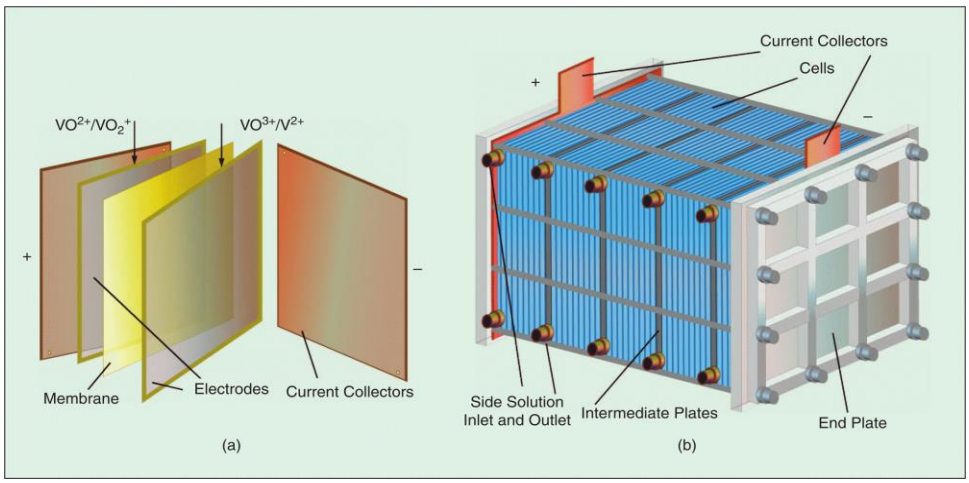

Figure 5-2: Vanadium redox flow battery : (a) Schematic illustration of a single vanadium redox flow battery (VRB) reaction cell showing the anolyte (V^{3+}/V^{2+}) and catholyte (VO_2^+/VO^{2+}) half-cells separated by an ion-conducting membrane. (b) Example of a typical VRB stack design composed of multiple cells connected in series through bipolar plates, with current collectors, electrolyte inlet and outlet channels, and end plates for structural support [2].

During discharge the following reaction occurs in the cell as two protons pass through the membrane and an electron pass through an external circuit:

$V^{2+} \rightarrow V^{3+} + e^-$ Anode side reaction

$VO_2^+ + 2H^+ + e^- \rightarrow VO^{2+} + H_2O$ Cathode side reaction

$V^{2+} + 2H^+ + VO_2^+ \rightarrow V^{3+} + VO^{2+} + H_2O$ Full cell reaction

During charge the reverse reaction occurs. The full reaction provides a cell voltage of 1.26 V. The battery operates at ambient temperatures. It is important to note that the polarity of the anolyte and catholyte electrodes reverses depending on the operating mode.

Flow batteries are different from other batteries with physically separated storage and power units. The volume of liquid electrolyte in storage tanks indicates the total battery energy storage capacity while the size and number of the reaction cell stacks indicate the battery power capacity. The energy storage capacity and power capacity can thus be varied independently according to desired application and customer demand [2].

A VRB installation consists, as a minimum, of a VRB unit as described above, a battery management system, and a power conversion system connecting the battery unit to the grid. Typical stack designs incorporate a number of bipolar electrodes with series of electrical connection and parallel electrolyte flow into each half-cell through internal or external manifolds and electrolyte distribution channels. The number of cells determines the stack voltage, whereas the electrode area determines the maximum current that can be delivered. The stack size thus sets the power capability of the redox battery, whereas the electrolyte volume and vanadium ion concentration dictate the energy storage capacity. Each cell contains a semi permeable membrane that prevents the two half-cell solutions from mixing while they are pumped through the stack. [3]

5.2. Input/output

Primary input and output are both electricity. Electricity is converted to electrochemical energy during charge and converted back to electricity during discharge in the reaction process described above.

5.3. Energy efficiency and losses

Electrolyte left in the cell stack during idle periods will self-discharge over time resulting in an energy loss. As the electrolyte volume in the cell stack is generally small compared to the total electrolyte volume, the total energy loss from self-discharge will be around 0.1%/day of stored energy during any idle period [4]. A major source of energy losses is the energy used by the mechanical pumps that circulate the electrolyte (around 9%) [5]. It is taken into account in the round-trip-efficiency.

For individual VRB reaction cells the energy conversion efficiency can be as high as 90% at low current densities [3]. The grid-to-grid efficiency is reported by multiple sources to be in the range of 65% to 73% at constant rated discharge power.

5.4. Regulation ability and other system services

The response time (i.e., the time it takes for the battery to supply a requested charge or discharge power) is according to manufactures is less than 100 ms if electrolyte is already present in the reaction cell [6], and less than 1 s if electrolyte need to be pumped into the cell [7], and less than 1 min if the pumps are turned off & time to turn on [7]. Large scale VRB installations have been demonstrated to be routinely capable of operating for 30 s at 150% rated power capacity [8]. While VRBs have slower response times than LIBs, they are still agile enough systems to be used for ancillary services.

Grid scale battery operation depends on the application. Batteries used for energy arbitrage will generally complete a single charge/discharge cycle over 24 hours. Batteries used for various other grid services including stabilization of input from renewables as exemplified below will often not undergo traditional battery cycling but frequently switch between being charged and discharged according to demand.

Due to its short response time combined with the ability to independently vary installation size of energy storage capacity and power capacity, VRB installations can provide a range of system services. The manufacturer lists the following applications for grid and utility installations [9]:

- T&D deferral (avoid need to upgrade transmission and distribution equipment)
- Flex capacity/ramping
- Load shifting
- Ancillary services

5.5. Typical characteristics and capacities

The non-exhaustive DOE Global Energy Storage Database [10] lists 21 different installations of capacities above 100 kW commissioned since 2011-23 and by 8 different manufacturers. A selection of these projects is depicted in Table 5-1 below.

Table 5-1: VRB plants with MW, MWh, and storage duration [10], [11], [12], [13].

Project Name	Rated Power (kW)	Energy (kWh)	Status
City of Painesville	1000	8000	Operational
Snohomish PUD - MESA 2 BESS	2000	8000	Operational
Zhangbei National Wind and Solar Energy	2000	8000	Operational
Guodian Hefeng Beizhen Wind Farm: VFB	2000	4000	Under Construction
Tomamae Wind Farm	4000	6000	Operational
GuoDian Long Yuan Wind Farm VFB	5000	10000	Operational
Dalian , Northeast China [14]	100	400	Operational
BHEL VRF plant	50	200	Operational

5.6. Typical storage period

The typical storage period depends on operation. It ranges from minutes to hours for grid scale installations [15]. The storage time is not technologically limited. Energy can be stored for extended periods of time as is the case in small local user level VRB units used for emergency power. VRB are typically economical for longer durations of 4+ hours. [16] [17]

5.7. Space Requirement

Comparison of Land Usage for Grid-Scale VRB Installations:

- The space requirements for grid-scale VRB installations vary significantly, ranging from 16.7 m^2/MWh to 140.2 m^2/MWh
- The VRB project in Hokkaido, Japan, commissioned in 2016, occupies a total land area of 5000 m^2, corresponding to a land use of 83.3 m^2/MWh [18]
- UniEnergy Technologies have suggested in promotional material that an installation with 240 MWh storage capacity would occupy a land area of 4000 m^2, translating to a land use of 16.7 m^2/MWh, the lowest value found [9]

The space requirements for VRB with various capacities from another manufacturer are given in Table 5-2.

Table 5-2: Space requirement for various capacities [19].

Output (MW)	Capacity (MWh)	L X W (m)	Area(m^2)	Area per MWh in m^2
2	8	39 x 12	468	58.5
2	12	38 x 15	570	47.5
2	16	34 x 23	782	48.9

5.8. Advantages/disadvantages

General advantages and disadvantages of VRB batteries in comparison to other technologies for energy storage are listed in Table 5-3.

Table 5-3: General advantages and disadvantages of VRB in comparison to other technologies for energy storage . [20] [21] [22].

S.no	Advantage	Disadvantage
1	Operate at ambient temperatures	May have lower energy density compared to other battery technologies
2	Utilize full energy storage capacity without degradation	Initial investment costs may be higher than traditional battery systems
3	Long technical lifetime (up to 20 years)	Flow batteries, including VRB, may have lower round-trip efficiency compared to other batteries
4	Electrolytes can be easily recycled and reused	Potential issues with electrolyte leakage, although less severe compared to other flow batteries
5	Leakage of reactants does not result in electrolyte contamination; energy storage capacity can be regained	Flow batteries, including VRB, may have more complex system requirements and maintenance
6	It is generally safe	Availability of vanadium may affect scalability and cost-effectiveness

In comparison to other grid-scale batteries, VRB and other flow batteries have the significant advantage to independently adjust energy storage and power capacities, allowing tailored optimization for specific applications. In contrast to molten sodium batteries (Na-S and Na-$NiCl_2$) also applicable for grid scale applications, VRB operate at ambient temperatures.

The reactants in a VRB are in a solution, this allows the full energy storage capacity of the battery to be utilized without battery degradation in contrast to batteries where charge/discharge products are solid state [1].

VRB also have the advantage that the electrolytes can easily be recycled and reused [1]. As vanadium is the active specie in both anolyte and catholyte, leakage of reactants from one electrolyte into the storage container of the other electrolyte will, in contrast to other flow batteries, not result in electrolyte contamination but only loss of energy storage capacity. The energy storage capacity can be regained by re-balancing the volume and vanadium content of the two electrolyte solutions [1]. Manufacturers promote VRBs as being highly safe [9], and recycling of the electrolyte is technically possible, however, in reality it is not yet commercially available, likely due to the addressable market size being small for the time being as VRB have not yet seen large scale deployment. The vanadium electrolytes are aqueous and non-flammable, and vanadium compounds used are relatively non-toxic compared to heavy metals in other battery chemistries, contributing to the overall safety of VRB operation.

VRB and other flow batteries have relatively low grid-to-grid energy efficiencies in comparison to other batteries. This is a consequence of losses related to mechanical pumping of electrolyte, undesired electrical currents known as shunt currents, which allows electrons to bypass the external circuit, and leakage of reactant vanadium ions through the reaction cell semi permeable membrane. Even though the energy density and specific energy for VRB is increasing with recent innovations, they remain relatively low in comparison to other batteries [1], [23].

R&D can and has previously allowed lower-cost sources of vanadium to be used as raw material [1]. The vanadium reactants have the potential to corrode the membrane. High quality and large cost membranes must thus be used in VRB reaction cells [1], [23]. Alternatively, the membrane must be replaced within the technical lifetime of the battery.

5.9. Environmental impact

- Raw Material Extraction: Flow batteries rely on metals like vanadium that are extracted through processes that can harm ecosystems and contribute to greenhouse gas emissions, but vanadium itself is not toxic to the environment and if sourced/recovered from waste stream, the environmental impacts due to extraction are also reduced.
- Manufacturing Process: The production of flow batteries involves energy-intensive operations, including refining raw materials and assembling components, leading to pollution and greenhouse gas emissions. However, the electrolyte can be reused in other VRB system.
- End-of-Life Management: Proper disposal or recycling of flow batteries is essential to minimize environmental harm as they reach the end of their lifespan. Mismanagement could release hazardous materials into the environment.
- Chemical Spills and Leaks: Liquid electrolytes should be carefully kept in flow batteries because they carry a risk of spills or leaks, potentially contaminating soil and water sources, and endangering human health and ecosystem
- Life cycle analysis (LCA) on a VRB prototype showed that the battery's cell stack and the vanadium electrolytes are the main contributors to the environmental impacts from the production stage. The quantified impacts can be reduced by using recycled or local materials and components [24].

5.10. Research and development perspectives

Flow battery technology, including VRB, is currently undergoing rapid development. Research and Development (R&D) efforts are concentrated on reducing the costs of battery components, with a particular focus on non-aqueous electrolytes [2]. While the vanadium cost remains a limiting factor, there is potential for the utilization of more cost-effective sources in production [1]. Furthermore, alternative redox couples, such as zinc-bromide, bromide-polysulphide, iron-chromium, and zinc-chloride, hold promise for significant

cost reduction in grid-scale redox flow batteries [25]. In this pursuit, researchers are coming up with new advancements like:

- Exploration of Alternative Electrolyte Materials: Researchers are exploring organic compounds like quinones as alternatives to expensive metal ions in electrolyte solutions [26]
- Optimized Flow Cell Design: Efforts are directed towards optimizing flow cell designs to achieve higher power density and efficiency [27].
- Development of Selective and Low-Resistance Membranes: Specific membranes with improved selectivity and lower resistance are being developed to enhance overall battery performance [28].
- Hybrid Redox Flow Battery Systems: Innovative approaches, such as hybrid flow battery systems combining carbon-based electrodes with metal-free electrolytes, are being pursued for improved efficiency and cost-effectiveness [28].

5.11. Examples of market-standard technology

Vanadium flow batteries, known for their large-scale capacity, are ideally suited for industrial and utility-scale energy storage applications. They may theoretically outperform other battery technologies such as Li-Ion and solid-state batteries in utility-scale scenarios due to their scalability, extended lifespan, and enhanced safety features. Moreover, when produced on a large scale, vanadium flow batteries are projected to be more cost-effective. Several prominent institutions in India, including IIT-Madras, IIT-Delhi, Rajiv Gandhi Institute of Petroleum Technology, IISc, and Indian Institute of Engineering Science and Technology (IIEST) - Shibpur, are actively engaged in the research and development of vanadium-based redox flow batteries [29].

Examples of existing projects are presented below.

5.11.1. BHEL 50 KW plant



Figure 5-3: BHEL 50 KW VRF plant battery [30].

The first vanadium redox flow battery, acquired by the Indian state-owned enterprise Bharat Heavy Electricals Limited (BHEL), was commissioned in Hyderabad, India, in September 2018 as a demonstration project. This battery system boasts a capacity to deliver 50 kW of power and can discharge 200 kWh of energy within a four-hour period. The project encountered challenges such as extensive cleaning of the container and pipelines to remove accumulated dirt and electrolyte residues, as well as addressing paint quality issues and rust stains. Initial water testing issues were promptly mitigated by clean, deionized water. Subsequent tests confirmed the battery's charging and discharging capabilities, followed by the positioning of stacks in

their designated locations, facilitated by a platform constructed from materials supplied by BHEL. The project will be used for output smoothening of power output, frequency regulation, time shifting of energy generation and consumption as well as for peak load saving.

Table 5-4: Specifications of the battery used in VRF plant [31].

Parameter	Value
Energy	200 kWh
Nominal Power	50 kW for 4 hours
DC-DC Cycle Efficiency	Min 70%
Service Life	20 years
No of cycles	>10000
Depth of Discharge (DOD) allowed	0-100% (no impact on battery life)
Response time	<75 ms
Self-discharge per day	<0.02%
Climatic operating conditions	0-50 degrees Celsius with 90% humidity

5.11.2. IIT MADRAS 25 kWh VRF BATTERY



Figure 5-4: IIT Madras VRF battery [32].

A kilowatt-scale vanadium redox flow battery has been successfully developed by scientists at the Indian Institute of Technology Madras (IIT Madras). This marks a significant milestone as it is the first battery of its kind to be manufactured in India, poised for direct deployment in industrial-scale stacks for grid-level storage. The researchers affirm that the new design's efficacy has been experimentally validated. The storage system boasts a rated power capacity of 5 kW and peak power of 8 kW, with a storage capacity of 25 kWh. Its energy density ranges from 30 to 40 watt-hours per liter of electrolyte solution, achieving a round-trip efficiency of over 70% at rated power and 60% at peak power [32].

Table 5-5: Technical specifications of the developed battery [32].

Parameter	Value
Rated Power Capacity	5 kW
Peak Power	8 kW
Storage Capacity	25 kWh
Energy Density	30-40 Wh/L
Round-Trip Efficiency (Rated Power)	>70%
Round-Trip Efficiency (Peak Power)	60%
Number of Cells per Stack	16
Cell Area	1,500 cm^2
Electrolyte Material	Vanadium Oxide Sulfate Hydrate
Electrode Material	Graphitized Carbon Felt
Computational Method	Three-Dimensional CFD Simulations

5.12. Projection of performance and cost

VRB cost projections are based on a literature review considering [16], [17], [33], [34]. Cost data from the various sources have been converted to the common reference unit, and all prices have been adjusted to 2023 levels. No cost reductions are anticipated between 2050 and 2070, as VRBs are assumed to have reached maturity, and further significant technological advancements are expected to be negligible.

5.13. Uncertainty

For 2024 and 2070, uncertainties are defined by the range between the minimum and maximum cost values identified in the reviewed literature.

5.14. Additional remarks

Since battery units are highly modular and equipment is the main cost of full installations, a close to linear scaling in total cost vs. installation size is expected from a technological point of view. Significant financial benefits from increasing installation sizes will rely on negotiations with manufacturers.

Even though VRB and other flow batteries have high commercial potential, rapid cost reduction of alternative storage solutions, e.g., Li-Ion batteries might halter commercial deployment and technological development of VRB and other flow batteries. This can prevent VRB and other flow batteries from reaching full commercial potential.

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5.16. Datasheet

Technology	Vanadium Redox Flow batteries										
	2024	2030	2040	2050	2070	Uncertainty (2024)		Uncertainty (2070)		Note	Ref
						Lower	Upper	Lower	Upper		
Energy/technical data											
Form of energy stored	Electricity										
Application	System, power- and energy-intensive										
Generating capacity for one unit (MW)	10	10	10	10	10	1	10	1	10	A	1, 8, 10
Storage capacity (MWh)	60	60	60	60	60	5	240	5	240	B, P	1, 8, 10, 15, 18
Depth of Discharge (%)	90	90	90	90	90	80	100	80	100	C	1, 4, 8
Round trip efficiency (%AC)	69	71	73	74	74	65	73	70	80		8, 10, 18, 14, 15
Round trip efficiency (%DC)	75	77	79	80	80	70	80	75	85		1, 8, 4, 6, 5, 14
- Charging efficiency (%)	87	88	89	89	89	84	89	87	92	D	
- Discharge efficiency (%)	87	88	89	89	89	84	89	87	92	D	
Energy loss during storage (%/day)	0.10	0.10	0.10	0.10	0.10	0.00	0.20	0.00	0.20	E	4, 6
Forced outage (%)	0.5	0.5	0.5	0.5	0.5	0	5	0	5		6
Planned outage (weeks per year)	0	0	0	0	0	0	0	0	0		6
Technical lifetime (years)	15	15	20	20	20	10	20	15	25		4, 8, 10, 6, 15
Construction time (years)	1.5	1.5	1	1	1	1	2	0.5	2	G	3, 6, 8, 15
Lifetime (battery cycles)	8000	12000	15000	20000	20000	5000	10000	15000	22500	O	4, 5, 8, 10, 15
Discharge time (h)	6	6	8	8	8	4	12	6	24		1, 8, 10, 15, 18
Regulation ability											
Primary load support (% per 30 seconds)	100	100	100	100	100						6
Secondary load support (% per minute)	100	100	100	100	100						6
Minimum load (% of full load)	na										
Financial data (in 2023₹)											
Capital cost (cr. ₹/MWh)	4.92	3.93	3.07	2.28	2.28	4.50	5.33	1.80	2.75	H	8, 9, 15, 16, 20
- energy component (cr. ₹/MWh)	3.77	3.01	2.36	1.74	1.74	3.45	4.09	1.38	2.11	J, I	9
- capacity component (cr. ₹/MW)	1.28	1.03	0.80	0.59	0.59	1.17	1.39	0.47	0.72	K, I	9
- other project costs (cr. ₹/MWh)	0.93	0.75	0.58	0.43	0.43	0.86	1.01	0.34	0.52	L, I	9
Fixed O&M (cr. ₹/MW/year)	0.147	0.118	0.092	0.068	0.068	0.071	0.295	0.071	0.137	M	9, 15
Variable O&M per output (₹/MWh)	43	43	43	43	43	39	47	17	24		5
Technology specific data											
Alternative Total investment cost (cr. ₹ per MW)	29.50	23.59	18.44	13.65	13.65	27.00	32.00	10.80	16.50	N	
Energy density (Wh/L)	45										15
Specific energy (Wh/kg)	35										18

Notes

A Literature mainly takes 10 MW as reference size

B Generally, VRB will be used for lager, more long-term storage. The power and energy capacity can be sized independently.

C VRFB have high DOD due to Chemical design of electrolyte and long life cycle

D Calculated as square root of DC RTE

E VRFB exhibit low self discharge rates due to Chemical Stability of Vanadium Redox Couples, energy being stored in liquid electrolytes contained in separate tank, and low Crossover of Electrolytes

F The auxiliary power consumption of a VRFB is high due to the power required to operate the pumps and other auxiliary equipment that circulate the electrolyte solution through the battery stack

G A project by Bushveld Energy, which included a 1 MW 4 MWh containerized vanadium flow battery, began site preparation for construction in Q1 2022 and was expected to be completed in H1 2023. This suggests a construction period of approximately 1 to 1.5 years for that specific project. The actual construction time can vary depending on geographical constrains.

H The 2024 upper uncertainty is from [9] while the lower uncertainty is from an Indian stakeholder. The 2070 values follow an Indian stakeholder and [20], the projected point estimates follow [20]

I The 2024 upper uncertainty is based on the point estimate in [9]. From here, cost contributions of the individual cost components have been derived and used for all other cost component breakdowns of the Capital cost in cr R/MWh

J Considering Storage Block cost + Storage Balance of System + System Integration [9]

K Considering Power Equipment Cost + Controls and Communication + Grid Integration [9]

L Considering Project Development + Engineering, Procurement, and Construction Cost (EPC) [9]

M up to 1% of CAPEX, 0.5 % is used for point estimate

N Calculated based on cost components and reference size

O The use of the Electrolyte is unlimited

P The key advantage of a VRB system is that, unlike many other battery types such as Li-ion, the energy component is very inexpensive: it is essentially just tanks of electrolyte. This energy part can therefore be scaled almost arbitrarily, so the storage capacity can be made as large as the system requires.

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6. Compressed Air Energy Storage

6.1. Brief technology description

Compressed Air Energy Storage (CAES) is a mechanical energy storage system that uses atmospheric air to store energy and generate electricity. During periods of low energy demand, energy from renewable sources is used to compress atmospheric air to a high pressure through a motor-compressor arrangement. The compressed air is then stored in underground containers, typically in caverns. When energy demand rises, the stored compressed air is expanded through a turbine to generate electricity using a generator (alternator).

CAES demonstrates several advantages among energy storage systems, such as a clean storage medium, long operational life, high scalability, low self-discharge, extended discharge times, relatively low capital costs on per energy capacity basis if suitable geology is available, and high durability. Key disadvantages include location dependency (suitable geology), fuel use in traditional systems, and relatively low round-trip efficiency compared to batteries. This chapter reviews CAES concepts and available compressed air storage (CAS) options, highlighting their respective strengths and weaknesses. [1]

6.1.1. Compression/expansion

In the most common form of CAES called Diabatic CAES, during the compression process, heat is released, which results in energy loss as it dissipates into the environment. If this heat can be stored, for example, in ceramic materials (thermal storage), it can be reinjected during the expansion process to improve efficiency. This method improves the overall energy conversion efficiency (electricity-to-electricity) and is termed Adiabatic CAES (A-CAES), as the heat exchanged between the storage system and the environment drastically reduced or is eliminated entirely. There is also Advanced Adiabatic CAES (AA-CAES), which is similar to A-CAES but pushes the concept further in pursuit of higher round-trip efficiency and zero emissions. Other variations of CAES, such as isothermal CAES, have been proposed, but no commercial installations for these alternatives exist. Therefore, only traditional CAES and A-CAES are discussed in this chapter. [2]

Table 6-1: Comparison of CAES technologies [3].

Property	Diabatic CAES	Adiabatic CAES
Heat Management	Heat of compression is wasted on the environment.	Utilises a thermal energy reservoir to store and absorb thermal energy during compression.
External Energy Sources	Requires external energy sources like natural gas burners to compensate for wasted energy.	Can be designed without needing external energy sources; relies on stored thermal energy.
Preheating Requirement	Preheating the air before expansion is necessary to improve efficiency.	Stored thermal energy is used to raise air temperature during discharge, enhancing efficiency.
System Efficiency	Lower efficiency due to energy loss during compression.	Higher efficiency by recovering and reusing thermal energy.
Technology Focus	Basic technology with significant energy loss.	Advanced technology aimed at improving efficiency by storing and reusing thermal energy.

6.1.2. Existing CAES Systems

Currently, CAES systems often rely on gas turbine combustion to compensate for temperature drops, meaning CO_2 is released during operation. Despite being considered a favourable technology for storing renewable energy, only two full-scale CAES plants have been operational commercially for a significant time-period: one in Huntorf, Germany (1978), and another in McIntosh, Alabama, USA (1991). Interestingly, the Huntorf facility was constructed to balance nuclear power generation by managing differences between electricity production and demand. Neither plant utilizes A-CAES technology, so their round-trip efficiencies remain relatively low. Figure 6-1 illustrates a plant diagram of two different CAES plants. This chapter focuses on the Huntorf and McIntosh plants, as they offer the most comprehensive operational experience with CAES.

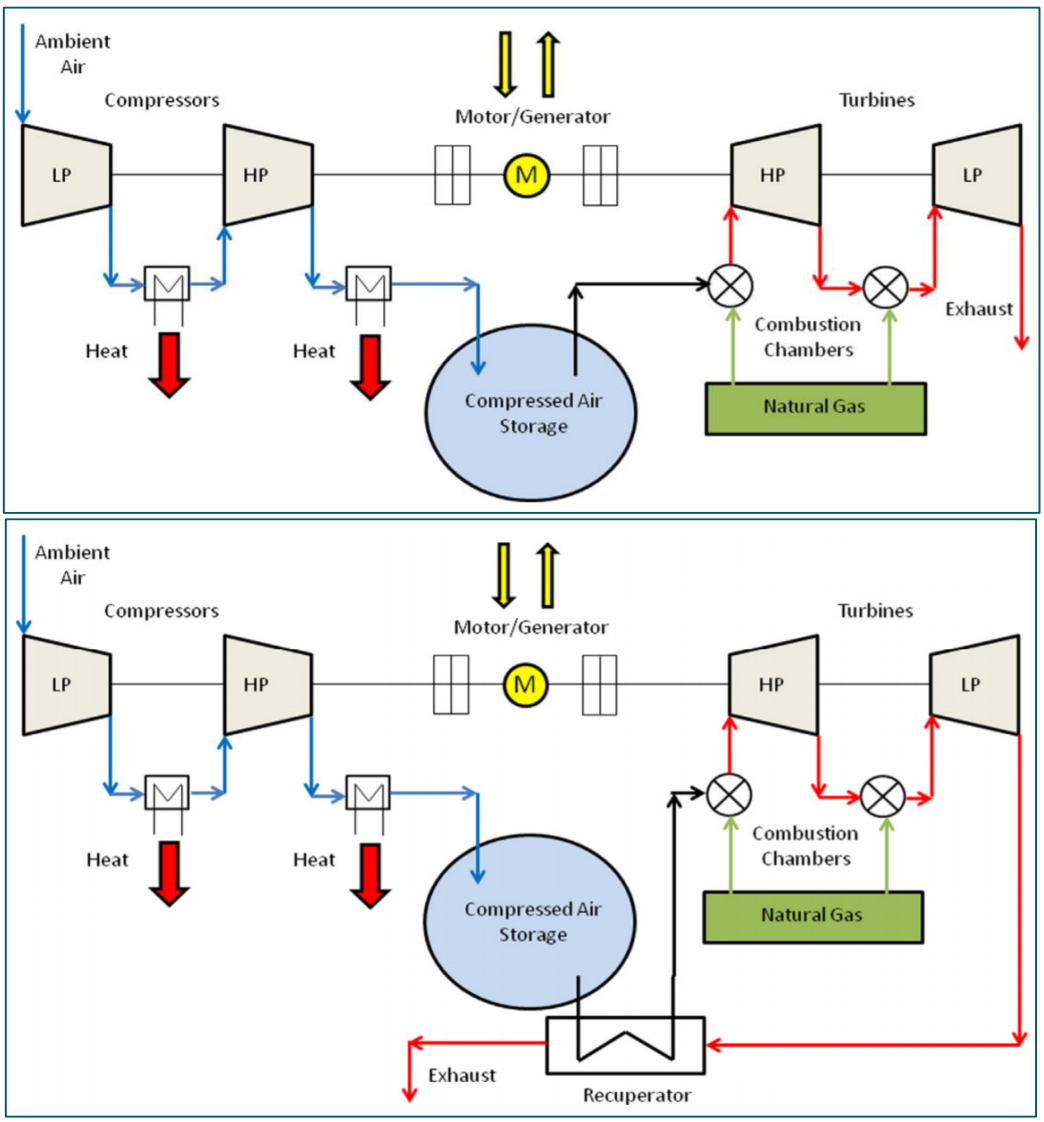

Figure 6-1: Operating principle of the CAES plant Huntorf (top) and the McIntosh (bottom) [4].

The Huntorf plant consumes 0.8 kWh of electricity and 1.6 kWh of natural gas to produce 1 kWh of electricity. The McIntosh plant, which incorporates a heat recuperator (recycles waste heat), uses 0.69 kWh of electricity and 1.17 kWh of gas per 1 kWh of electricity produced. [5] [6]

6.1.3. Components of CAES

A typical diabatic CAES system consists of five key components [3] as also illustrated in Figure 6-1:

- **Motor/Generator:** Alternates engagement between the compressor and turbine
- **Air Compressor:** Multi-stage compressor with intercoolers and after-coolers to improve compression efficiency and reduce air moisture
- **Turbine Train:** Includes both high- and low-pressure turbines
- **Storage Cavity:** Underground rock caverns, salt caverns, or porous media reservoirs such as depleted gas or oil fields

- **Control Equipment:** Includes system controls, fuel handling, heat exchangers for intercooling and recuperation, and auxiliary components for thermal and safety management.

6.1.4. Working Principle

Compressed Air Energy Storage (CAES) decouples the compression and expansion stages of gas turbine technology to store energy in the form of high-pressure air. During periods of low electricity demand, surplus energy is used to compress atmospheric air to pressures typically between 4.0 and 8.0 MPa, which is then stored in underground caverns. [1] When electricity demand increases, the stored compressed air is released and reheated before being expanded through turbines to generate power.

In diabatic CAES systems, the compressed air is first expanded through a high-pressure turbine, then mixed with fuel and combusted before passing through a low-pressure turbine. Both turbines are coupled to a generator to produce electricity. Waste heat from the exhaust may be partially recovered using a recuperator to preheat incoming air, improving overall efficiency.

In contrast, adiabatic CAES systems store the heat generated during compression and reuse it during expansion, eliminating the need for combustion. These systems aim to improve efficiency and reduce emissions by avoiding external fuel use. [7]

6.1.5. Air storage volumes

The capacity of a CAES system depends on its storage volume. Small units utilise high-pressure gas cylinders (surface level). However, for large amounts of energy (hundreds of MWh) CAES is usually established in conduit with large underground formations able to hold significant amounts of compressed air. Such formations could be depleted oil or gas fields, aquifers, salt caverns, lined rock caverns and abandoned mines [8]. An illustration of some of the storage principles is shown in Figure 6-2.

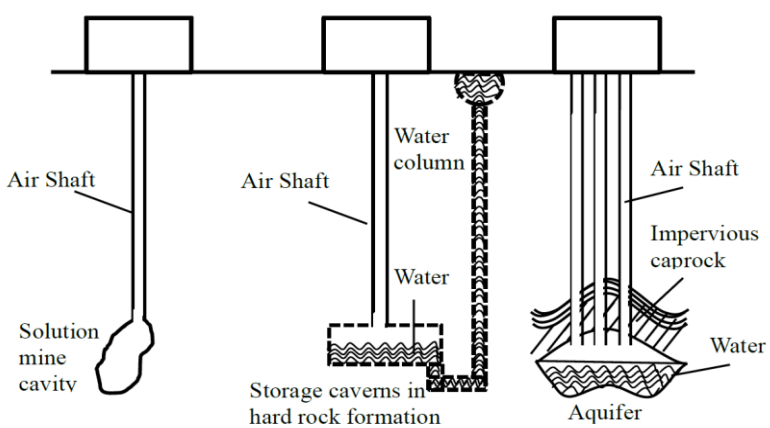

Figure 6-2: Various Geological Formations for Underground Storage [9].

The Huntorf and McIntosh CAES plants are connected to salt domes, which are cost-effective but not widely available. However, environmental concerns can limit the development of such caverns.

6.2. Input/output

The input for CAES is electricity. In Adiabatic Compressed Air Energy Storage (A-CAES), no fuel is required. The output for CAES is also electricity. In contrast, traditional CAES requires some fuel (typically natural gas)

during the electricity output phase. Traditional CAES generates heat during the compression phase, while A-CAES captures and stores this heat, preventing it from being released into the external environment.

6.3. Energy efficiency and losses

Figure 6-3 illustrates the energy losses during both the compression and expansion stages of a Diabatic CAES plant. The estimated charging efficiency of about 72% and a discharge efficiency of around 72% result in a round-trip efficiency of approximately 52% (electricity-to-electricity, with heat recuperation) (see datasheet).

During the compression stage, a portion of the electrical energy used to compress air is converted into heat, much of which is lost to the environment because diabatic systems do not store this heat for reuse. Additional losses arise from mechanical and electrical inefficiencies in compressors and motors. In the storage phase, there are relatively minor losses due to air leakage and thermal exchanges with the surrounding rock or cavern. During the expansion stage, further losses occur because the stored air must be reheated—typically by burning natural gas—to reach the turbine inlet temperature required for power generation. This combustion process introduces fuel-related inefficiencies and additional thermal losses in the heat exchangers and turbine. Overall, these combined losses—thermal, mechanical, and chemical—significantly reduce the system's round-trip efficiency compared to adiabatic or isothermal CAES designs, which better conserve or reuse compression heat.

In Adiabatic CAES or Isothermal CAES, the heat losses are reduced allowing for round trip efficiency to range from 60% to in some tests higher than 70% [3].

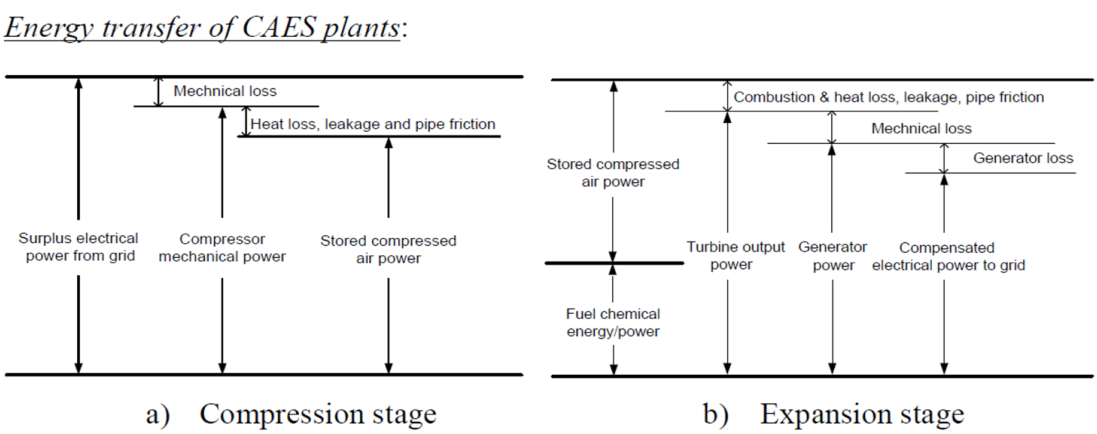

Figure 6-3: Energy transfer of a conventional CAES plant [10].

6.4. Regulation ability and other system services

Compressed Air Energy Storage (CAES) systems offer valuable grid regulation capabilities, though they have certain limitations in terms of response time. Diabatic CAES plants typically have startup times ranging from 10 to 15 minutes which makes them less suitable for immediate grid balancing but effective for medium-term load shifting and peak shaving. [11] Their relatively slow ramp rates limit their use in fast frequency regulation. However, CAES systems can provide spinning reserve, voltage control, and ancillary services, such as stabilizing grid frequency and balancing supply-demand mismatches over longer periods. Adiabatic CAES systems, if developed further, could offer faster response times and enhanced flexibility for grid applications due to improved thermal management. [11]

Furthermore, A-CAES is expected to offer faster ramping due to their advanced thermal management and temperature control, theoretically allowing for a quicker response time. A-CAES can potentially respond in a matter of minutes, enabling them to participate more effectively in frequency regulation and load-following services, where faster ramping is crucial. While exact ramp rates depend on the specific design, A-CAES generally promises greater flexibility for grid stabilization applications.

6.5. Typical characteristics and capacities

As mentioned above only two CAES plants have been operational for a significant period. The characteristics of the two existing plants are listed in Table 6-2.

Table 6-2: Supplementary descriptive data for the Huntorf and McIntosh facilities. The indicated heat rates (thermal energy in over electrical energy out) can be recalculated to 1.96 kWh/kWh for Huntorf and 1.20 kWh/kWh for McIntosh [1] [12] [23].

	Huntorf (1978) Germany	McIntosh (1991) USA
		
Turbine Power / Discharge time	Old 290 MW/2hrs New 320 MW/3 hrs	110 MW/24 hrs
Compression Power / Charging time	60 MW/8 hrs	50 MW/38 hrs
Power ratio	0.19	0.45
Charge/Discharge time Ratio	1.6	2.7
Cavern Pressure	45-74 bar	46-72 bar
Efficiency Heat Rate	42% 6700 BTU/kWh (without heat Recuperator)	54% 4100 BTU/kWh (with heat recuperator)
Availability **Reliability** **Start-up reliability**	90% 97% 95%	90% 97% 95%
Cavern	2 x 150000 m^3 (Salt Cavern)	538000 m^3 (Salt Cavern)

As can be seen in the table above, the CAES plants have been built for up to 50-60 MW charging power and 100-300 MW discharging power. The energy storage capacities of the plants are 480 MWh for Huntorf and 1,900 MWh for McIntosh. The energy density of compressed air naturally depends on the pressure difference

between the upper and lower limits of the pressure variation. For the Huntorf facility, the energy density is approximately 0.3 kWh/m^3. [12] For the McIntosh, the number is about the same since the same pressure range is used. However, the energy densities of CAES, measured in kWh/m³ and kWh/kg, are generally not considered critical factors. This is largely because CAES is a stationary technology, typically deployed in fixed locations with ample space, such as underground caverns. Therefore, optimizing for energy density is less important than it would be for mobile or compact storage solutions.

6.6. Typical storage period

The practical duration of storage periods for CAES can be inferred from Figure 6-4 showing the number of starts per year for the Huntorf plant in the period from 1978 to 2000. During this period, the number of starts ranged from 50-200 per year, with occasional outliers reaching up to 400 starts and as low as 25 starts. This shows that practical storage periods vary between hours and days. However, these durations reflect the facility´s operational pattern in practice rather than its technical capability. Since compressed air is stored in underground salt caverns which are highly air tight (similar to their use for natural gas storage) the air can be stored for a much longer time if so desired. That said, the levelized cost of energy storage will increase with longer storage times due to reduced frequency of cycling and extended idle periods.

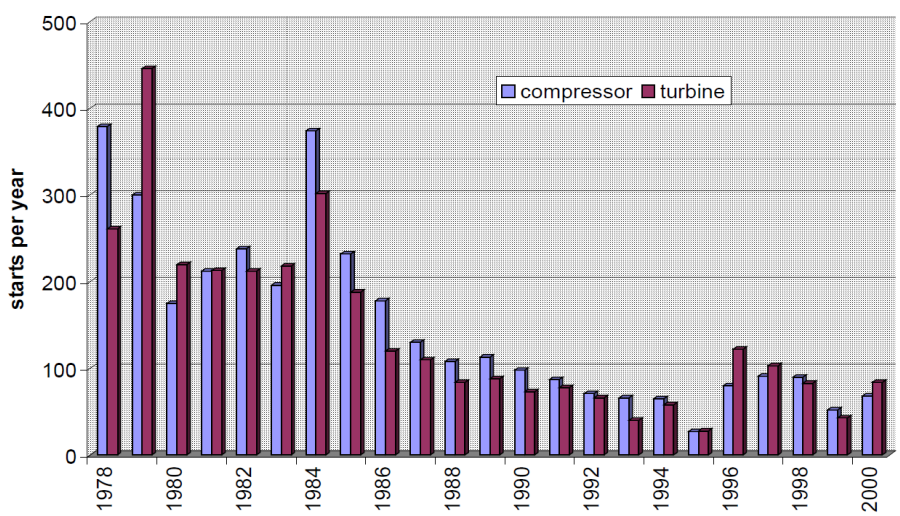

Figure 6-4: Number of compressor starts (charges) and turbine starts (discharges) for the Huntorf facility for the period between 1978 and 2000 [12].

6.7. Space requirement

Figure 6-5 shows the Huntorf CAES plant. This gives a visual idea of the space requirements for a CAES plant. An area of approx. 200x200 m (40,000 m^2) is required for 320 MW_{el} output [6]. However, according to reference [13] 1 acre, which corresponds to approximately 4000 m^2 (63x63 m), is required for a 100 MW output plant.



Figure 6-5: Aerial photo of the Huntorf facility [14].

A critical factor that influences the location of a CAES plant is accessibility to sites suitable for storing large amounts of compressed air. Since the energy storage capacity depends on the volume of underground formations it is not possible to give a number in m^2/MWh. As mentioned, the two plants utilise underground caverns in salt domes.

6.8. Advantages/disadvantages

6.8.1. Advantages

The following advantages are cited from [13] :

- The CAES plant can provide significant energy storage (in the thousands of MWhs) at relatively low costs (approximately (in 2003 USD) $400/kWac to $500/kWac). The plant has practically unlimited flexibility for providing significant load management at the utility or regional levels.
- Expanders have a large size range. Commercial turboexpander units range in size from 10 -20 MWac (Rolls Royce-Allison) to 135 MWac (Dresser-Rand) to 300-400 MWac (Alstom).
- The CAES technology can be easily optimized for specific site conditions and economics.
- CAES plants are capable of black start. Both the Huntorf and McIntosh plants have black start capability that is occasionally required.
- CAES plants have fast startup time. If a CAES plant is operated as a hot spinning reserve, it can reach the maximum capacity within a few minutes. The emergency startup times from cold conditions at the Huntorf and McIntosh plants are about 5 minutes. Their normal startup times are about 10 to 12 minutes.
- CAES plants have a ramp rate of about 30 % of maximum load per minute.
- A CAES plant can (and does) operate as a synchronous condenser when both clutches are opened (disconnecting the motor-generator from both the compressor train and the expander train), and the motor-generator is synchronized to the grid. Reactive power can be injected and withdrawn from the grid by modulating the exciter voltages. Both the Huntorf and the McIntosh plant are used in this manner. Since this operation does not require the use of stored air, the plant operator can choose to operate the plant in this mode for as long as necessary.

6.8.2. Disadvantages

The following disadvantages are cited from [6] :

- For traditional CAES the use of natural gas implies CO_2 emissions. However, for A-CAES there is no use of natural gas and no exhausts.

- Geographical placement is limited to places, where high-pressure air can be stored in sufficient amounts. Several geological underground formations are suitable, but the restriction puts limitations on where CAES can be placed.
- In the basic form (without intermediate heat storage) CAES shows relatively low electricity-to-electricity efficiency around 45 % without recuperation.

6.9. Environmental impact

The main environmental impacts of operating a CAES plant - except surface footprint – relate to the use of fossil energy in the expansion phase [15]. CAES plants emit air pollutants during the compression process, including nitrogen oxides (NOx) and particulate matter. This problem could be overcome by the development of A-CAES (Adiabatic CAES), where heat is stored from the compression phase and redelivered in the expansion phase. The impact of land disturbance during CAES facility construction is generally similar to or less severe than that associated with conventional electrical generating facilities

However, in the construction phase, it has been found that the environmental impacts correlate strongly with the size and method of construction of the underground storage cavity [16]. However, the impact is generally lower than that of fossil fuel-based power generation technologies. Particularly for solution-mined salt caverns the dissolved salt may (depending on location) contain concentrations of heavy metals, which may not readily be disposed of in rivers or lakes or even in the sea. [17]

6.10. Research and development perspectives

Researchers are increasingly examining Compressed Air Energy Storage (CAES) systems beyond their nominal operating conditions, with a focus on off-design considerations. Understanding CAES performance under varying loads and ambient conditions is crucial for optimizing efficiency and reliability [18].

Adiabatic CAES (A-CAES) aims to improve efficiency by minimizing heat exchange with the environment during compression and expansion. Recent trends involve integrating thermal energy storage (TES) systems into A-CAES, which can store excess heat generated during compression and release it during expansion, thereby enhancing overall system efficiency. Furthermore, researchers are exploring ways to integrate CAES with combined heating and cooling systems, allowing the use of excess heat from CAES processes for space heating or industrial applications, thus increasing the system's versatility and economic viability.

Regarding operational conditions, research and development efforts are focused on improving the relatively low round-trip efficiency of CAES by storing heat generated during the compression phase and reusing it during the expansion phase [19]. Figure 6-6 illustrates how the German utility company RWE envisions integrating a heat storage facility into a CAES plant. Heat may be stored at temperatures up to 600°C or higher in rock or other ceramic materials, and this technology is being developed for various applications. Looking ahead, it is reasonable to anticipate that A-CAES will become commercially available. This advancement is expected to improve power-to-power efficiency to around 70%, placing A-CAES in a more attractive efficiency class.



Figure 6-6: RWE's vision for an A-CAES plant [20].

6.11. Examples of market-standard technology

Currently, there is no active market for CAES plants in India. With only two CAES plants operating globally for an extended period, neither of these can serve as definitive benchmarks for the technology. In 2024, the commissioning of the Feicheng CAES plant in Shandong, China, marked a significant advancement in the field. This 300 MW facility, developed by Zhongchu Guoneng (ZCGN), boasts an energy storage capacity of 1,800 MWh and a discharge duration of six hours, making it capable of providing essential grid services such as peak shaving, frequency stabilization, and emergency backup power. [21]

Operating with an estimated efficiency of 72%, the Feicheng plant is expected to store around 600 GWh annually. The facility uses underground salt caverns for air storage, with gas wells reaching depths of 1,000 meters and a total air storage volume exceeding 500,000 cubic meters. It is also noted for its cost efficiency, with unit costs 30% lower than older systems. The plant is projected to save 189,000 tons of coal annually and reduce carbon dioxide emissions by approximately 490,000 tons. [21] As the plant has only recently been commissioned, the technical and economic parameters will need further verification once the plant has been operational for a significant period.

Looking ahead, if demand for CAES grows, it is likely that market standards will evolve based on modern technologies, particularly in compressors, turbines, and thermal energy storage. A-CAES and isothermal CAES are expected to set the standard for future technology and market practices.

One example of an existing project is presented below.

6.11.1. McIntosh Compressed Air Energy Storage (CAES) Plant

The McIntosh Compressed Air Energy Storage (CAES) plant, located in the town of McIntosh, Alabama, USA, stands as a pioneering achievement in the field of energy storage. As one of only two large-scale CAES facilities currently operational worldwide—the other being the Huntorf plant in Germany—the McIntosh plant plays a critical role in advancing energy storage technology. Commissioned in 1991, this plant was strategically constructed using vast, solution-mined salt cavern situated 1,500 feet underground. This subterranean cavern, specifically engineered for compressed air storage, boasts a capacity of approximately 19.8 million cubic feet of compressed air, making it a vital asset for energy management in the region [22]. The plant's operation is based on a simple yet effective principle: it utilizes off-peak electricity, typically generated during periods of low demand, to compress and store air in the cavern. This compressed air is then

released during peak demand periods, when electricity is most needed, to generate power. This approach not only helps in balancing the electricity grid by shifting energy use from times of low demand to periods of high demand but also enhances the overall efficiency and reliability of the power supply [23].

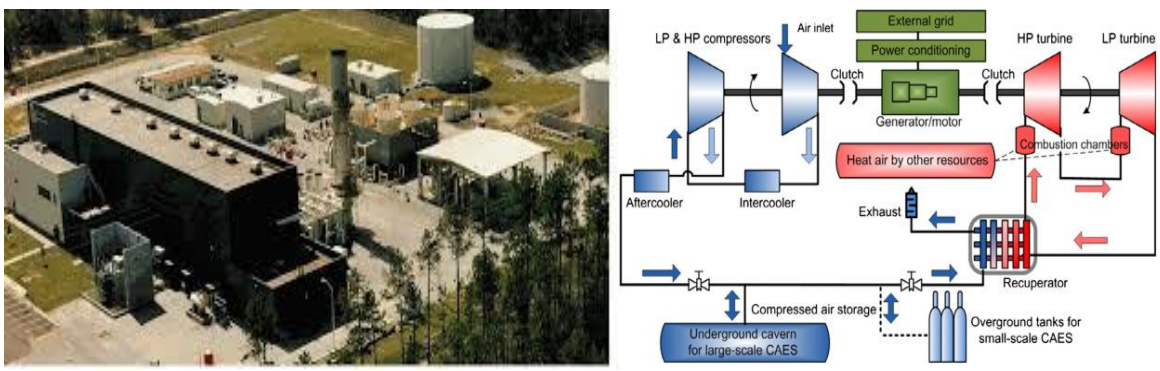

Figure 6-7: McIntosh Plant (a) site view [24] & (b) schematic [25].

The McIntosh CAES plant features a robust combination of a 50 MW compressor and a 110 MW power generation unit, which together form the core of its operation. This system is designed to compress air during off-peak hours—when electricity demand and prices are lower—and store it in the underground salt cavern for later use. The plant's design allows for continuous air compression for up to 41 hours [1]. When electricity demand peaks, the stored compressed air is released, heated using natural gas, and expanded through turbines to generate electricity. This process enables the plant to produce up to 110 MW of electricity for a continuous period of 26 hours, providing a reliable supply of power during critical times [26]. A key technological innovation at the McIntosh plant is the integration of a recuperative heat exchanger. This device captures the high-temperature exhaust from the low-pressure turbine and reuses it to preheat the inlet air of the gas turbine, thereby significantly improving the plant's overall thermal efficiency. This recuperation process enhances the plant's system efficiency by 25%, allowing it to achieve an overall efficiency of 54% [26]. Additionally, the plant's use of advanced compression and expansion techniques minimizes fuel consumption, reducing the amount of natural gas required per kilowatt-hour of electricity produced by about one-third compared to conventional combustion turbines. This lowers operational costs as well as results in significantly reduced emissions, making the McIntosh CAES plant an environmentally friendly and cost-effective solution for energy storage and generation.

Table 6-3: Technical Specification of McIntosh Compressed Air Energy Storage [1] [26].

Parameter	Details
Commissioned	1991
Underground Storage	Solution-mined salt cavern at 1,500 feet depth
Storage Capacity	Approximately 19.8 million cubic feet of compressed air
Compressor Power	50 MW
Power Generation Capacity	110 MW
Compression Duration	Up to 41 hours
Electricity Generation Duration	Up to 26 hours continuous at 110 MW
Efficiency Improvement	25% efficiency improvement due to the recuperation process
Overall System Efficiency	54%

6.12. Projection of performance and cost

The current cost and technical parameters used in this analysis refer to diabatic compressed air energy storage (D-CAES) systems, which represent the most established CAES technology today. However, starting from 2030, it is assumed that adiabatic CAES (A-CAES) will become the dominant market technology. This transition is expected to lead to increased investment costs, due to the more advanced system requirements of A-CAES, as well as improved performance characteristics.

Projections of both cost and technical parameters are based on a comprehensive literature review [27], [28], [29], [30]. Cost data also incorporate input from stakeholders. Cost data from the various sources have been converted to a common reference unit, and all prices have been adjusted to 2023 levels. No cost reductions are anticipated between 2050 and 2070, as CAES are assumed to have reached maturity, and further significant technological advancements are expected to be negligible.

6.13. Uncertainty

For 2024 and 2070, uncertainties are defined by the range between the minimum and maximum cost values identified in the reviewed literature mentioned in the previous section.

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6.15. Datasheet

Technology	Compressed Air Energy Storage										
	2024	2030	2040	2050	2070	Uncertainty (2024)		Uncertainty (2070)		Note	Ref
						Lower	Upper	Lower	Upper		
Energy/technical data											
Form of energy stored	Electricity to mechanical and heat										
Application	System, energy-intensive										
Output capacity for one unit (MW)	150	200	200	200	200	50	165	50	350	G	11, 13
Input capacity for one unit (MW)	120	120	120	120	120					G	12
Storage capacity (MWh)	1500	2000	2000	2000	2000	580	2860	600	8000		10, 13
Depth of Discharge (%)	80	90	90	90	90	80	90	80	100		8, 11
Round trip efficiency (%AC)	52	70	70	70	70	42	54	60	80		8, 10, 11, 13, 14, 15, 18
Round trip efficiency (%DC)	not applicable										
- Charge efficiency (%)	72	84	84	84	84	65	73	77	89	A	
- Discharge efficiency (%)	72	84	84	84	84	65	73	77	89	A	
Energy losses during storage (%/period)	0	0	0	0	0						1, 5
Forced outage (%)	5	4	4	4	4						5
Planned outage (weeks per year)	5	4	3	3	3						5
Construction time (years)	6	5	4	3	3	3	10	2	5		8, 10, 19
Technical lifetime (years)	40	45	45	45	45	25	60	30	60		5, 8, 11, 13, 14, 18
Discharge time	10	10	10	10	10	8	24	8	100		5, 8
Regulation ability											
Primary load support (% per 30 seconds)											
Secondary load support (% per minute)	25	25	25	25	25	20	30	20	30		11, 12
Minimum load (% of full load)											
Financial data (in 2023₹)											
Capital cost (cr. ₹/MWh)	1.25	1.72	1.36	1.08	1.08	0.94	1.55	0.81	1.34	C, F	8, 14, 18, 20
- energy component (cr. ₹/MWh)	0.09	0.12	0.12	0.12	0.12	0.07	0.11	0.06	0.09	H, I	
- capacity component (cr. ₹/MW)	11.28	15.48	11.88	9.04	9.04	8.46	13.99	7.30	12.06	H	
- other project costs (cr. ₹/MWh)	0.04	0.05	0.05	0.05	0.05	0.03	0.05	0.02	0.04	H	
Fixed O&M (cr. ₹/MW/year)	0.38	0.52	0.41	0.32	0.32	0.28	0.47	0.24	0.4	J	8, 18
Variable O&M per output (₹/MWh)	162.00	162.00	162.00	162.00	162.00	122.00	201.00	122.00	201.00	D, E	4, 7
Technology specific data											
Specific investment (cr R/MW)	12.54	17.20	13.60	10.76	10.76	9.40	15.54	8.11	13.40		8

Notes

A The value has been derived by taking the square root of the round trip efficiency

C In general it is assumed that by 2030 adiabatic CAES plants will dominate the market. This means that investment costs will increase and performance characteristics will improve.

D From data in section 5.1.3.5.2 Fixed and Variable Operations and Maintenance cost in [4]

E without fuel costs

F Capital costs are mainly the power capacity component. Storage is assumed to happen in existing caverns or similar

G The turbine (discharging) power and the compression (charging) power are mostly sized differently

H Cost contributions derived from [8] as Energy: 7%, Power: 90%, Other: 3% for both D-CAES and A-CAES, but projections of Energy and Other of A-CAES assumed to be constant, only cost reductions in Power are expected.

I existing natural cavern assumed. [21]: Utilising natural reservoirs offers significantly higher cost efficiency, while constructing a cavern
exclusively for CAES in hard rock can escalate costs by as much as 80% (IRENA - International Renewable Energy Agency, 2020)

J BNEF LDES [18] and DOE&PNNL [8] report between 1 and 6 %, here 3 % is chosen and rounded to nearest multiple of 100000

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7. Molten Salt Thermal Storage

7.1. Brief technology description

Molten salt thermal storage is a commercial energy storage solution widely applied in concentrated solar power (CSP) plants. It enables CSP plants to generate power consistently by storing thermal energy during sunny periods and releasing it as needed, such as at night or during cloudy conditions. This storage technology utilizes a form of thermal energy, where nitrate or nitrite salts—such as sodium nitrate and potassium nitrate—act as the primary storage medium. These salts are heated by surplus solar energy and stored in insulated tanks, where they retain heat until required. During discharge, the heat from the molten salt is transferred to a fluid, like water, to produce steam that drives a turbine, generating electricity. This allows CSP plants to provide reliable, renewable energy for applications such as electricity supply and grid stability through load shifting and peak shaving, as well as primary frequency regulation [1].

The system boundaries for molten salt storage focus on the storage tanks and heat transfer system, excluding the solar collectors and steam turbines. The most common configuration is the two-tank direct system, also known as the dual-tank system. This setup includes separate hot and cold storage tanks and uses molten salt both as a heat transfer medium and as the storage material. In this system, molten salt from the cold tank is pumped to a heat exchanger, where it absorbs heat and is then stored in the hot tank. During discharge, the molten salt is directed from the hot tank to a steam generator, where it cools as it transfers heat to produce steam. The cooled salt then returns to the cold tank to complete the cycle. The single-tank thermocline system is also under examination, as it offers a lower-cost alternative, reducing costs by approximately 35% compared to the two-tank system [2].

Illustration: The accompanying illustration in Figure 7-1 of the two-tank molten salt thermal storage system shows its primary components, including the cold and hot storage tanks, the heat exchanger (for both charging and discharging), and the steam generator. This layout highlights the working principle, where heat transfer between the molten salt and a fluid produces steam to drive turbines, ultimately generating electricity.

The thermocline system (see Figure 7-1) uses a single tank such that hot and cold salts are separated by a vertical temperature gradient (due to buoyancy force) to prevent mixing [3]. There are two cycles in the thermocline system:

a. charging
b. discharging

During charging, salt flows out of the cold side, is heated by the heat exchanger (reactor), and flows into the tank's hot side. During discharging, salt flows out of the hot side, transfers heat to generate power (turbine), and flows into the tank's cold side.

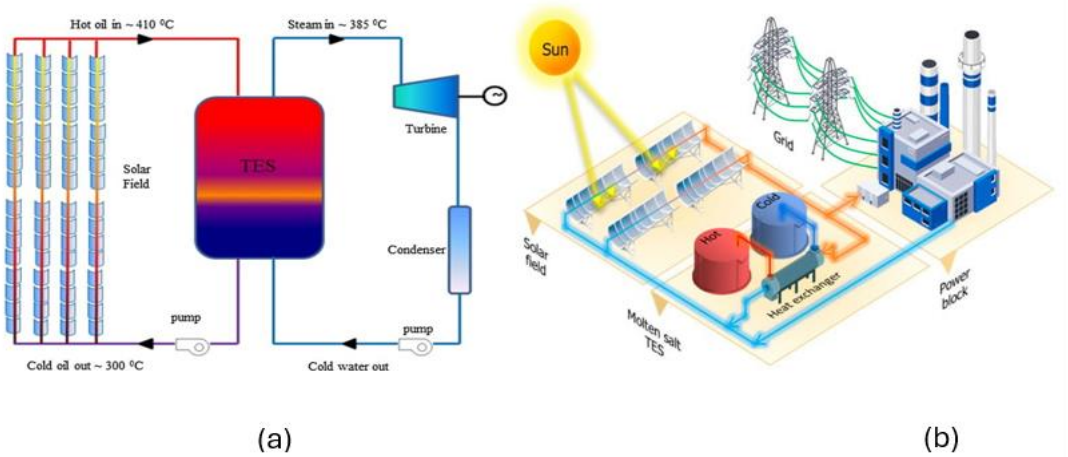

Figure 7-1: Molten salt thermal energy storage: (a) Thermocline system [4] (b) Two tank storage system [5].

Table 7-1: Comparison between two tank and thermocline system.

Aspect	Two-Tank System	Thermocline System
Configuration	Consists of separate hot and cold storage tanks. Molten salt serves as both heat transfer fluid and storage fluid.	Utilizes a single tank with a thermocline region where the temperature gradient separates hot and cold salt.
Cost	Higher investment cost due to the need for two separate tanks.	Lower investment cost compared to two-tank systems.
Mechanism	Heat transfer fluid and storage fluid are the same (molten salt).	Heat transfer fluid and storage fluid are separate.
Efficiency	Efficient heat transfer but higher thermal losses due to the two-tank design.	Lower thermal losses due to the thermocline design.
Economic Feasibility	Commercialized solar thermal power plants often use two-tank systems.	Thermocline systems with low-cost filler material offer better economic feasibility.
Commercial Considerations	a) Higher initial capital expenditure b) Higher Maintenance costs for two tanks	a) Lower initial capital expenditure b) Reduced maintenance costs

7.1.1. Components

The system utilizes molten salt, a commonly used blend comprising 40% KNO_3 and 60% $NaNO_3$ by weight. Its operation is based on the rise in temperature within the salt caused by energy transfer through solar energy. Molten salts used for Thermal Energy Storage (TES) applications remain solid at room temperature but become liquid at higher operating temperatures. Their high-temperature characteristics, such as volumetric storage density, viscosity, and transparency, resemble those of water at room temperature. Molten salts offer several advantages including cost-effectiveness, non-toxicity, non-flammability, high thermal stability, and low vapor pressure. Their low vapor pressure enables storage designs without pressurized tanks. Molten salts can serve dual purposes as both heat storage medium and heat transfer fluid (HTF). They have a long history of industrial applications in heat treatment, electrochemical treatment, and heat transfer [6].

It is also crucial to consider the temperature thresholds for molten salts. The upper limit is determined by factors like thermal stability, corrosion rates, and other thermo-physical limitations. Salts are typically categorized based on their anions, which largely dictate their chemical properties (e.g., nitrates, nitrites, chlorides, carbonates). The lower temperature limit is defined by the melting temperature, which can vary considerably [6].

7.1.2. Working Principle

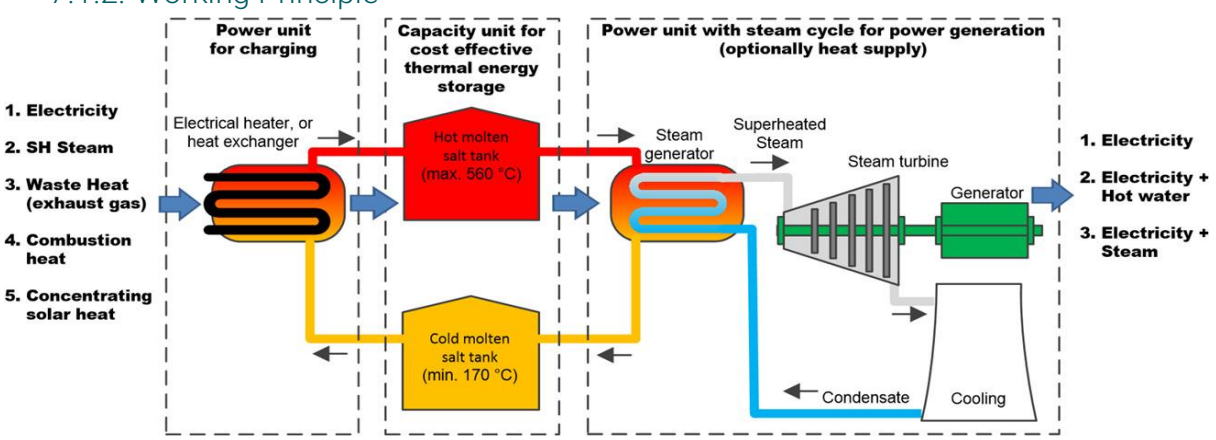

Figure 7-2: Illustration of a two tank molten salt thermal storage system [6].

Modern molten salt thermal energy storage (TES) systems utilize dual-tank setups. This configuration consists of a "cold" tank operating at around 170°C-290°C and a hot tank reaching a temperature range of approximately 395°C to 565°C, depending on the specific technology employed [7].

The main advantage of using molten salt thermal storage lies in their storage efficiency, with potential annual efficiencies reaching up to 99%, as demonstrated in Concentrated Solar Power (CSP) plants like Andasol and Solar Two [6]. Losses in this system primarily stem from heat dissipation through tank walls and foundations, as well as from heat exchange occurring between different media, which can be mitigated through effective insulation. Another advantage of this system lies in its reversibility. The same molten salt mixture can be charged and discharged repeatedly without significant degradation. The dissolution and precipitation reactions are reversible, allowing efficient energy storage and retrieval.

7.2. Input/Output

Here, the input for the molten salt thermal storage system is electricity that heats the molten salt through resistive heating and the output is heat that can be converted to electrical energy by a steam cycle. Other energy sources can also be used to heat the salt, e.g., solar energy captured by solar collectors.

7.3. Energy efficiency and losses

Energy losses in molten salt thermal storage occur due to thermal conduction, convection, and radiation. Heat is lost through the storage tank's walls, pipes, and fittings, especially if the insulation is inadequate. There are also losses during the transfer of thermal energy between the molten salt and the heat exchanger. The efficiency of molten salt storage systems depends on the quality of insulation, the temperature difference between the storage medium and the environment, and the overall system design [7].

Losses can occur due to the following reasons in the molten salt thermal storage system:

- High operating temperatures and the corrosive nature of molten salts can lead to material degradation in storage tanks and piping systems. Corrosion-related losses can impact the overall efficiency and reliability of the system.
- Losses primarily result from heat dissipation through tank walls and foundations. Effective insulation is crucial to mitigate these losses [5]. The transfer of heat between different mediums, for instance, between molten salt and tank materials, may also result in energy losses.
- The distribution of temperature within the tank affects losses, the heat losses decrease as the temperature of the molten salt drops [8]. Proper design features can help minimize temperature stratification and improve overall system performance.

7.4. Regulation ability and other system services

The primary purpose of molten salt thermal storage systems is to store energy for regulatory capabilities. This technology is designed to be flexible, allowing the system to store excess energy and deliver it when needed. With a quick start time of 15 to 30 minutes, these systems can effectively respond to fluctuations in electricity demand. Once operational, they maintain a minimum runtime of 30 minutes to ensure stable energy delivery during peak periods. A minimum downtime of 30 minutes facilitates efficient cycling between charging and discharging modes [7].

These systems can support a minimum stable load of 10% of their rated capacity, enabling adaptable output to align with grid requirements. Additionally, a ramp rate of 10% per minute allows for swift adjustments in output as necessary. [7] A hot system can deliver up to 100% ramping per minute.

7.5. Typical characteristics and capacities

The first CSP plant with a molten salt tank TES system was the Solar Electric Generating Station I, built in 1984 in the USA and decommissioned in 1999. It had a nominal capacity of 13.8 MW and 3 hours of storage. This plant was followed by many others, such as Andasol 1, which was commissioned in 2008 in Spain. This was the first to use this technology on a large scale, with a storage capacity of 375 MWh, almost 10 times larger than the Solar Electric Generating Station I. By the end of 2021, the capacity of approximately 27,500 MWh of TES from molten salt tanks installed worldwide, and it is expected to continue to increase [6].

Large-scale molten salt storage is a commercially viable technology used in concentrating solar power (CSP) applications, with a global installed capacity of approximately 27 GWh [5] [9], and an average storage

duration of 7 hours [9]. Molten salt thermal energy storage has been demonstrated on a large scale commercially, with storage systems reaching up to about 4 GWh_{th} [6]. Additionally, separate power components, such as heat exchangers, and capacity components, such as tanks, ensure consistent temperature and power levels during both charging and discharging processes.

Table 7-2: Characteristics of selected large-scale molten salt storage systems.

Plant Name	Storage Type	Capacity (MWh_{th})	Storage Duration (hours)	Maximum Electrical Power Output (MW_{el})	Operating Temperatures (°C)
Andasol	Indirect	1000	8	50	N/A
Solar Two	Direct	107	3	11	290°C to 565°C
Gemasolar	Direct	N/A	15	20	292°C to 565°C
Crescent Dunes Solar Energy project	Direct	1100	10	110	280°C to 600°C

The Andasol power plant serves as a prominent example of indirect storage systems. On the other hand, the Solar Two central receiver power plant, operational from 1996 to 1999, demonstrated the first direct storage concept utilizing molten salt as both heat transfer fluid (HTF) and heat storage medium. This facility, based on the SolarOne project, employed a two-tank storage system with a total volume of about 1700 m^3, containing 1400 tons of Solar Salt. Operating temperatures ranged from 290°C to 565°C, facilitating a thermal capacity of 107 MWh_{th}, sufficient to operate the turbine for 3 hours. [2]

The Crescent Dunes Solar Energy Project is a solar thermal power project located near Tonopah, about 190 miles (310 km) northwest of Las Vegas [2], [5], [6]. The project is the first commercial concentrated solar power (CSP) plant with a central receiver tower and advanced molten salt energy storage technology at full scale (110 MW), following the experimental Solar Two and Gemasolar in Spain. As of 2023, it is operated by its new owner; ACS, and in a new contract with NV Energy, the project is now primarily providing electricity during nighttime hours.

Commercial ventures such as the Gemasolar plant in Andalusia, Spain, further demonstrate the capabilities of molten salt storage. Numerous larger tower plants with direct storage capabilities have since been commissioned or are under construction worldwide, including projects in the United States, Morocco, the United Arab Emirates, Chile, and China [6].

Molten salt thermal storage allow other energy sources, such as wind and solar, to become more feasible by smoothing out the fluctuations in demand and weather [10].

Thermal Storage System Capacities:

- Smaller-scale molten salt systems, often utilized for research or pilot projects, typically possess energy capacities of several megawatt-hours (MWh).
- In contrast, a standard concentrated solar power (CSP) plant equipped with molten salt storage can achieve capacities of 100 MWh or more, enabling electricity generation during cloudy periods or at night.

7.6. Typical storage period

Traditional molten salt storage in concentrating solar power (CSP) plants typically provides 4-15 hours of storage, but can theoretically retain energy for up to two weeks, making it suitable not only for daily peak shifting but also for bridging extended periods of low renewable generation. [11] [12]

7.7. Space requirement

Due to the high temperatures used in high temperature molten salt thermal energy storage, the energy densities are high, leading to low space requirements for the energy storage part. In addition, since thermal energy storage tanks can be built high instead of wide, compact designs are possible especially for very large energy storage capacities.

7.8. Advantages/disadvantages

Table 7-3: Advantages of molten salt thermal energy storage.

Advantage	Description
High Energy Density [13]	Molten salt systems store large amounts of thermal energy efficiently, the range can be from 980 MJ/m³ to 1230 MJ/m³
Long Thermal Stability [14]	Stable at high temperatures, and withstands repeated heating and cooling cycles. It can be stored for up to 2 weeks with proper insulation.
Non-Toxic and Non-Flammable	Safe for operation and handling. Molten salts can have thermal stability up to 800 °C. However, common nitrate-based salts used in CSP typically begin to decompose above ~600-700 °C, depending on the exact mixture and atmosphere.
Low Vapor Pressure	Allows storage without pressurized tanks.

Table 7-4: Disadvantages of molten salt energy storage.

Limitation	Description
High Cost [15]	Implementation is expensive due to specialized materials and infrastructure.
Corrosion and Compatibility	Molten salts can corrode materials hence compatibility with tank materials is crucial.
Limited Efficiency [16]	Some energy loss during the charging and discharging processes, since mechanical processes are also involved the overall efficiency of the system is around 65-70%
Design Challenges	Structural integrity, thermal expansions, and safety considerations are critical for success.

7.9. Environmental impact

The operation of molten salt thermal storage has no direct emissions and can increase the utilization of renewable energy by storing solar power. However, there is a carbon footprint from the construction of the plant and from producing the salt. Nevertheless, the salt is in a closed system and can be reused for decades. Using salt as the storage medium has the benefit that in the event of a leak, the salt will be exposed to lower temperatures and solidify, making it easy to clean. Additionally, the salt is non-toxic.

7.10. Research and development perspectives

Recent advances in concentrated solar power (CSP) research focus on using low melting point molten salts to reduce capital investment and operational costs. These salts, with melting points below typical CSP system operating temperatures, act as intermediaries to heat a heat transfer fluid (HTF), which then heats the working fluid for power generation. The benefits of using these salts include lower operating temperatures, which result in less stress on materials, longer equipment lifetimes, and potentially higher energy conversion efficiency. Nanoparticles' impact on molten salts for thermal energy storage (TES) in CSP is also a critical area of study, as understanding their behaviour can enhance energy storage efficiency [17]. Ensuring the salt mixture remains liquid over a wide temperature range is crucial for consistent energy storage and release, while salts with high heat capacity can store more energy per unit mass, directly improving system performance. Researchers aim to fine-tune the thermal conductivity and specific heat of these mixtures to optimize energy storage and retrieval. Ongoing research is developing novel low melting point mixtures with stable liquid temperature ranges, high heat capacity, and suitable thermal properties for efficient energy storage, with prospects of achieving higher energy density and lower power generation costs

7.11. Examples of market-standard technology

The Andasol molten salt thermal storage plant in Andalusia, Spain, exemplifies efficient performance and cost-effectiveness in solar power generation. The plant's molten salt thermal storage system, using a mixture of 60% sodium nitrate and 40% potassium nitrate, is crucial for its operation. Heated to around 390°C, the molten salt is stored in large tanks, each capable of holding up to 30,000 tons. This system allows the plant to store excess thermal energy and generate electricity for up to 7.5 hours after sunset or during cloudy conditions, nearly doubling its operational hours. The Andasol project, with a total investment of approximately €900 million ($1.2 billion), includes three units with a combined capacity of 150 MW. The cost of thermal energy storage is about $50 per kWh of capacity, constituting roughly 13% of the initial cost. This investment significantly enhances the plant's efficiency and reliability, making it a consistent and sustainable source of renewable energy [18].

Another example of an existing project is the Gemasolar plant as presented below.

Gemasolar Plant, Seville, Spain

The Gemasolar plant is located in Fuentes de Andalucía, Seville, Spain. Gemasolar is a concentrated solar power (CSP) facility that utilizes a central tower receiver system. This plant is notable for being the first commercial-scale CSP plant to incorporate molten salt thermal storage, allowing for extended electricity generation even without direct sunlight [19].



Figure 7-3: Central tower receiver surrounded by heliostat mirror arrangement [20].

The Gemasolar power plant with an estimated cost of $360 million USD is a ground-breaking example of concentrated solar power (CSP) technology, representing the first commercial-scale application of central tower receiver and molten salt heat storage technology. Covering nearly 200 hectares, this facility is equipped with 2,650 heliostats. These large mirrors have a reflective area totalling 304,750 m². They are arranged in concentric rings around a 140-meter-tall central tower. The heliostats, each spanning 115 m² track the sun's movement throughout the day. Sunlight is focused at a concentration ratio of 1000:1 onto a solar receiver located at the top of the tower, where the intense solar energy is absorbed by molten salt, heating it to approximately 565°C (1,049°F). [21] [23]

The heated molten salt is then stored in insulated tanks, with one cold storage tank maintaining the salt at 290°C and a hot storage tank holding it at 565°C. This thermal energy is later used to produce steam, which drives a two-cylinder reheat steam turbine connected to a generator, producing 19.9 MWe of electricity. The plant's wet-cooling system condenses the steam back into liquid form. [19] [21]

One of the key innovations of Gemasolar is its thermal storage system, which allows the plant to store excess heat during periods of sunlight. This stored energy can power the plant for up to 15 hours in the absence of direct sunlight, such as during cloudy conditions or overnight, effectively enabling 24x7 power generation. This capability significantly enhances the reliability of solar energy, making it a more viable alternative to traditional fossil fuels. The plant also integrates a 15% fossil fuel backup system, utilizing a natural gas heater to ensure uninterrupted power supply if needed. [22]

Table 7-5: Technical specifications of Gemasolar plant [23].

Parameter	Details
Project Cost	3000 cr INR
Plant Capacity	19.9 MWe (gross)
Heliostats	2,650 units
Total Reflective Area	304,750 m^2
Heliostat Size	115 m^2 per heliostat
Concentration Ratio	1000:1
Central Tower Height	140 meters
Solar Receiver	120 MW capacity
Molten Salt Temperature (Cold Tank)	290°C
Molten Salt Temperature (Hot Tank)	565°C
Hot Storage Tank Size	23 meters in diameter, 14 meters in height
Thermal Storage Duration	Up to 15 hours
Cooling System	Wet cooling
Backup System	15% fossil fuel backup (natural gas heater)

7.12. Projection of performance and cost

Thermal energy storage with an attached steam cycle is a system of components that are technologically mature [24], except for the molten salt thermal energy storage component. The construction and operation of thermal energy storage as an integrated system is however still new. This leads to uncertainty in both current and future costs. Since molten salt thermal energy storages as a system are novel, they are expected to exhibit learning curves for their overall costs [25]. Together this implies that the overall cost of thermal

energy storage systems will likely be significantly lower in coming years as the accumulated production increases – this will be more pronounced for the energy storage component. For the energy storage component, technological breakthroughs allowing for better handling of e.g. corrosion risks at high temperatures are also expected to have a major impact on costs, since less and cheaper materials can be used as corrosion mechanism and mitigation develop. Increasing to higher temperatures in the storage and in applications also suggests lower maturity and corresponding higher uncertainty and current costs. In a similar manner, for high temperature applications, these are expected to have a more pronounced learning effect for the near-term costs compared to lower temperature versions [25]. The reported costs in the datasheet are only for the storage component, i.e. without a steam cycle that can convert the heat into electricity. Based on [26], [27], and [28], the cost projection assumes a fixed annual cost decline of 3% until 2030, and a fixed annual cost decline of 4% between 2030 and 2040. The 2050 value is chosen the same as given in [26]. The current values are taken from [27] for high temperature molten salt.

7.13. Uncertainty

For prediction of performance, the main uncertainty pertains to energy losses to the environment and lifetime. In general, larger installations in big tanks reduce losses, while increasing temperatures will tend to increase them. However, these kinds of losses are largely controlled by adding sufficient insulation to the tanks and pipes. Depending on the expected storage period, this becomes an optimization parameter for a particular installation and is thus rather site specific. Losses from pumping of heat transfer fluids are well known, however for some of the more unusual salts, e.g. NaOH, systematic peer-reviewed results to confirm simulation studies are still needed and thus the uncertainty here is relatively greater compared to the case of air or thermal oils used in rock-based systems.

Uncertainty regarding costs is mainly on the thermal energy storages themselves, where initial cost estimates still need to be verified when going to large scale commercial deployment, and thus the cost estimates for these should be considered as subject to significant uncertainty. In contrast, most of the supporting [26] systems, as well as input and output conversion, are very mature where costs are known to a high degree of certainty.

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7.15. Datasheet

The data provided in the datasheet refers specifically to the thermal energy storage component of a molten salt system that utilizes resistive heating for energy input. This means that only the costs associated with thermal energy storage itself—excluding the conversion back to electricity—are considered. The cost of the steam cycle, which would be required to convert the stored heat into electrical energy, is not included in the presented figures. However, the round-trip efficiency, expressed as Power-to-Power (PtP), does take the full system into account, including both the resistive heating input and the conversion of thermal energy back into electricity via a steam cycle.

Technology	**High temperature molten salt thermal storage**										
	2024	**2030**	**2040**	**2050**	**2070**	**Uncertainty (2024)**		**Uncertainty (2070)**		**Note**	**Ref**
						Lower	**Upper**	**Lower**	**Upper**		
Energy/technical data											
Form of energy stored	Heat										
Application	Industrial steam										
Output capacity for one unit (MW)	12	50	50	50	50	10	100	10	100	B, Q	1, 4
Input capacity for one unit (MW)	30	120	120	120	120	10	120	10	240	B,R	1, 4
Storage capacity (MWh)	200	800	800	800	800	100	800	100	1600	B	1, 4
Depth of Discharge (%)											
Round trip efficiency PtP (%)	30	30	30	30	30	10	40	10	40	C	1
System efficiency PtH (%)	92	92	92	92	92	92	92	92	92	D	1
- Charge efficiency (%)	98	98	98	98	98	98	98	98	98	E	1
- Discharge efficiency (%)	95	95	95	95	95	95	95	95	95		1
Energy losses during storage (%/day)	0.5	0.3	0.3	0.3	0.3	0.3	1	0.3	1	S	4
Auxiliary electricity consumption (% of input)	1	1	1	1	1	1	1	1	1	F	1
Forced outage (%)	5	4	3	2	2	3	15	1	5	G	1
Planned outage (weeks per year)	3	3	3	3	3	3	3	3	3		1
Technical lifetime (years)	25	25	25	25	25	20	30	20	30	H	1, 3
Construction time (years)	1	1	1	1	1	0.5	1.5	0.5	1.5		1
Regulation ability											
Primary load support (% per 30 seconds)	30	30	30	30	30	30	30	30	30	I, J	1
Secondary load support (% per minute)	100	100	100	100	100	100	100	100	100	I, J	1
Minimum load (% of full load)	10					10	10			O	4
Financial data (in 2023₹)											
Specific investment (cr. ₹/MWh Capacity)	1.14	0.95	0.63	0.40	0.40	0.74	1.55	0.33	0.54	K, G	1, 2, 3
- here of equipment (%)	40	40	40	40	40	40	40	40	40	L, G	1
- here of installation (%)	60	60	60	60	60	60	60	60	60	M, G	1
Fixed O&M (cr. ₹/MWh/year)	0.023	0.019	0.013	0.008	0.008	0.015	0.031	0.0065	0.011	G, N	1
Variable O&M per output (₹/MWh)										P	
Technology specific data											
Tank volume of example (m3)	500	3000	3000	3000	3000	200	3000	200	6000		1
Storage medium	Molten salt										
Max. storage temperature, hot (^{o}C)	560	560	560	560	560	560	560	560	560		5
Storage temperature, discharged (^{o}C)	290	290	290	290	290	290	290	290	290		5

Notes

A A turbine generator can be included to produce electricity and widen ancillary services capabilties, see technology catalogue on power and heat producing technologies for data on CHPs

B Storage, input and output capacity can be dimensioned to fit to a particular installation, these are typical design values

C In a power-to-power scenario, the excess energy can be used for process heat or district heating leading to system effiencies above 90%

D Assumes 0,75% loss from storage period (24-48 hours)
E Charging by resistive heating elements
F Mainly pumping power and loss of heat to environment
G Large uncertainty in indicated value
H Large uncertainty in indicated value. Pumps and other components will need replacement periodically within this time frame. Estimates based on comparable installations in other fields
I Requires hot system
J Upregulation only possible when charging
K Without steam cycle, i.e. only thermal storage itself; Local grid connection and grid reinforcements not included. Based on danish and international data.
L Equipment is all major pieces of equipment, e.g. pumps, heaters etc.
M Installation includes all costs that are not major pieces of equipment including EPC costs
N Assumed to be 2% of specific investment costs
O Not sufficient data available to perform a prediciton
P Likely to have non-zero variable O&M but not sufficient data available to give an estimate
Q Output will typically be delivered as high-temperature thermal heat to industrial processes or converted to electricity via a steam turbine, often using a Rankine cycle.
R Input will typically be supplied via electric heaters, but fuel-fired heaters can be installed either in parallel with the electric heaters or as the sole heat source.
S Literature indicates that daily storage losses for well-insulated molten salt tanks typically range from about 0.3% to 1% per day of stored energy.
T For Molten Salt storage the fixed annual O&M is related to the capacity of the energy storage

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8. Liquid Air Energy Storage

8.1. Brief technology description

Liquid Air Energy Storage (LAES) technology is the process of compressing and cooling air into a cryogenic liquid as a means of energy storage. When needed, the liquid air is converted back into a gas, which drives a turbine-generator to produce electricity. It comprises three independent parts: a charging system, the storage, and a power recovery system.

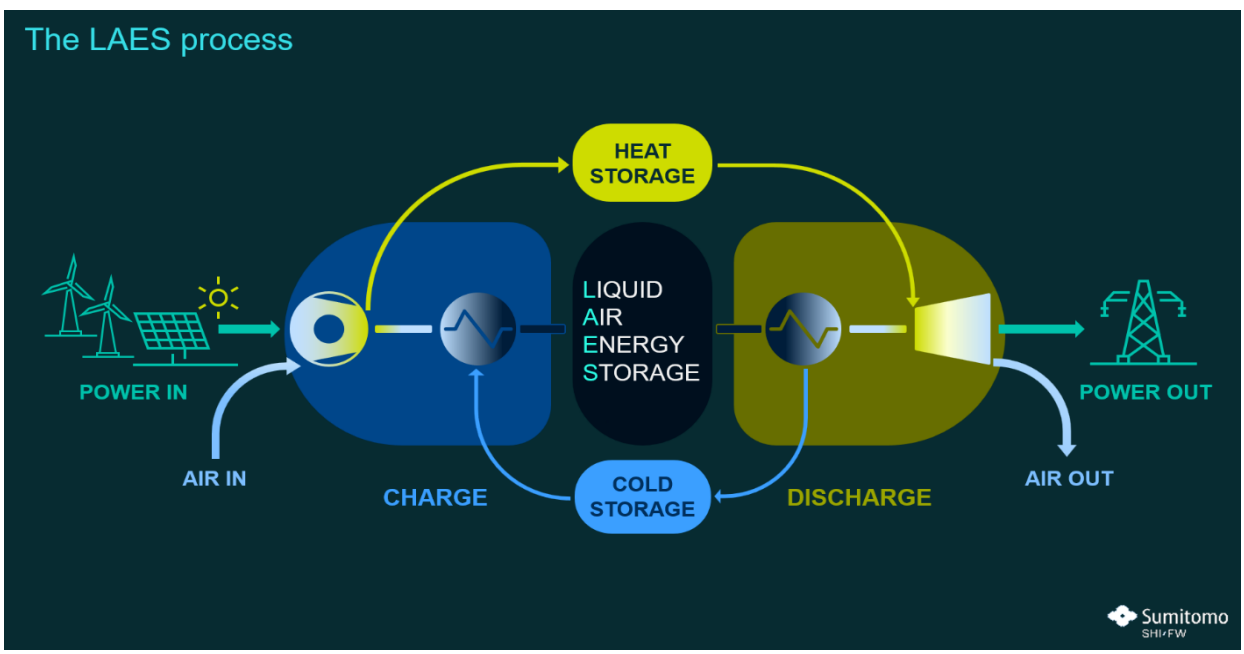

Figure 8-1: Simplified Flow Diagram

Charging system

The charging system of the LAES process is a liquefier. A modified Claude cycle liquefaction process converts gaseous ambient air into liquid air. The liquefier uses compression trains powered by synchronous motor, to compress air to the required pressure. Compression heat is removed by heat recovery systems, and the pressurized process gas is cooled to cryogenic temperatures in a main heat exchanger after being expanded. This converts the fluid to both a gas and liquid. The liquid product is removed from the liquefaction system in a separator and stored in cryogenic storage vessels. Refrigeration is provided to the process gas in the Main Heat Exchanger by the cryogenic gas returning from the separator. The rest of the refrigeration is provided by the High-Grade Cold Store, a system designed to recycle cryogenic cold from discharge to charge.

Energy storage

Liquid air storage vessels receive the liquid cryogen produced by the liquefaction system and provide the working fluid for the power recovery system. This storage system is complemented by heat storages, which allow the transfer of heat from charging compression losses to superheat the air during discharge. The High-Grade Cold Store (HGCS) system is used as a heat sink, providing low grade heat for the power recovery

process while refrigerating itself down to cryogenic temperatures. In its refrigerated state, it is used on the liquefaction process to enhance charging efficiency. In doing so, it provides approximately 50% of the liquefier's refrigeration requirements. The HGCS contains a sensible thermal storage device, so when it charges or discharges thermal energy, the storage medium's temperature will also change.

Power recovery

Discharge is handled by a power recovery unit. The system is based on an open Rankine cycle. Cryogenic liquid air is pumped to high pressure and converted to a gas by introducing heat to the working fluid. The fluid is then expanded across a multi-stage turbine with reheats, where power is recovered and converted back into electricity via a generator. The first heating phase of the working fluid involves evaporating it in a heat exchanger. The fluid on the other side of the heat exchanger cools down to a temperature that is close to the stored liquid air, and it runs through the HGCS vessels, refrigerating them for use in the next charging cycle. The working fluid is then superheated and subsequently re-heated with thermal energy from the heat storages as it is expanded in the turbine.



Figure 8-2: LAES plant in Hiroshima, Japan

LAES utilizes synchronous machines directly connected to the grid for both charge and discharge. Therefore, it is capable of black starting the grid. It contributes to overall grid inertia, nodal SCR, and has a wide range of dynamic reactive power support, both leading and lagging. A LAES system can be designed to provide such services continually by decoupling the generator from the power recovery unit with a self-synchronizing clutch. This allows for independent operation of the generator as a grid-supporting synchronous condenser.

LAES provides additional value by e.g. dynamic reactive power, inertia, system strength and congestion management to the power system. These help to eliminate costs towards grid stability services. For example, in Carrington, UK and Hunterston, Scotland LAES projects, these services are value additions apart from bulk shifting of energy.

8.2. Input/output

In a LAES system, the inputs are electrical energy, which is used to run the compressors, and ambient air which is liquefied during the charging process.

The system outputs are electricity, produced by the synchronous generator, and dry air, as the stored liquid air is evaporated, expanded and exhausted back to the atmosphere.

The process can also have heat as a secondary input/output. LAES can make use of or release low-grade heat, and it can provide heating to cryogenic processes as it uses the cold source to improve charging liquefaction, depending on integration with external sources.

8.3. Energy efficiency and losses

Liquid Air Energy Storage (LAES) typically achieves a round-trip efficiency (RTE) of about 50–60% [1, 2, 3, 4, 5], reflecting combined losses across charging, storage, and discharge processes. Charging efficiency is limited primarily by the electrical demand of cooling, cleaning, and liquefying air, and thermal and mechanical losses during compression and refrigeration are mitigated by the utilization of thermal storage, cold storage and integration with external processes [6]. Discharge efficiency is very high, but it is influenced by losses in reheating, expansion, and turbine operation. LAES cryogenic vessels and heat storages exhibit very low self-discharge due to insulation. Unavoidable heat ingress does cause a small self-discharge which contributes to overall efficiency losses, but this phenomenon is accounted for in RTE calculations.

8.4. Regulation ability and other system services

A LAES facility provides a similar response to a gas peaking plant. It can be designed to reach a startup time to steady state (nameplate capacity) under 20 minutes for both charge and discharge, assuming warm startup. During discharge startup, the output power can ramp up at a rate of 10% to 15% of the rated capacity/minute after synchronization [1, 3].

The system can quickly respond to changes in the grid demand (up or down) to provide grid-following services, and switchover from charge to discharge and vice versa. Stored liquid air can be pumped, evaporated and expanded in short notice, therefore LAES can respond rapidly to demand changes. During steady state operation the plant output set point can be readjusted with a response time of about 2 minutes. Charge partial load operation is heavily dependent on plant size. Single train charge can continuously operate between 75% to 100% load. Larger facilities employ multiple compressor trains and have higher operational flexibility. Discharge can continuously operate between 25% and 100%. Part-load operation influences overall plant efficiency, but it is not substantial for part-load operation above 80%.

8.5. Typical characteristics and capacities

A commercial-scale LAES unit starts from 50 MW of discharge and 8 hours of energy storage, reaching up to 200 MW discharge with a single turbine. The storage can be increased substantially, to 24 hours or more, given the relatively small footprint. Liquefied air has significantly reduced volume when compared to its

gaseous form, about 700 L of ambient air becomes 1 L of liquid air, resulting in high volumetric energy density.

The technology is modular and scalable. Input and output capacities can be dimensioned independently according to application, while storage capacity (MWh) can be expanded, including over the lifetime of the project, by adding tanks. LAES state-of-charge is informed as the actual useful parcel of liquified air that is available for discharge. A small fraction of liquid air is always kept at the bottom of the cryogenic tanks, but this already factored out of the available storage.

8.6. Typical storage period

Ideally, a LAES system will cycle several times a week. Partial charge or discharge are not an issue. Self-discharge is low due to tank insulation, and the charge can be kept over several days, up to a few weeks. However, the system needs to charge, even if partially, after being idle for more than a week. This limitation is related to the nature of cryogenic liquid air, as it is a mixture of oxygen and nitrogen, and nitrogen boils at a lower temperature than oxygen, which leads to oxygen enrichment. The stored cryogen will be discharged or disposed of before it is inactive for such a time in which such phenomenon reaches a reference threshold.

8.7. Space requirement

LAES system has no geographic limitations, and the footprint does not increase linearly with the MWh capacity of the system. The charging, discharging, and storage components of the plant can each be scaled independently, and the space requirements do not scale proportionally with the charge capacity, storage duration, or discharge capacity.

A benefit of the LAES technology is the flexibility to deploy the system precisely where it is needed on the grid, enabling the provision of targeted and meaningful grid services such as synchronous inertia, reactive power support, improved SCR or grid congestion management at critical locations [3].

For reference, a 100 MW charge, 100 MW discharge, 1000 MWh storage system occupies about 4 hectares (10 acres), and doubling the storage to 2000 MWh increases the area requirement by just ¼, to 5 hectares (12 acres).

8.8. Advantages/disadvantages

Advantages

- LAES is a synchronous-based technology, which means it provides grid ancillary services such as inertia, SCR and dynamic reactive power compensation by default.
- Small footprint.
- Storage is easily scalable and expandable over project life.
- Technology is based on well established equipment supply chain from industrial gases, LNG and conventional generation, readily available globally. This reduces risks related to material and equipment sourcing and provides opportunities for production localization.
- No need for any special geological formations, ponds or water access means that the plant has no significant geographical limitations for deployment. This synergises with provision of grid ancillary services because it allows the deployment of a LAES plant wherever will benefit grid operation the most.
- Short start-up and shut-down time, comparable to open cycle gas turbines.
- Long asset lifetime.

- Minimal performance degradation due to wear of rotating equipment, which is recovered during scheduled plant maintenance over the project life.
- The plant is comprised of equipment largely manufactured from recyclable materials and no hazardous waste. Once the plant reaches end-of-life, all materials have well established procedures for recycling or disposal.

Disadvantages

- Lower round trip efficiency and higher CAPEX.
- Liquid Air Energy Storage enables storing of energy in GWh scale in a small footprint without requirement for extensive earth works or prevailing geological formations. Furthermore, a turbine and a synchronous generator are required to harness the potential of liquid air, which also provides additional value to the grid though local system strength services. The trade-off for achieving the locational flexibility and the characteristics of synchronous machines is lower round-trip-efficiency and higher cost of LAES.

8.9. Environmental impact

LAES systems have no emissions besides ambient air, and no effluents. It has minimal environmental impact due to small footprint and no need for substantial excavation or land grading. Long life, employment of mostly recyclable materials and no hazardous waste result in excellent cradle-to-grade sustainability profile.

8.10. Research and development perspectives

Some development activities are ongoing on performance at higher temperature as well as material for high temperature thermal storage. Please refer section 13 – Uncertainty. It has been observed that, Institute for Advanced Engineering, Korea has started working on a LAES plant.

8.11. Examples of market-standard technology

Demo projects have been carried out in the past, mostly in the UK, with a pilot in Slough, Greater London (0.35 MW / 2.5 MWh) commissioned 2011 [3] and a larger (5 MW / 15 MWh) demo plant in Pilsworth, Greater Manchester in 2018 [7].

LAES is currently in commercial operation in Hiroshima, Japan (5 MW / 20 MWh) since December 2025 [8], and in the Gobi Desert, China (60 MW / 600 MWh), developed with a 250 MW solar PV park also starting operations on December 2025 [4, 9, 10]. The Hiroshima project was jointly implemented by Sumitomo Heavy Industries and Hiroshima Gas Company. The plant utilizes waste cold from the regasification process at the Hatsukaichi LNG terminal to improve the charging efficiency. Another commercial project is under way in Manchester, UK (50 MW / 300 MWh), planned for full plant commissioning in 2027 [5, 14], with further plans to support the expansion of the British NESO renewable integration with two large projects (each 200 MW / 2500 MWh) in Hunterston, Scotland, and Killingholme, Lincolnshire, UK, to help handle curtailment from offshore wind and support grid stability [5, 11, 12]. In South Korea, collaboration between local and international industry was started on Q1 2026 for deployment of large-scale LAES facilities [13].

Overall, LAES is still an emergent and niche technology.

8.12. Projection of performance and cost

LAES can currently be assessed to be in the pioneering phase with limited application. The estimation of costs needs to be treated carefully as LAES projects are still first-of-a-kind projects that come with a cost premium. If the technology gains relevance and more LAES will be constructed, declining costs can be expected.

Going forward, as LAES becomes more commonplace, we expect thermal integration (heat / cold) with industrial processes to be more common (the Hatsukaichi Hiroshima plant is an early example of thermal integration). This would positively impact the CAPEX and / or RTE of the plant in the future.

8.13. Uncertainty

Future performance improvements may be achievable as related technologies continue to advance. From a process-optimization standpoint, operating the molten-salt heat storage system at higher temperatures would be advantageous. Commercial molten salts used in concentrated solar power plants already operate at temperatures up to approximately 600 °C. However, on the compressor side, commonly used materials as of 2026 restrict the allowable operating temperature to around 460 °C. Growing interest in high-temperature heat pumps from sectors such as iron and steel could accelerate the development of heat-resistant alloys for rotating equipment. Such advancements would enable the use of higher-temperature salts, improving LAES RTE.

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8.15. Datasheet

Disclaimer: These numbers shall be treated with care as LAES is still an emergent and niche technology. Especially first-of-a-kind projects are expected to come with a cost premium.

Technology	Liquid Air Energy Storage										
	2027	2030	2040	2050	2070	Uncertainty (2027)		Uncertainty (2070)		Note	Ref
						Lower	Upper	Lower	Upper		
Energy/technical data											
Form of energy stored											
Application	System										
Output capacity for one unit (MW)	100	100	100	100	100	50	200	50	250	D	1, 4, 5, 9, 10, 11, 12, 14
Input capacity for one unit (MW)	50	50	50	50	50	50	200	50	250	D	1
Storage capacity (MWh)	1200	1200	1200	1200	1200	400	2500	400	3000	D	1
Depth of Discharge (%)	100	100	100	100	100					E	
Round trip efficiency (%AC)	55%	55%	60%	60%	60%	50%	60%	50%	65%	F	1, 2, 3, 4, 5
Round trip efficiency (%DC)	not applicable									E	
- Charge efficiency (%)	65	65	70	70	70	48	82	48	82	G	1, 2
- Discharge efficiency (%)	85	85	85	85	85	77	95	77	95	G	1, 2
Energy losses during storage (%/period)	1.5%/day	1%/day	0.75%/day	0.75%/day	0.75%/day	1%/day	2%/day	0.5%/day	1%/day	H	1
Forced outage (%)										I	1
Planned outage (weeks per year)	4	4	3	3	3						1
Construction time (years)	3 ~ 6	3 ~ 6	3 ~ 6	3 ~ 6	3 ~ 6					J	1
Technical lifetime (years)	40	40	40	40	40						1
Discharge time	8 - 20 hours	8 - 20 hours	8 ~24+ hours	8 ~24+ hours	8 ~24+ hours						1
Regulation ability											
Primary load support (% per 30 seconds)	10%	10%	10%	10%	10%	1%	25%	1%	25%	K	1
Secondary load support (% per minute)	20%	20%	20%	20%	20%	2%	50%	2%	50%	K	1
Minimum load (% of full load)	25%	25%	25%	25%	25%	20%	30%	20%	30%	L	1
Financial data (in 2026₹)											
Capital cost (cr. ₹/MWh)	2	1.90	1.33	1.33	1.33	-30%	+30%	-50%	+50%	M	1
- energy component (cr. ₹/MWh)	0.7	0.67	0.47	0.47	0.47	-30%	+30%	-50%	+50%	M	1
- capacity component (cr. ₹/MW)	14.4	13.68	9.58	9.58	9.58	-30%	+30%	-50%	+50%	M	1
- other project costs (cr. ₹/MWh)	0.10	0.10	0.07	0.07	0.07	-30%	+30%	-50%	+50%	M	1
Fixed O&M (cr. ₹/MW/year)	0.609	0.609	0.609	0.609	0.609	-30%	+30%	-50%	+50%	N	1
Variable O&M per output (INR/MWh)	300	300	300	300	300	-30%	+30%	-50%	+50%	N	1
Technology specific data											
Specific investment (cr R/MW)	24.00	22.80	15.96	15.96	15.96	-30%	+30%	-50%	+50%		1

Notes

A The CAPEX and OPEX are based on present currency

B The CAPEX provided includes all storage tanks

C Development costs, including land lease, grid connection, insurance, taxes / duties etc. are excluded

D LAES can be configurable with separate charge / discharge & storage capacity as per the application requirement. At present, design is available for 50 - 200 MW charge / discharge capacity with 8 - 20 hours storage; with target to increase storage to 24+ hours in future. The capacities provided in column H-I are the available capacity range (50 - 200 MW) at present.

E Not a electro - chemical storage

F Higher RTE up to 10% points possible through thermal integration

G Various different configurations and integration possible.

H Depends on configuration, ambience and required level of readiness

I Forced outage cannot be stated yet due to lacking operational experience

J Depends on configuration, scale and country

K Varies with unit size, number of turbine stages, control principle (IGV, pump), pipe length, buffer tank usage

L Typical for steam turbine, LAES uses the same type

M CAPEX varies depending upon configuration. Energy component is based on the CAPEX for the storage component, while capacity component is based on the CAPEX for the charging and discharging equipment. Other project costs indicate BoP. The split is approx., as several equipment are used in charge / discharge and storage. The CAPEX indicated is for India.

N The O&M cost is indicative and may vary based on geography / country, application requirements.

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9. Compressed CO_2 Energy Storage (CCES)

9.1. Brief technology description

Compressed carbon dioxide energy storage (CCES) is a mechanical energy storage technology, sharing some characteristics of compressed air energy storage (CAES) and liquid air energy storage (LAES), however using carbon dioxide instead of air as the working fluid.

Carbon dioxide is well suited for energy storage application due to its thermodynamic and physical properties – in particular ease of liquefaction at moderate pressure and ambient temperatures. Carbon dioxide is also an abundant, widely available gas already widely used commercially in numerous industrial applications.

Technically proven, commercially available CCES utilizes CO2 in a closed loop thermodynamic process, manipulating CO2 between a low-pressure gas phase and pressurised liquid phase. Pressurized liquid CO2 is stored above ground in standard pressure vessels near ambient conditions. Temperature and pressure conditions within the process are moderate which enables use of low cost, widely available carbon steel grades for construction of the plant and use of standard turbomachinery equipment which is widely used in oil & gas and conventional power applications.

Thermal energy storage is applied within the process to efficiently capture, store and reuse the thermal energy which is produced in the compression stage during charging of the system. The thermal energy storage components of the plant are based on use of widely available inert material, with water also utilized for CO2 evaporation and condensation purposes in a closed loop water system which avoids impact on water resources. In commercial operation RTE greater than 70% has been proven.

Since CCES operates with CO2 in a closed loop, in addition to the storage of pressurized liquid CO2 when charged, it is necessary to have a corresponding gas storage system to store the low-pressure CO2 gas when the plant is discharged. Commercial CCES has adopted proven dome technology as widely used over decades in the biogas industry and other industrial and commercial applications, enabling safe and cost-effective storage of large volumes of CO2 gas.

9.1.1. Operating modes

The CO2 Battery has four main operating points summarized below. The charging and discharging modes are shown diagrammatically in Figure 9-1:

- Ready for charge: stand-by with system discharged;
- In charge: charging phase;
- Charged: stand-by with system charged;
- In discharge: discharge phase.

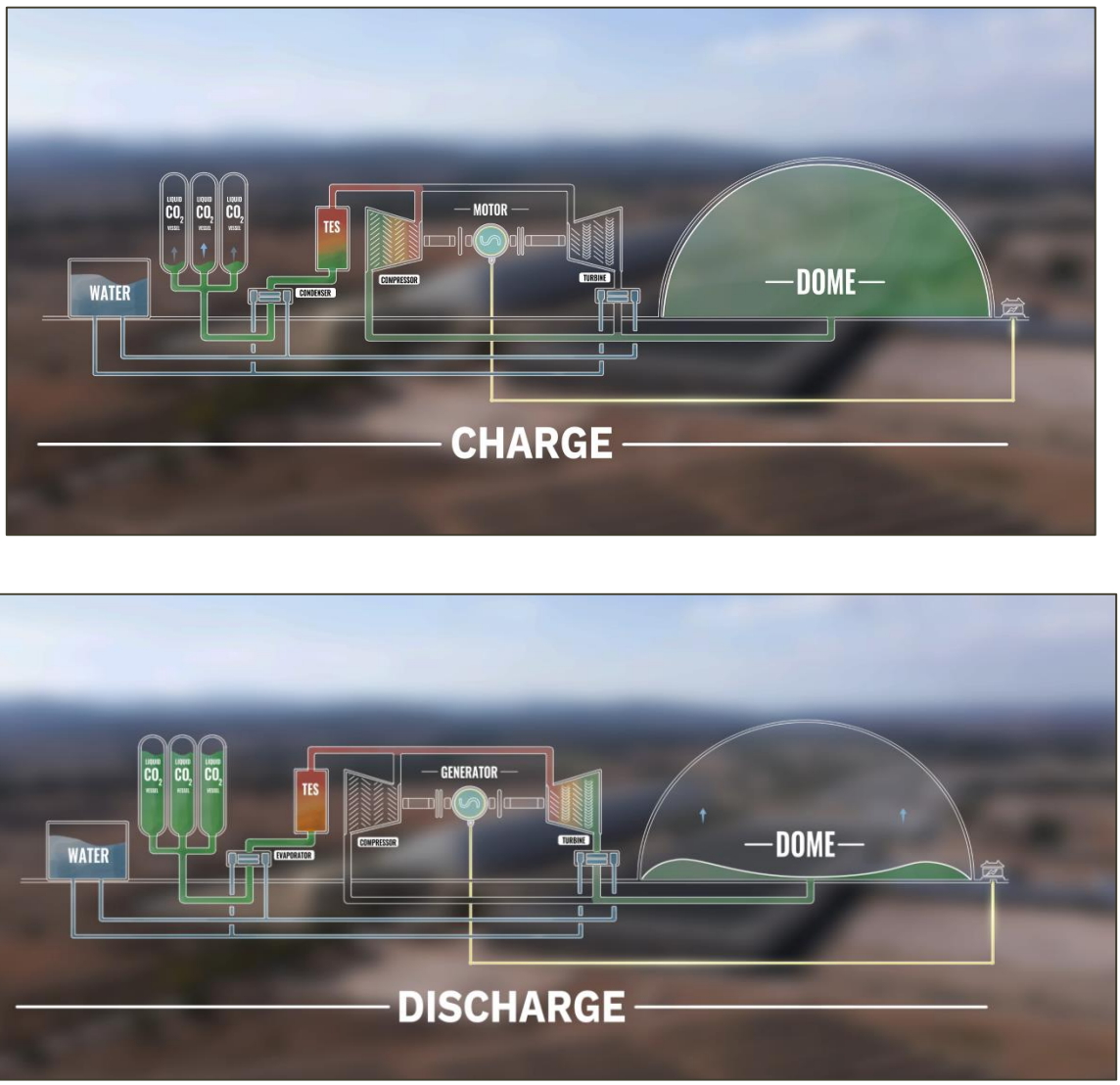

Figure 9-1: CO2 Battery charging and discharging modes - Block Flow Diagram

In the initial phase, the system is in the stand-by operating point with the system discharged. In this condition all the CO2 is stored in the gaseous phase at atmospheric pressure inside the gas holder (dome). The motor and generator, as well as the compressor and turbine are in standby. The liquid CO2 tanks are empty.

In the charging phase, the motor absorbs power from the grid and drives the compressor. The CO2 is taken from the gas holder and compressed. The CO2 increases in both pressure and temperature in the compression stage, and the heat generated is stored in the thermal energy storage (TES). The CO2 gas can then be condensed in the condenser, where the heat of condensation is transferred to the circulating water which is stored in the water basin. The resulting pressurised liquid CO2 is then stored in CO2 tanks. At the end of the charging phase, the system is in the stand-by operating point with the system charged.

In the standby operating point with the system charged, the CO2 is entirely stored in the form of a pressurised liquid and the gas holder is near empty. The motor and generator, as well as the compressor and turbine are in standby mode.

When the system works in the discharge phase, the liquid CO2 is taken from the CO2 liquid storage tanks and evaporated in the evaporator with the low temperature heat stored in the water. The cool gaseous CO2 then passes through the TES and recovers heat stored during the charging phase. The hot, pressurized CO2 then expands inside the turbine which drives the generator, produces electricity which is fed back into the grid. The CO2 at the turbine outlet is finally reintroduced into the dome where it is stored again as a low-pressure gas. At the end of the discharge phase, the system returns to the discharge stand-by operating point.

9.2. Input/output

CO2 Battery technology operates with electricity as the only input - primarily to drive an electrical motor connected to the CO2 compression equipment, and electricity as the only output - produced through the expansion of the pressurized CO2 in a turbine driving a generator.

The process scheme utilized in such CCES Battery technology does not require any separate external heat or cold inputs. Similarly, since the thermal energy produced during the compression stage is stored and utilized within the closed loop process, the process does not produce significant excess thermal energy which could be exported.

Variations of the standard process (where electricity is the only input/output), are technically feasible and commercially available, for example integration with external heat sources (e.g. heat recovery from gas turbine exhaust gas).

9.3. Energy efficiency and losses

CCES targets to reach 75% RTE in the future, while RTE has been demonstrated exceeding 70% in operating plant to date [ref. 2].

Losses are primarily due to (a) the mechanical efficiencies of rotating machines, (b) some thermal losses from the high temperature thermal energy storage (TES) when the plant is charged, (c) some limited heat rejection from the process for auxiliary cooling purpose and (d) electrical losses including relatively low plant auxiliary consumption.

9.4. Regulation ability and other system services

CCES utilizes conventional synchronous electrical generator and motor, typically 11kV for 50Hz market, which provide a full range of grid support services similar to those which can be provided by other mechanical energy storage technologies such as PSP and CAES.

9.5. Typical characteristics and capacities

CO2 Battery has been developed as a standardized, pre-engineered, modular solution with replicability and scaling in mind. The CO2 Battery is available in two main product categories – (1) the standard configuration of 20MW and 8-10 hours of energy storage and (2) the giga-scale solution which adopts larger component sizes for economy of scale, having a power capacity of approximately 125MW and energy storage capacity of 1 GWh per unit.

Larger plant sizes are achieved by implementation of multiple blocks of either the standard or giga-scale CO2 Battery plant. This means that it is straightforward to scale to very large plant sizes comparable to large PSP, however with quickly deployable, site-independent modular plant. For example, a 1000MW / 8GWh CO2 Battery installation is achieved with 8 giga-scale units.

9.6. Typical storage period

CCES is well suited to long duration (8+ hours) energy storage (LDES), and up to 24 hours of energy storage.

9.7. Space requirement

While compressed, liquified CO2 enables high density energy storage, there is an associated requirement to store a large volume of CO2 gas on the low-pressure side of the system with relatively large footprint. Typical footprint for a CO2 Battery energy storage plant should be considered in the range of 4kWh/m2, i.e. generally in similar range as for PSP.

9.8. Advantages/disadvantages

Advantages:

CCES shares advantages of other mechanical energy storage technologies, in particular the high suitability for longer (8h+) energy storage durations, use of well proven technological equipment, long project life-times of 40+ years and use of synchronous electrical generator/motor which provide natural inertia and other grid stability support.

In contrast to PSP and CAES, a CCES plant can be located wherever required, independent of specific geographical features.

CCES is well suited to regions where water resources are limited. Water is used purely in a closed loop for heat exchange purposes within the process and is not lost to evaporation or otherwise consumed.

CCES uses widely available materials and well proven process equipment.

As mentioned above, compared with some other technologies the footprint of CCES is higher, however comparable with typical PSP.

Disadvantages:

The footprint is larger than for Li-ion BESS, it is comparable with PHES.

CCES is still a very new and niche technology with little operational knowledge.

The gas storage dome creates a notable visual impact.

9.9. Environmental impact

CCES represents a low environment impact and minimal environmental risk. As mentioned in other sections, CCES does not consume water and does not represent a significant fire risk.

A typical concern specific to CCES is visual impact of the low-pressure gas storage dome – this impact can be addressed through appropriate site selection, mitigation such as screening with trees and variations on dome design.

CCES is based on use of widely available, non-toxic, low-cost materials (e.g. standard steel grades, CO2) and avoids use of critical minerals required in electrochemical battery technologies.

Water requirements are limited to first fill of the closed loop water system during construction phase, and as such CCES does not consume water during operational phase.

9.10. Research and development perspectives

CCES has been the subject of extensive research in recent years, as outlined in publicly available reviews of the technical literature [ref. 6].

Commercial CCES has quickly emerged based on development of a novel CCES process [ref. 1] and Energy Dome's work on its 2.5MW CO2 based energy storage demonstration plant which commenced operation in 2022 [ref. 2]. The first full commercial CO2 Battery was commissioned with 20MW/200MWh capacity in mid-2025, with several projects now in construction or advanced development stage globally.

Significant research is being carried out on the utilisation of carbon dioxide in its supercritical state [ref. 5].

9.11. Examples of market standard technology

Commercial CCES is now technically mature and proven in operation in Europe (Sardinia, Italy) following successful commissioning of the first full commercial CO2 Battery installation, developed and owned by Energy Dome.

NTPC Limited is implementing a similar project at its Kudgi power station in Karnataka state [ref. 7], under a contract which was signed in January 2025. The project is due to be commissioned in 2026.

There are numerous projects under development. Partial list of known projects is provided in table below.

Size (MW/MWh)	Location	Owner	Status	Reference
20/200	Sardinia, Italy	Energy Dome	Operational	https://spectrum.ieee.org/co2-battery-energy-storage
20/200	Wisconsin, US	Alliant Energy	Execution	https://www.alliantenergy.com/news/news-center/2025/07/071825-columbialongdurationenergystorageapproved
20/200	Arizona, US	Confidential	Advanced Development	
20/160	Kudgi, India	NTPC	Execution	https://www.pib.gov.in/PressReleaseIframePage.aspx?PRID=2097424&reg=3&lang=2
50/400	Rhode, Ireland	Energy Dome	Advanced Development	
160/1600	Vaasa, Finland	EPV	Advanced development	https://www.epv.fi/en/project/energy-storage-based-on-co2-battery-technology/

9.12. Projection of performance and cost

Recent assessment [ref. 4] has placed CCES as a promising LDES technology based on assessment of cost and broader market potential.

Since commercial CCES follows a standardized, modular product design using standard equipment, the costs are well understood and not exposed to pricing volatility of critical minerals. Cost reductions are expected to be achieved by a combination of factors including mass production of standard components for multiple

projects, economy of scale from larger projects, progressive learning effect from multiple installations as well as localization in India.

Performance parameters such as RTE are also expected to show some improvements as a result of optimisation of process and plant operations and other incremental improvements at component level.

9.13. Uncertainty

Although CCES is recently commercialized the technology benefits from two important aspects of de-risking which significantly reduce uncertainty / risks and add confidence for widespread adoption:

- CCES has achieved global commercial interest with support from major energy consumers such as Google [ref. 3], and projects in several countries which will build operating experience in various site conditions and enable accelerated learning;

- Commercial CCES has demonstrated technical maturity and is based on very well proven materials and equipment, which adds resilience to the supply chain and enables local production with multiple benefits for the economy and strategic independence.

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9.15. Datasheet

Disclaimer: These numbers shall be treated with care as CCES is still an emergent and niche technology. Especially first-of-a-kind projects are expected to come with a cost premium.

Technology	**CO_2 Battery**										
	2024	**2030**	**2040**	**2050**	**2070**	**Uncertainty (2024)**		**Uncertainty (2070)**		**Note**	**Ref**
						Lower	**Upper**	**Lower**	**Upper**		
Energy/technical data											
Form of energy stored											
Application	System										
Output capacity for one unit (MW)	18										1
Input capacity for one unit (MW)	25										1
Storage capacity (MWh)	144									B	1
Depth of Discharge (%)	100										1
Round trip efficiency (%AC)	70										1
Round trip efficiency (%DC)	not applicable										
- Charge efficiency (%)											
- Discharge efficiency (%)											
Energy losses during storage (%/period)	1%/day										
Forced outage (%)	2										1
Planned outage (weeks per year)	1										1
Construction time (years)	1.5										1
Technical lifetime (years)	40										1
Discharge time	8-10										1
Regulation ability											
Primary load support (% per 30 seconds)	7.5										1
Secondary load support (% per minute)	15										1
Minimum load - discharge (% of full load)	40									C	1
Minimum load - charge (% of full load)	80									D	1
Financial data (in 2025₹)											
Capital cost (cr. ₹/MWh)	2.01										1
- energy component (cr. ₹/MWh)	0.60										1
- capacity component (cr. ₹/MW)	11.28									A	1
- other project costs (cr. ₹/MWh)											
Fixed O&M (cr. ₹/MW/year)	0.16										1
Variable O&M per output (₹/MWh)	0										1
Technology specific data											
Specific investment (cr. ₹/MW)	16.11										1

Notes

A Based on output capacity

B Considered on net discharge capability basis

C discharge (turbine)

D charging (compressor)

References

1 Provided by stakeholder

I. Appendix. Cost Projections Methodology

This section replicates the structure used in the Appendix of the Colombian Technology Catalogue [1], adapting its contents to these Technology Catalogues.

Historic data shows that the cost of most technologies have decreased over time. It can be expected that further cost reductions and improvements of performance will also be realized in the future. Such trends are important to consider for future energy planning and therefore need to be considered in the technology catalogue.

To estimate the trend of each technology, four different approaches to projecting costs are often applied:

1. Engineering bottom-up assessment:
    a. Detailed bottom-up assessment of how technology costs may be reduced through concrete measures, such as new materials, larger-scale fabrication, smarter manufacturing, module production etc. Costs are also influenced by the asset size, i.e. by the development of design parameters over time; for instance, how the design of a wind turbine is expected to evolve over time.
2. Delphi-survey:
    a. Survey among a very large group of international experts, exploring how they see costs developing and the major drivers for cost-reduction.
3. Learning curves:
    a. Projections based on historic trends in cost reductions combined with estimates of future deployment of the technology. Learning curves express the idea that each time a unit of a particular technology is produced, some learning accumulates which leads to cheaper production of the next unit of that technology.
4. Literature review:
    a. Aggregating previously published projections to create a metaprojection, based on the premise that combining individual predictions can enhance overall accuracy. The variety of literature values allows to derive low, median and high estimates.

Each of the four approaches comes with advantages and disadvantages, which are summarized in Table I-1.

Table I-1: Advantages and Disadvantages of possible approaches to cost projections.

	Advantages	Disadvantages
Engineering bottom-up	• Gives a good understanding of underlying cost-drivers. • Provides insight into how costs may be reduced.	• Requires information at a very detailed level. • Difficult to obtain objective (non-biased) information from the experts, who possess the best knowledge of a technology. • Potentially very time consuming.

Delphi-survey	• Input from a large number of experts improves robustness of forecast.	• Costly and time-consuming to carry out surveys. • Challenge to identify relevant and unbiased experts.
Learning curves	• Large number of studies have examined learning rates and documented that learning rates correlations are real. • The overarching logic of learning rates has proved correct for many technologies and sectors. • Data available to perform learning curves for most important renewable technologies, e.g. wind and solar.	• Does not explain why cost reductions take place. • One-factor learning rates are usually adopted, but in practice cost drivers included in the learning curves follow different developments. Multi-factor learning rates potentially make up for this issue, but they are difficult and time-consuming to obtain. • The theory assumes that each technology makes up an independent technology complex, but in practice there may be a significant overlap between different technologies, which makes the interpretation and use of learning curves more complicated. • Forecasting based on learning curves depend on the deployment level of the single technology, which is uncertain in the future.
Literature review	• Uses a wide range of data from multiple sources which can be used as low, median, high estimates. • Captures recent trends by focusing on up-to-date publications • Enables comparison of projections across different studies. • Supports transparent methodology by referencing specific publications. • Leverages peer-reviewed and industry-recognized sources.	• Definitions of key parameters (e.g., dollar year, lifetime) are often unclear or inconsistent across sources. • Requires interpretation of ambiguous or undefined values. • Some projections are based on or influenced by others, leading to potential bias or circular reasoning. • Difficult to determine appropriate weighting of projections, especially in rapidly evolving markets like batteries. • Limited real-world data may reduce the accuracy or reliability of projections.

For the purpose of the present catalogue, the one-component and multi-component[7] learning curve approaches [2] and literature review [3] are the most suitable way forward in combination with consultation of relevant companies within the sector where possible and public hearings. While Delphi-surveys are too costly and time-consuming and bottom-up engineering requires information at a very detailed level which is outside the scope of this study.

Learning-curve-based cost projections are dependent on two key inputs, once a cost baseline is established: a projection of the technological deployment and an estimated learning rate [2]. Essentially, this is the only information required to perform cost projections.

Table I-2 below provides an overview of the applied cost projection methods for the technologies in the Energy storage Catalogue. The choice of method depends on the maturity of the individual technology.

Table I-2: Overview of applied cost projection methods for Energy Storage technologies.

Technology	Method
LiB – LFP	LR
LiB – NMC	LR
Na-ion	LR and trend of LFP
PSP on-river	Constant
PSP off-river	Constant
VRB	Literature review
CAES	Literature review
Molten salt thermal energy storage	Literature review

The learning curve method

The learning curve method is a common way to estimate how technology costs change over time. It's based on the idea that costs drop by a consistent percentage (called the *learning rate*) every time the cumulative installed capacity or cumulative output (*experience indicator*) doubles.

This cost-experience relationship is mathematically described as a log-linear expression:

[7] The one-component and multi-component learning curve approaches are two variants of the one-factor learning curve method found in literature, as they both link cost declines to cumulative production or capacity. The key difference is that the one-component approach assumes a single learning rate for the entire system, whereas the multi-component approach assigns different learning rates to individual technological components (e.g., for solar PV, these could be modules, inverters, etc.). In contrast, the multi-factor learning curve method extends this concept by incorporating additional influences such as R&D expenditures, economies of scale, and material input costs to provide a broader perspective on technological progress. Multi-factor learning curves are not considered in this study.

$$Cost_t = Cost_0 \cdot \left(\frac{C_t}{C_0}\right)^{\epsilon}$$

$Cost_t$ is the unit cost after deploying a total of C_t units, $Cost_0$ is the initial unit cost at the starting cumulative output C_0, and ε is the experience parameter. The learning rate (LR) is related to ε by the equation:

$$LR = 1 - 2^{\epsilon}$$

This basic model (called a one-factor learning curve) doesn't explain why costs drop — it just tracks the trend. Real-world cost reductions may come from innovation, economies of scale, redesigns, or input price changes.

For Lithium-ion batteries, a multi-component learning curve approach was used, which breaks costs into parts or include other factors like R&D spending. But for this report, we use the one-factor model, as it's the most widely applied.

Global demand for technologies

To estimate the future demand of each of the technologies this study relies on analyses of the future global electricity supply from the International Energy Agency (IEA). Indeed, how the global demand and composition of electricity will develop is associated with a high level of uncertainty related to climate policy ambitions, costs and availability of fossil fuel resources and the development of existing and new electricity generation technologies.

The World Energy Outlook 2024 presents three different scenarios, the STEPS, APS and the NZE [4]. For this study, the capacity development from the Announced Pledges Scenario (APS) is used as reference for lithium-ion batteries, whose values fall in between the other two IEA scenarios.

Literature review

The literature review includes both international and Indian studies relevant to the technology, with the objective of compiling a comprehensive dataset of cost projections. All cost figures extracted from the literature were converted to Indian Rupee and adjusted to a uniform cost year—2023—enabling consistent comparison across studies.

While international studies were included to provide broader context and comparative insights, the projections prioritized Indian data to ensure relevance to the local context. International data were integrated to supplement domestic sources, particularly in cases where Indian data were limited or unavailable. For certain technologies with scarce Indian data, only estimates from international sources such as the Danish Technology Catalogue on Energy Storage [5] are utilized.

Uncertainty ranges were established based on the minimum and maximum values reported in the included studies. Outliers were excluded to maintain robustness. The point estimate for each cost item was either calculated as the mean of the defined uncertainty range or with a greater weight assigned to Indian data when possible to reflect the local cost environment more accurately.

Global and regional learning

The learning rate effects found in this review express a global view on technology learning. Considering that the majority of technology providers today are global players this seems to be a reasonable assumption. Therefore, cost reductions generated in one part of the world will easily spread to the other regions.

The literature review based projections are combining both international and Indian data sources.

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