2. Technology Catalogue for energy storage

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Technology Roadmap and Mitigation Potential of Utility-scale Electricity Storage in Mexico

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Executive Summary

The Technology Catalogue for Energy Storage is divided into three main sections: The first one is a guide to the structure and issues of the catalogue; where the basic concepts of energy storage are defined and described: technology and storage classification, technical characteristics for each of the technologies considered. It also shows a general framework of energy storage, the existing technologies, and the main applications or services that storage technologies can provide to the grid at utility scale. In this section an overview of the applications of energy storage around the world is included, identifying the application trends of different technologies, its main uses, the main components of each system, the technological maturity, the characteristics or conditions that restraint or enable its application, among other things.

The second section presents the energy storage options or technologies that are considered to have the potential to be implemented in the context of the Mexican national electricity system, their main characteristics, and the technical data that can be used to perform further analysis for each energy storage technology in a system.

The third part of the Technology Catalogue include the summary tables (Excel files) with the technical and financial data and the projections and uncertainties to 2030, the complete list of data sheets will be mentioned in the section "Web-only Materials".

The process of developing this catalogue was designed to enable the continual participation of stakeholders within this area of expertise. Therefore the stakeholder institutions within the academic, developer, and public administration sectors directly related to the subject were invited to an introductory workshop followed by the integration of a working group to discuss in detail the different aspects of the catalogue: the technology selection, the structure of the technology descriptions and the technical and financial data gathering as well as the best way to present projections and uncertainties.

The participative process consisted of the preparation and realization of three sessions with the working group where the interested parties were asked to review the documents of the catalogue and to provide feedback on the work in the different stages of realization of the project. As part of the preparation of the working group session, main files were shared. During the sessions, presentations were made regarding the different aspects of the technologies. The goal of this process was to keep the stakeholders inform about the progress and to get the most possible feedback from the participation of the greatest number of experts in the different areas.

In the case of this catalog of technologies, a working group was formed made up of experts from different sectors and institutions such as CENACE, SENER, CRE, INEEL, INVENERGY, AMDEE, AMSOL, CONACYT, UAM, IER-UNAM, among others; which enriched this work with their support, review and valuable contributions throughout the development process. The full list of working group participants for the technology catalog, the regulatory issues and study cases is at the end of this summary. We thank the participants for their contributions and comments.

1 Introduction

A challenge for the transformation of electricity systems is the increasing penetration of intermittent renewable generation. Low-carbon technologies like solar and wind have high capital costs and low operating costs, but intermittent outputs cannot be easily forecasted or controlled. The deficits and surpluses from renewable generation could be greatly managed in the future if it is incorporated through energy storage systems. But this is not the only way to approach the benefits of energy storage since the electricity network system needs a lot of different services for their optimum operation and to guarantee the levels of efficiency, reliability, continuity, and security of the National Electric System. At the same time, these services refer to issues such as management of voltage levels, frequency, congestions in the network, load balancing, among others directly linked to the availability and management of electrical energy.

This catalogue addresses technologies for energy storage at utility scale for the Mexican electricity system. The focus is on the specific storage technologies that are considered relevant for Mexico (for more details on the selection, see Appendix A). The interaction with the system and the combination with other technologies are not considered.

The present catalogue is based only on information available in the literature, and each storage technology unit is defined by its energy carrier such that the boundary to each storage system is the input and output of the same energy carrier. For example, while a flywheel stores kinetic energy, it is in this catalogue for all intend and purposes defined as electricity storage. Therefore, the conversion from electricity to kinetic energy and back is included in the storage technology. Each chapter contains the necessary qualitative description and quantitative data to complete the storage of the energy carrier.

Three groups of storage technologies are studied closely in the present report: Electrochemical storage (Batteries), Thermal storage, and Electro-mechanical storage. It focuses on only eight technologies and one special mention that were considered with the potential for deployment in the short and medium-term in México: Pumped Hydro Storage, Lithium-Ion batteries, Lead Acid Batteries, Sodium Sulfur (NaS) batteries, Flow batteries (Va-Redox), Flywheels, Molten Salt, CAES and the special mention Supercapacitors.

The main purpose of the catalogue is to provide generalized data for long term analysis of energy systems, including economic data and a qualitative description of the technologies with an overview of the most significant application trends of specific technologies for energy storage systems.

The mapping should be done on a research-based foundation, but at the same time with a focus on the development- and market-related challenges the technologies are facing for their deployment in the Mexican electricity system. The outcome of the work should be published aimed at decision makers related to the development and implementation of storage technologies in Mexico, industry and the research community.

To the presentations of the different technologies in the catalogue, the general assumptions are described in Section 1.1. The following sections (1.2 and 1.3) 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 General classification

There are different forms of energy stored and different possible applications of certain technologies, but since the focus of this catalogue is utility scale in the national Mexican network these are categorized as shown in the following table.

Table 1.1. Categories of electricity storage. Source: Own elaboration.

	Principle	Application within the electricity value chain		
		Transmission system operation	Distribution system operation	End user
Form of energy stored	Electro-chemical	Lithium-Ion Sodium Sulfur (NaS) Lead Acid Vanadium Redox Flow	Lithium-Ion Sodium Sulfur (NaS) Lead Acid Vanadium Redox Flow	Lithium-Ion Sodium Sulfur (NaS) Lead Acid Vanadium Redox Flow
	Thermal	Molten Salt	Molten Salt	
	Mechanical	Pumped Hydro Flywheel CAES	Pumped Hydro Flywheel CAES	Flywheel
	Electrical	Supercapacitors		Supercapacitors

The possible forms of energy stored considered are Electrochemical (Batteries), Thermal, Mechanical, and Electrical. While the considered applications include large scale technologies to provide system services, other smaller sizes are possible for specific applications in the optimum managed of the network. The consumption level is not considered in this catalogue. The table only lists the technologies included in the catalogue.

Based on the service provided, 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 electricity 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 (Danish Energy Agency-Energinet, 2018).

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 (Danish Energy Agency-Energinet, 2018).

Table 1.2. Trends in a type of services provided by technologies. Source: Own elaboration.

Technology	Service provided	
	Power-Intensive	Energy-Intensive
Lithium-Ion	⚡	⚡
Sodium Sulfur (NaS)	⚡	⚡
Lead Acid		⚡
Vanadium Redox Flow (VRF)	⚡	⚡
Molten Salt		⚡
Pumped Hydro		⚡
Flywheel	⚡	⚡
CAES		⚡
Supercapacitors	⚡	

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

1.2 Qualitative description

The qualitative description covers the key characteristics of each technology as concise as possible. The following paragraphs are included where relevant for the technology and when the information is available.

1.2.1 Brief technology description

Brief description for non-engineers of 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. Further, the type of services that the storage technology can provide is explained.

The system boundaries are identified in this section. An illustration of the technology is included, showing the main components and working principles.

1.2.2 Input/output

The form of energy input to be stored (electricity, hot water, natural gas etc.) and the output(s).

1.2.3 Energy efficiency and losses

The energy conversion efficiency:

- Charge/discharge efficiency
- Round-trip efficiency, and
- Energy losses such as self-discharge (batteries), heat loss, mechanical loss, etc.

1.2.4 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 kWh/m^3 and Wh/kg respectively.

For some storage technologies, there is a certain amount of energy that must 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 (SOC) and for gas storage in caverns a certain amount of cushion gas[1] is normally required. In such cases, only the "active storage capacity" is specified, meaning the amount of energy between maximum and minimum level.

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

1.2.5 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.

1.2.6 Regulation ability

How fast can they start up and how quickly are they able to respond to demand changes or provide grid services.

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[1] Base gas (or cushion gas) is the volume of natural gas intended as permanent inventory in a storage reservoir to maintain adequate pressure and deliverability rates throughout the withdrawal season (eia https://www.eia.gov/naturalgas/storage/basics/)

1.2.7 Examples of market standard technology

Recent full-scale commercial projects, which can be considered market standard, are mentioned, preferably with links. For technologies where no market standard has yet been established, reference is made to best available technology in R&D projects.

1.2.8 Advantage/disadvantage

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.

1.2.9 Environment

Environmental characteristics are mentioned, for example special emissions or the main ecological footprints. (e.g. for batteries the use of critical, toxic or regulated materials is specified).

1.2.10Research and development

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.

1.2.11 Prediction of performance and cost

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 2020 as well as the improvements assumed for 2030 and 2050.

The specific technology is identified and classified in technological maturity, indicating the commercial and technological progress, and the assumptions for the projections are described. In formulating the section, the following background information is considered:

Data for 2020

In case of technologies where market standards have been established, performance and cost data of recent installed versions of the technology in the region countries in relation to the specific technology are used for the 2019 estimates.

If consistent data are not available, or if no suitable market standard has yet emerged for new technologies, the 2019 costs may be estimated using International references such as the IEA, NREL etc.

Assumptions for 2030 and 2050

A detailed analysis of the combined technological and economic suitability of the wide range of applications and service provision possibilities in diverse local contexts involves a much profound examination. A robust analysis of the value that the storage systems provide at the electricity system level requires detailed modelling of the specific electricity system that is investigated. It is heavily influenced by the specific market design and the costs and benefits of providing these services through alternative means within the studied market. It also involves a determination of the locations and the size of ESSs that minimize the cost of serving-system demand and a study of the real-time operation of proposed storage systems. (IRENA, 2017).

However, in the interest of providing some initial insights diverse studies analyzes the future costs-of–service that allows a user to identify the approximate annual cost of electricity storage service in different applications.

This report does not contain simulations on which investment decisions can be made, but provides technology data which can be used for e.g. systems analyses and assessments of specific applications to identify some of the potentially more cost-effective options available for initial screening and conducted to more detailed analysis of their suitability for the specific application, their performance in the specific real-world application and relative economics, this specific studies usually are made by the developer companies in identified projects with high-value opportunity.

Learning curves and technological maturity

The development for predicting the future costs of technologies may be done using learning curves. Learning curves express the idea that each time a unit of a technology is produced, learning accumulates, which leads to cheaper production of the next unit of that technology. The learning rates also consider 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 (Technology Readiness Level).

1.2.12 Uncertainty

The catalogue covers technologies with different Technology Readiness Level (TRL) 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.

This section 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.

1.2.13 Additional remarks

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

1.3 Quantitative description

To enable comparative analyses between different technologies it is imperative that data are comparable: All cost data are stated in fixed same year prices excluding value added taxes (VAT) and other taxes. The information given in the tables relate to the development status of the technology at the point of final investment decision (FID) in the given year (2020, 2030 and 2050). 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 made to allow for an easy comparison.

Each cell in the table contains one number, which is the central estimate for the market standard technology, i.e. no range indications.

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 of cost and performance data, the bounds expressing the confidence interval could result in large intervals. The uncertainty is related to the market standard technology.

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. 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:

Table 1.3. Template table for presentation of technical data. Source: Own elaboration.

Technology	Name / description								
	2020	2030	2050	Uncertainty (2020)		Uncertainty (2030)		Note	Ref
Energy/technical data				Lower	Upper	Lower	Upper		
Form of energy stored									
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 (%)									

Technology	Name / description								
	2020	2030	2050	Uncertainty (2020)		Uncertainty (2030)		Note	Ref
- Discharge efficiency (%)									
Energy losses during storage (%/period)									
Auxiliary electricity consumption (% of output) (Expressed only for heat and gas storages)									
Forced outage (%)									
Planned outage (weeks per year)									
Technical lifetime (years)									
Construction time (years)									
Response time from idle to full-rated discharge (sec)									
Response time from full-rated charge to full-rated discharge (sec)									
Total investment cost (MUSD$2020 per MWh)									
- energy component (MUSD$/MWh)									
- capacity component (MUSD$/MW)									
- other project costs (MUSD$)									
Fixed O&M (% total investment)									
Variable O&M (USD$2020MWh)									
Alternative Total investment cost (MUSD$2020 per MW)									

1.3.1 Energy/technical data

Energy storage capacity for one unit

The storage capacity, nominal capacity (not maximum capacity), represents the size of a standard unit in terms of energy stored.

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, large battery installation.

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 could be found in the notes. The unit MWh is used for electrical energy 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. 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.

Round trip efficiency (Charge and discharge efficiencies)

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

The round-trip efficiency is the product of charging and discharging efficiencies:

$$RT\varepsilon = CH\varepsilon \ x \ DCH\varepsilon;$$

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.

Energy losses during storage

The energy lost from the storage unit due to losses in a specific time horizon is specified here. It is prudent to mention that for different technologies these losses will depend on the storage time, and this catalog does not contain those specifications.

Technologies with different storage periods will show very 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

Storage systems who involve heat and gas usually need auxiliary systems to operate, such as pumps and/or compressors. The auxiliary consumption expresses the consumption of electricity from such equipment as a percentage of output, which has gone through the full storage cycle.

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.

Technical lifetime

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 stay within acceptable limits. For instance, efficiencies often decrease slightly (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 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 the data reported in the bibliography consulted. The expected technical lifetime considers a typical number of start-ups and shutdowns.

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.

Construction time

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

1.3.2 Regulation ability (Type of services provided)

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

- Response time from idle to full-rated discharge (sec)
- Response time from full-rated charge to full-rated discharge (sec)

The response time from idle to full-rated discharge is defined as the time, in seconds; the electricity storage takes to reach 100% of the discharge capacity from idle condition.

The response time from full-rated charge to full-rated discharge is defined as the time, in seconds; the electricity storage takes to go from charging at full capacity to discharging at full capacity.

1.3.3 Financial data

Financial data are all in US dollars ($), fixed 2020 prices and exclude value added taxes (VAT) and other taxes. The generalizations of the costs of storage technologies as per IEA reporting from 2015 (International Energy Agency, 2014), should not be above the costs at the regional or local level since the costs are largely determined by local conditions. Mexico is a country that has just opened its energy sector to a market that allows more direct participation of private investment, and the energy storage sector is barely in sight, but a rapid deployment is expected. These emerging conditions of value chains and markets mean that local costs will hardly be less than the generalizations presented.

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, is assumed 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.

The total investment cost is reported on a normalized basis, i.e. cost per MWh of storage capacity. It is the total investment cost divided by the energy storage capacity for one unit, 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 components considered are the following:

- Cost of Energy component (CE) [M$/MWh]: cost related to the equipment to store the energy (incl. their installation) for example battery modules or reservoirs in a pumped-hydro plant.;
- Cost of Capacity component (CP) [M$/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) for example converter and grid connection for a battery system, turbine/pump and grid connection for pumped-hydro plant.
- Other project costs (Cother) [M$]: 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 M$/MWh, by dividing the Total Capital Expenditure by the Energy storage capacity (Esc) for one unit in MWh.

$$Total\ Capital\ Expenditure = C_E x E_{SC} + C_P x P_{out} + C_{other} \qquad [M\$]$$

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

Where:

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

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

$h = \frac{E_{SC}}{P_{Out}}$ = Total number of unloading hours [h]

For electricity storage applications with a power-intensive service, an alternative Total investment cost in M$/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. The trend was general and global. An example is combined cycle gas turbines (CCGT), where prices 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 are specified for the technologies. It 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 cost per energy storage capacity for one unit per year ($/MWh/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 are available.

The variable O&M costs ($/MWh) are calculated as costs per MWh of energy effectively released by the storage. They include 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).

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.

1.3.4 Technology specific data

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

For electricity 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 electricity storage technologies (batteries in particular) the power density PD (W/m^3) and energy density ED (Wh/m^3) are stated, as well as the specific energy SE (Wh/kg) and specific power SP (W/kg). Depending on data availability, in this catalog, these parameters are linked through unloading hours and volume, weight and energy characteristics for the specific applications shown in the datasheets for consistent estimation:

$$\left(SP = \frac{SE}{h}\ ;\ PD = \frac{ED}{h}\right)$$

The total investment cost per MW is also stated, as an alternative figure to the total investment in $/MWh.

$$\text{Alternative Total Investment cost} = Total\ Capital\ Expenditure / P_{out}$$

The following table summarizes the technology specific data:

Table 1.4. Possible additional specific data. Source: Own elaboration.

Electricity
Alternative Total investment cost (M$/MW)
Lifetime in total number of cycles
Specific power (W/kg)
Power density (W/m^3)
Specific energy (Wh/kg)
Energy density (Wh/m^3)

1.4 Electricity storage

Electricity 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 (Danish Energy Agency-Energinet, 2018). The technologies presented in this chapter are intended to assist in the challenges that arise in the integration of intermittent energy sources such as maintaining the balance of production and demand in real-time and maintaining the reliability and quality of the energy supply while taking efficiently advantage of the overproduction of electricity in different time horizons (minutes, hours or weeks). But also diversify the technological options to provide the services required in the operations of the electric network for its optimal operation and to guarantee the levels of efficiency, reliability, continuity and security of the National Electricity System.

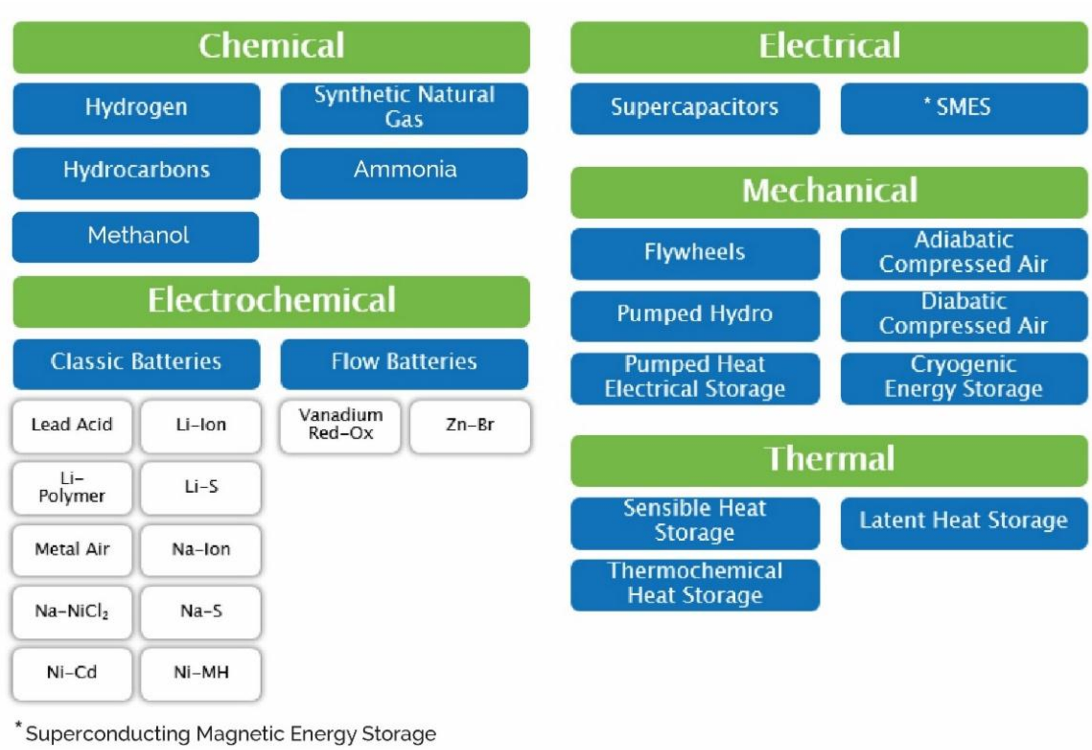


Figure 1.1. Classification of electrical energy storage systems according to energy form. Source: Adapted from (EASE/EERA, 2017)

In 2017, it is estimated that 4.67 TWh of electricity storage exists. The total amount of electricity storage worldwide is set to triple from 2017 to 2030, with a foreseeable reduction of the share of pumped-hydro, in favor of battery energy storage (BES) systems, which capacity is set to increase 17-fold driven by growth of utility scale and local behind-the-meter applications (IRENA, 2017).

While electrical energy storage systems are identified by the fact that they can be utilized to exchange power (the energy carrier) with the grid, energy storage technologies are commonly classified according to their type, depending on the energy form ultimately stored as seen in

Figure 1.1. Although, the examples in each category should not be an exhaustive list of potential family members.

For 2019 this distribution in accordance with the data (registered in January 2019), of Department of Energy of the United States of America (DOE), the total installed storage operational power capacity of Pumped Hydro storage is 171.35 GW (96.01%) and the other electricity storage technologies in significant use like thermal storage with 3.01 GW (1.69%) ; electro-chemical (batteries) with 2.76 GW (1.55%), and other mechanical storage with 1.34 GW (0.75%) (US DOE., 2019).

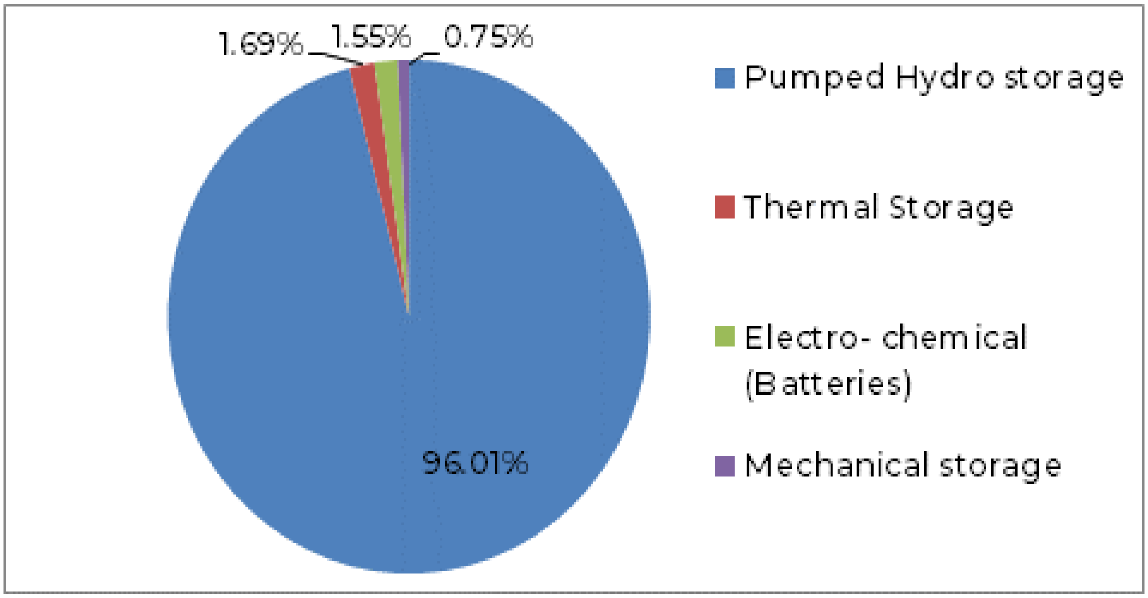


Figure 1.2. Global electricity storage power capacity installed and operating (GW) by classification of technology in 2019. Source: (US DOE., 2019)

The pumped hydro storage (PHS) has highly mature technology for energy storage. Its capital requirements and technology risk are relatively low. Furthermore, compressed air energy storage (CAES), sodium-sulfur batteries, flywheel (low speed), molten salt, and lithium-ion batteries are in the stage of deployment technology, but its capital requirements and technology risk are high. Finally, flow batteries and supercapacitors are in the demonstration technology stage. Its capital requirements and technology risk are high, too (Figure 1.3).

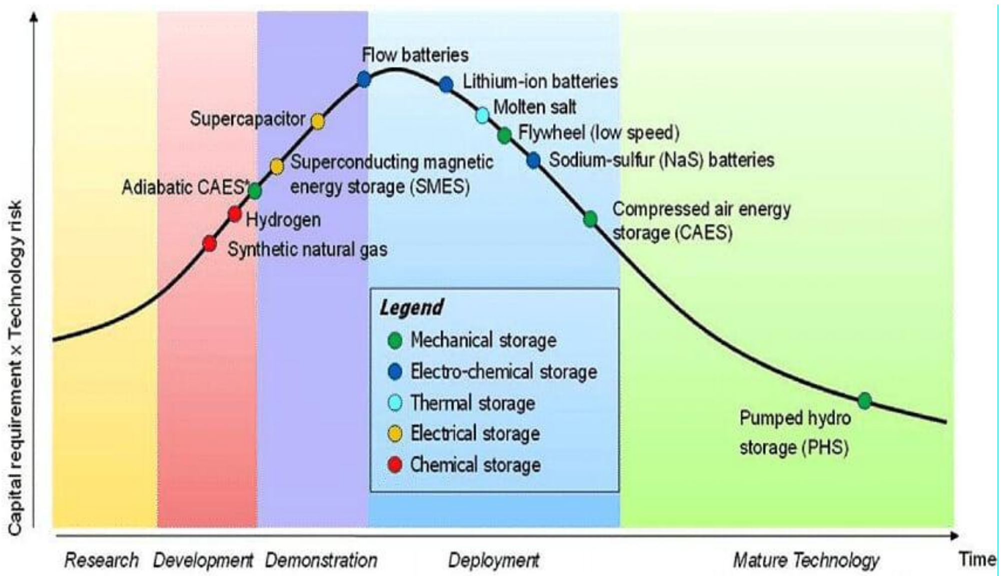


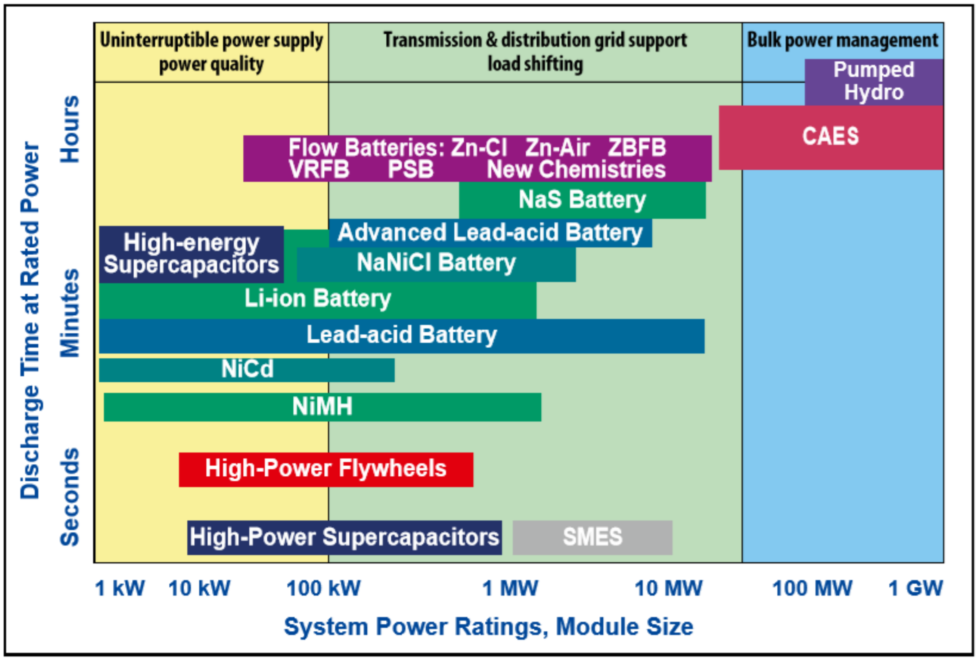
Figure 1.3. Maturity curve graph of energy storage technology. Source (IEA, 2014)

1.4.1 Electricity storage characteristics and services

Numerous energy storage technologies are under development, with a wide range of characteristics that make them suitable for different roles in the energy system, at the same time the services necessary for the optimal operation of the national electricity grid can be identified in different sectors in relation to their technical requirements. One way to categorize the different storage systems and the potential service they can provide is by looking at their power rating and the discharge time at rated power. They are distinguished mainly by their level of operation and field of application. In its study ELECTRICITY STORAGE AND RENEWABLES: COSTS AND MARKETS TO 2030 the International Renewable Energy Agency, distinguishes in a main 3 levels (IRENA, 2017):

- Bulk Power management, where large module sizes and system power ranges are distinguished (> 50 MW) and in general a longer response time (> 60 seconds).
- Transmission & distribution grid support-load shifting where the module sizes and power ranges are more moderate (> 100 kW <50 MW) and the response times are faster (> 10 seconds) although not instantaneous.
- Uninterruptible power supply-power quality: which request an immediate response time (<10 seconds), but in general with smaller modules and power ranges (<100 kW).

These are categorized as shown in the following figure 1.4. The different services that electricity storage can provide are various and are inherently related to the physical characteristics of the storage media and the storage system.



Source: US DOE/EPRI, 2015.
Note: Zn-Cl = zinc chlorine flow battery; Zn-Air = zinc air flow battery; ZBFB = zinc bromine flow battery; VRFB = vanadium redox flow battery; PSB= polysulfide bromine flow battery; NaS = sodium sulphur; NaNiCl = sodium nickel chloride; NiCd = nickel cadmium; NiMH = nickel–metal hydride; SMES = superconducting magnetic energy storage.

Figure 1.4. Positioning for different energy storage technologies in system power rating vs discharge times at rated power. Source: (IRENA, 2017)

The potential applications for electricity storage across the entire value chain are various. Some of these applications refers to more energy-intensive services, while others refer to power-intensive ones. The most important ones can be categorized as follows (Danish Energy Agency-Energinet, 2018):

- 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 the generation pattern of conventional plants, and a reduction of the peak demand (peak shaving), resulting in a lower utilization of more expensive generators 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].
- 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.

[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 cost, becomes competitive with gas or other peaker technologies in terms of capital cost expenditure.

- **Network support and investment deferral:** Postponement of costly expansion of the power network thanks to the reduction of situations with overload and congestions in transmission or distribution networks. In connection to variable renewables, it refers also to the reduction of curtailed energy.
- **Primary regulation:** Participation in the primary frequency regulation, ensuring the balance between production and consumption is restored in the event of frequency deviations. The response time for the primary regulation is 15-30 sec. It is also referred to as Frequency Containment Reserve (FCR).
- **Secondary regulation:** Participation in the secondary frequency regulation, ensuring the frequency is brought back to its nominal value after a major system disturbance. The response time of secondary regulation is 15 min. It is also referred to as Automatic Frequency Restoration Reserve (aFRR).
- **Tertiary regulation:** Participation in the tertiary frequency regulation, which partially complements and replaces secondary reserve by re-scheduling generation. The response time must be within 15 minutes. It is also referred to as Manual Frequency Restoration Reserve (mFRR).
- **Black-start:** Service of reestablishment of the grid after a generalized black-out. It can be provided by plants that are able to start operation autonomously, i.e. without alimentation from the grid.
- **Voltage support:** Provision of reserve for the modulation of reactive power in specific nodes of the grid for voltage management purposes.
- **Power quality:** Refers to several 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).

The suitability of different storage technologies for the specific applications considered relevant for the development of energy storage in the National Electricity System network (SEN) of Mexico, are shown in Figure 1.5[3].

TECHNOLOGY\CRITERIA	Energy arbitrage ($)	Primary regulation (sec)	Secondary regulation (min)	Peak Shaving	Congestion management	Long term storage	Investment deferral of T&D	RE Capacity Firming	Potential improvement of performance-cost relation	Consideration for México	Cost	Environmental impacts
Pumped Hydro Storage (PHS)	Suitable	Not suitable	Suitable	Not suitable	Suitable	Suitable	Suitable	Suitable	Less suitable	Suitable	Less suitable	Less suitable
Compressed Air Energy Storage (CAES)	Suitable	Less suitable	Less suitable	Not suitable	Suitable	Suitable	Less suitable	Less suitable	Less suitable	Less suitable	Less suitable	Less suitable
Molten Salt	Suitable	Not suitable	Less suitable	Not suitable	Less suitable	Suitable	Suitable	Suitable	Less suitable	Suitable	Less suitable	Less suitable
Hydrogen	Suitable	Less suitable	Less suitable	Suitable	Suitable	Suitable	Less suitable	Suitable	Not suitable	Less suitable	Not suitable	Less suitable
Flywheels	Not suitable	Suitable	Suitable	Suitable	Not suitable	Not suitable	Not suitable	Less suitable	Suitable	Suitable	Less suitable	Suitable
o LeadAcid based batteries	Suitable	Suitable	Suitable	Suitable	Suitable	Not suitable	Less suitable	Suitable	Less suitable	Suitable	Suitable	Not suitable
o Lithium based batteries	Suitable	Suitable	Suitable	Suitable	Suitable	Not suitable	Suitable	Suitable	Suitable	Less suitable	Suitable	Less suitable
o Sodium based batteries	Suitable	Suitable	Suitable	Suitable	Suitable	Not suitable	Suitable	Suitable	Less suitable	Less suitable	Suitable	Less suitable
o Flow batteries	Less suitable	Less suitable	Suitable	Suitable	Suitable	Not suitable	Suitable	Suitable	Not suitable	Less suitable	Less suitable	Less suitable
o Other Based batteries (Zn,Ni)	Suitable	Suitable	Suitable	Suitable	Suitable	Not suitable	Suitable	Suitable	Less suitable	Less suitable	Suitable	Less suitable
Super Capacitors	Not suitable	Suitable	Suitable	Less suitable	Not suitable	Not suitable	Not suitable	Less suitable	Less suitable	Less suitable	Not suitable	Less suitable

Relevant for México | ● Suitable | ● Less suitable | ● Not suitable

Figure 1.5. Suitability of different electricity storage technologies for different applications. Source: (Adapted from (EASE/EERA, 2017))

[3] The suitability for the different services is primarily based on (Oliver Schmidt, 2019), (EASE/EERA, 2017). And (IRENA, 2017). Additional and recent information have been considered. For example, thanks to the current reduction in cost, Li-ion batteries are starting to be deployed for energy-intensive services such as time-shift and load management. See for example: (Enel, 2017) and other Li-ion projects with more than 4h of storage duration in (US DOE., 2019). Further details are in the Appendix A.

Based on data from the U.S. DOE Database of Storage project (US DOE., 2019), today the main uses of electricity storage by technology group are those displayed in Figure 1.4, 1.5, 1.6 and 1.7. The vast majority of pumped-hydro storage is used for Time-shift applications (90.0%), followed by black start (3.5%) and Electric Supply Capacity (2.9%). Differently, electro-chemical storage is mainly used for frequency regulation (51.5%) and provision for electric time shift (13.1%) and the electric bill management (10.3%) have an important role, with a lower share dedicated to services like Electric Supply reserve capacity-spinning (4.6%) and renewables capacity firming (4.4%), however, it is necessary to highlight the versatility of services that this sector can offer, as can be seen in figure 1.6. Electro-mechanical storages, like flywheel systems, see the largest deployment in on-site power (34%), frequency regulation (33.4%) and black start (21.5%). For its part, thermal storage is deployed mostly through molten salts associated with the production of electrical energy by solar concentrating solar plants, so the main services it provides are renewables capacity firming (85.5%), onsite renewable generation shifting (6.0%) and the electric energy time shift (3.2%).

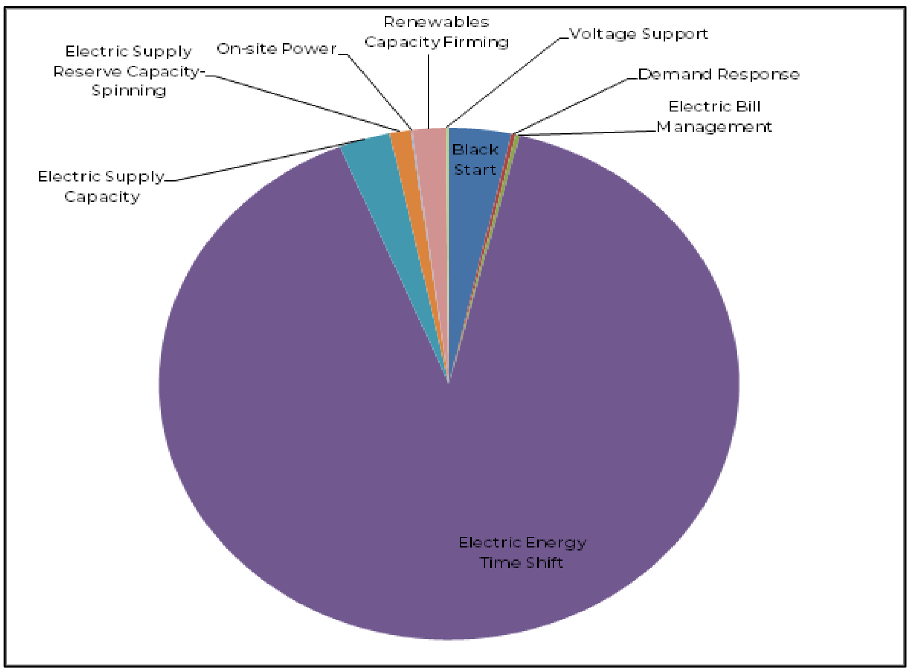


Figure 1.6. Distribution of provided services of operating PHS power capacity. Source: Developed by authors with data of (US DOE., 2019)

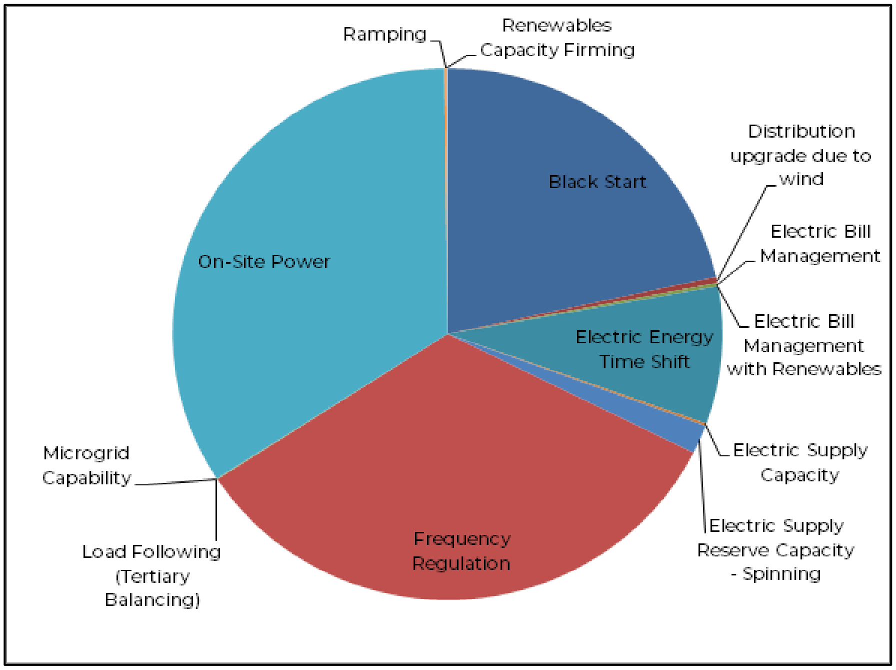


Figure 1.7. Distribution of provided services of electromechanical storage power capacity. Developed by authors with data of (US DOE., 2019)

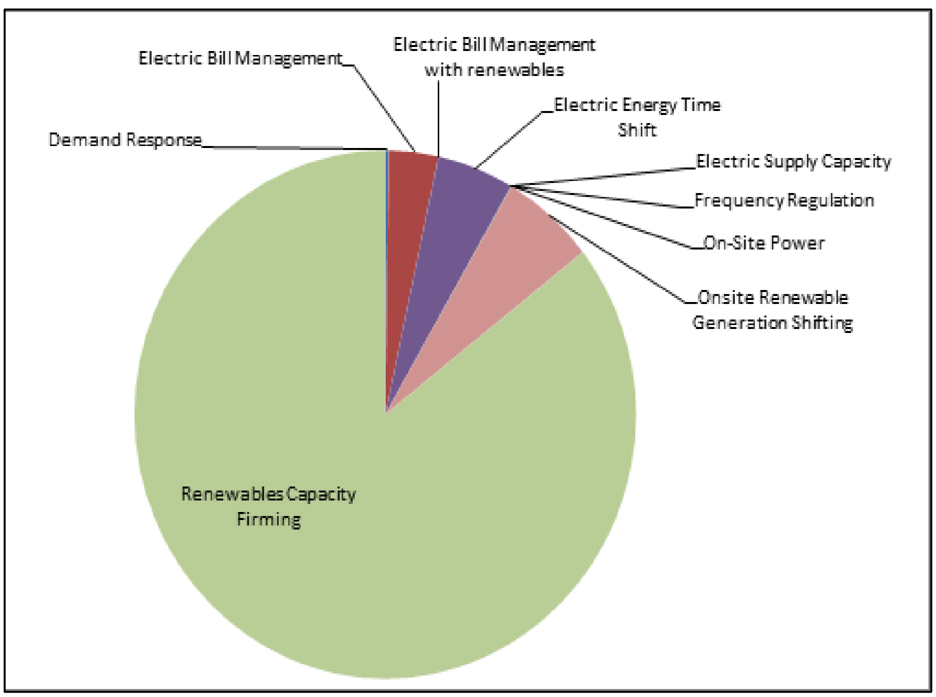


Figure 1.8. Distribution of provided services of thermal storage power capacity. Developed by authors with data of (US DOE., 2019)

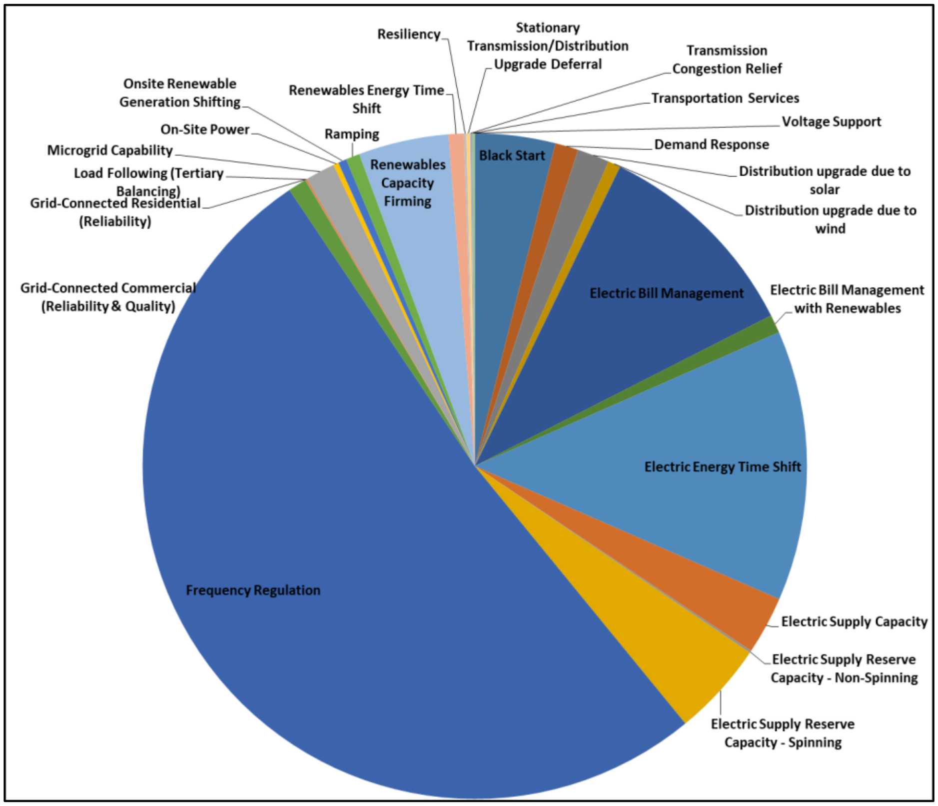


Figure 1.9. Distribution of provided services of electrochemical storage power capacity. Developed by authors with data of (US DOE., 2019)

In the future, electro-chemical storage is expected to experience an evolution towards more energy-intensive applications, following the reduction of battery cost (IRENA, 2017) estimates that its main applications will be:

- Energy shifting for PV to increase self-consumption (60-64%)
- RE capacity firming and smoothing at utility scale (11-14%)
- Frequency regulation (10-15%)
- Ability to provide multiple services and “stack” revenues

1.4.2 Components of electricity 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 (Danish Energy Agency-Energinet, 2018) The system boundaries and the subdivision of the equipment in the three cost component (an energy component, a capacity component and other fixed costs), as defined above in the Investment cost of the main guide, an example are shown below for cell-based batteries electricity storage technologies.

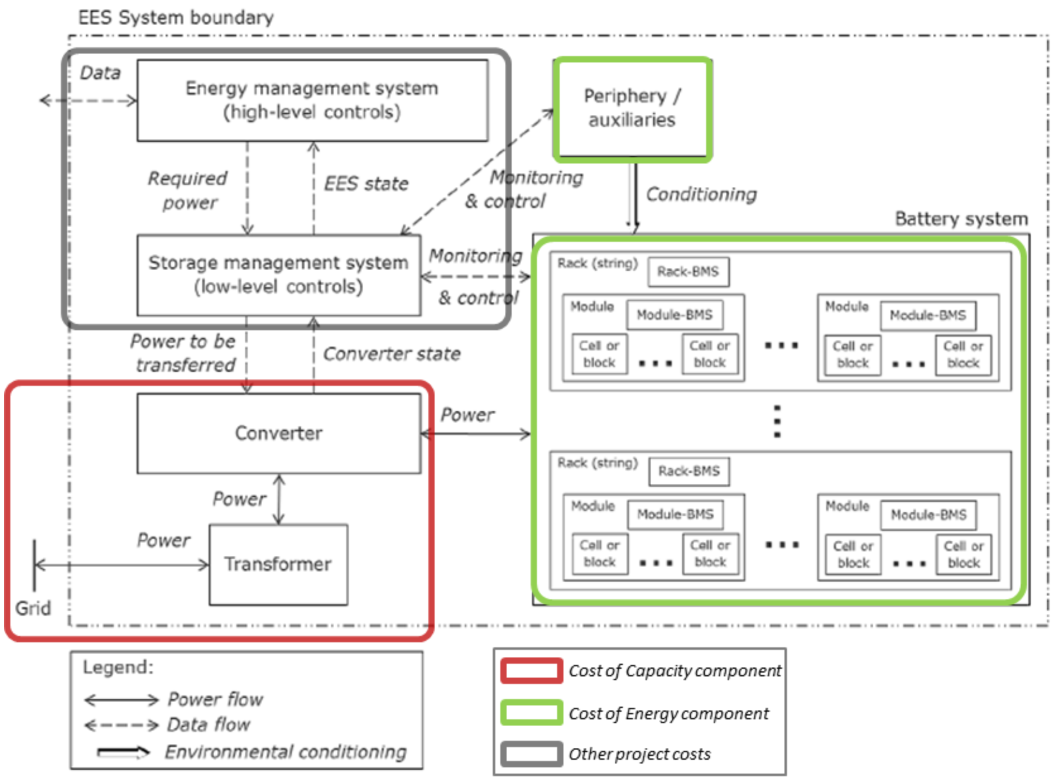


Figure 1.10. Components and their categorization for cell-based batteries, such as Li-ion, NaS and NaNiCl.
Source: (DNV-GL, 2015)

Energy component

The energy component includes the following equipment and its installation: Battery modules, battery management system (BMS), local protection, racking frame/cabinet.

Capacity component

The capacity component includes the following equipment and its installation:

- Cell-based batteries (including Li-Ion) 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. The costs include step-up transformer (low-medium voltage for BES), switchgears, breakers, meters and dedicated cabling to reach the connection point.

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 (Andriollo, Benato, Bressan, Sessa, Palone, & Polito, 2015).

An important design parameter is the voltage range in which the converter works. Today's applications are typically at 1000V, but some 1500V applications are emerging (Danish Energy Agency-Energinet, 2018).

The cost of power conversion for battery storage systems, based on a number of references (Benato, Bruno, Palone, Polito, & Rebolini, 2017) (Zakery & Syri, 2015) (Sandia National Laboratories, 2013), is higher than the inverter cost for photovoltaic (PV) plants.

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 (Danish Energy Agency-Energinet, 2018).

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

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2 Technology descriptions

2.1 Pumped Hydro Storage

Brief technology description

Pumped Hydro Storage (PHS) is a mature and widespread large-scale electrical energy storage technology and works with a simple principle: convert electrical energy into potential energy by elevating water to a higher-level reservoir.

To operate in this way, electrical energy is used by the pumping system; therefore, it is sought to operate in periods of low demand or when electricity has low cost. Subsequently, the electrical energy is generated by releasing the water that was stored in the upper reservoir through turbines. This occurs in the same way as a conventional hydroelectric plant. In general, this electricity is generated when the demand is high and therefore, the market prices high. When the water travels through the circuit of the lower reservoir to the upper one, then a storage cycle is completed. PHS currently represents more than 96 percent of the installed global storage capacity, and more than 99 percent in terms of stored electrical energy (IRENA, 2017). PHS has been used as a balancing component for power generation plants that have limited monitoring of demand curve (inflexible) (IRENA, 2017), due to the possibility of absorbing electricity to power a pumping system and its ease of delivering energy quickly, favoring efficient operation of the electricity grid.

The PHS might balance the variation of wind and solar energy by providing reliable energy by meeting the demand during sustained and increasingly prolonged changes, while avoiding the need for curtailment during periods of excess supply. Therefore, PHS could further support the deployment of variable renewable energy, as it makes the operation of the power grid flexible (Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, 2019).

In the 1960s, most of the thermal generators that delivered energy were high capacity, high temperature and high-pressure units, with little possibilities of specific improvements in efficiency. These generators were the equipment with lowest cost for constant high performance to reduce equipment stress and maintenance costs while optimizing operational efficiency.

However, the thermal power plants are less capacity to provide energy in the maximum demand, resulted in a firm operation for these types of plants, because they find it difficult to adapt to sudden variations in demand. This firm operation refers to power plants that deliver energy constantly almost all the time, plants which at the same time provide support to the base load energy matrix.

As renewable variable energy sources continue to displace the generation of dispatchable fossil fuel based power plants, the flexibility of the energy system becomes a crucial tool to avoid disruptions to end users and reduce price volatility that might be created in markets whose prices are identified through marginal operational costs.

In Mexico, before the energy reform that took place in 2013, hydroelectric power plants were built to absorb excess energy by operating as synchronous capacitors. These services came mainly from power plants with base load. Subsequently, hydroelectric plants were operated in a conventional manner, with the purpose of delivering energy during peak hours of high demand. Therefore, the power generation by these power plants is just cover the peak hours without considering the economic benefits.

Therefore, the Federal Electricity Commission (CFE), which was a state-owned company, was responsible for bringing energy to the entire population and industry of the country, as well responsible for the operation and the expansion of the grid.

In this way, some hydroelectric projects were facilitated where, in addition to the electric service, collateral benefits were offered for water management, such as the supply of water resources to the main consumption centers, water available for irrigation and industrial use, as well as the security provided by a dam against severe weather events, such as large runoffs that flood cities or growing areas (Lindström & Granit, 2012). Very few projects were conceived to supply only electricity and less for the control or storage of energy as PHS do.

In recent years, interest in PHS has increased in several countries, especially in China, but also in Europe and in relatively new markets. As variable energy sources are increasingly integrated into electrical networks, PHS could facilitate their integration. At the end of 2017, the global installed capacity was 161,000 MW (REN21, 2018). China has contributed to a large part of recent growth, managing to add almost 15,000 MW of capacity since 2010.

Mechanical principle

PHS system works with the potential gravitational energy. When there is an excess power on the grid, the water in the lower reservoir is pumped to the upper one. When the grid needs energy, the water in the upper reservoir is dropped to a hydro turbine (HT) to produce power. Energy production is because there is a positive pressure difference between the upper and lower reservoir.

Components in a pumped hydro storage system

PHS is composed of four main elements: hydro turbine, pumping system, and upper and lower reservoir (Mahmoud, Ramadan, Olabi, Pullen, & Naher, 2020) (see Fig. 2.2).

Input/output

PHS systems store potential energy and produce electricity, using electrical energy as input to pump water and delivering electrical energy as output.

Energy efficiency and losses

PHS loading and unloading efficiencies reach more than 80% for both cases and can provide load balancing within the general power system (Morante, 2014). Pumped storage might prevent electrical blackouts, as their reaction time is 15 seconds to go from 50% generation to 100%; although it takes about two minutes to go from 0% to 100% generation. On the contrary, the complete inversion of the cycle, from 100% generation to 100% pumping, takes about 10 minutes. Modern pumping plants, with variable speed machinery, allow a regulation of the power produced, from 50% to 100%. This is useful for those services necessary to keep the transmission of electric power under control (Morante, 2014).

The efficiency of PHS is between 70 – 85 %. Its energy losses during storage are 0.01 % per day (IRENA, 2017).

Typical characteristics and capacities

Types of pumped hydro storage systems

Conventional PHS systems are classified according to the operation in its pumping, i.e. it is necessary to differentiate the route that the water takes between deposits (see Table 2.1 for a description of the main elements):

1. Closed-loop pumped storage (see Figure 2.1): A body of water that is stagnant, such as a lagoon or an artificial basin (build by the dam) represents the lower reservoir (containment work is required). The volume of water stored in the basin is the same as that circulated throughout the system; therefore, it feeds exclusively on the water pumped from the lower basin to the upper basin. In this case, there are no additional contributions of water, and a first filling is required.
2. Open-loop pumped storage (see Figure 2.1): This type of power plants have natural water inlets to the lower basin and its main characteristic is that the water follows its natural course; therefore, it requires an inlet tap that only captures the volume necessary to be pumped, and after storage and the energy generation, the water returns to its natural channel. It is possible that the basin is oversized to capture an additional volume that allows the correct operation of the PHS.

Table 2.1. Different elements of the generation and pumping plant of PHS. Source: (ICOLD, 2019)

Element of a PHS	Description
Dam (Containment work)	It refers to the civil work that fulfils the function of retention, specified and modifies the natural conditions of a given river, in order to obtain a deposit for its use. Traditionally they are known as "dam" and are made of stone, concrete or loose materials, which are usually built on a mountain and on a river or stream.
Water intake	A set of structures that are constructed to extract water in a controlled way and store it for later use in water supply or irrigation; to raise its level with the objective of referral to irrigation pipes; to protect an area from its flood effects; or for the production of electrical energy. The dimensioning of the admission

Element of a PHS	Description
	works includes, as a base, the knowledge of the water demand, as well as the operation, the minimum and maximum levels of the source from which it is extracted.
Penstock	Set of pipes, valves, fittings and structures that transfer water from the collection to the tank, taking advantage of the existing static load. They usually follow the terrain profile.
Powerhouse	It consists of the electromechanical pump-turbine / motor-generator equipment. At this point the force that brings water acts on the turbine blades. The impeller remains attached to the alternator rotor, which, when rotating with the electromagnetic poles, induces an alternating current in the alternator stator coils. It is known as reversible because the motor runs on alternating current that rotates the pump to raise the water to the upper tank, operating in the direction opposite to the turbine.
Reservoirs	The deposits or regulation reservoir are intended to change a regime of contributions (of driving) that is always constant, to a regime of consumption or demands that is always variable. It allows the storage of a volume of water when the demand is less than the arrival expense and the stored water is used when the demand is greater. Generally, this regulation is done for periods of 24 hours. When an additional volume for storage is provided, an amount is then available as a reserve in order not to suspend the service in case of damage to the collection or conduction, the volume of reserve water is generally used to meet demands extraordinary.
Spill-over	Also known as overflow dumps are built in order to give way to the volumes of water that cannot be retained in the reservoir or reservoir of a dam and must be removed to prevent structural damage to the containment work.

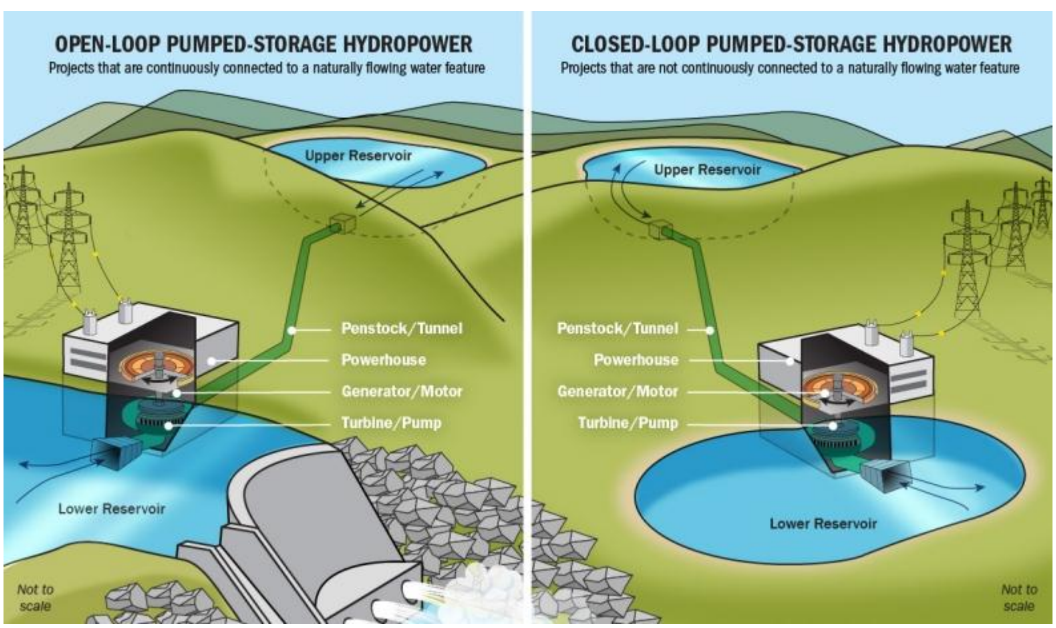


Figure 2.1. Illustration of the PHS technology. Source: (EERE, 2019)

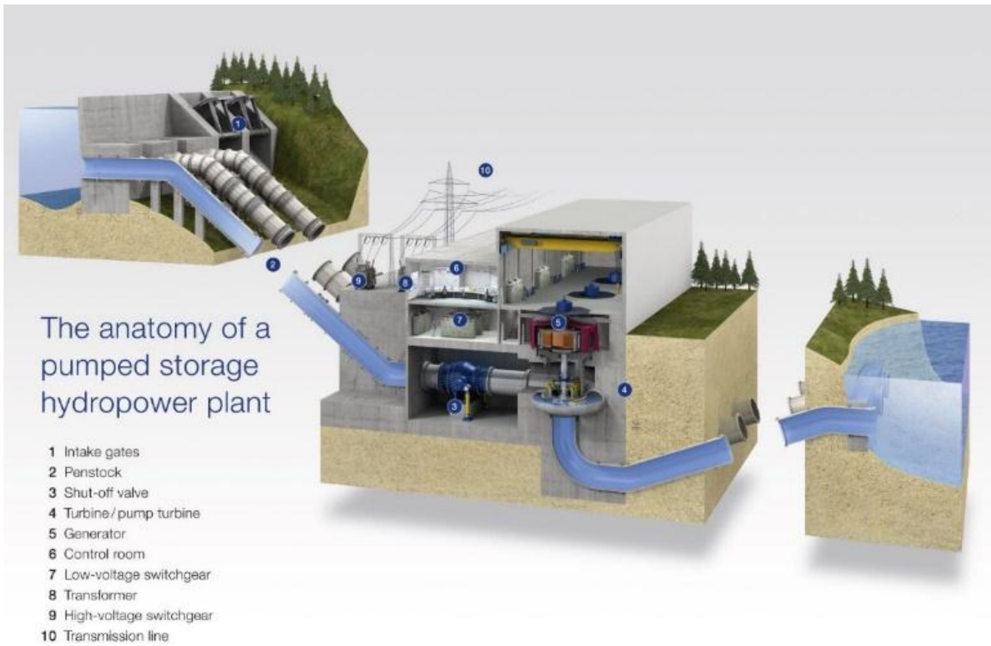


Figure 2.2. Main installation that constitute a hydroelectric plant. Source: (CERI, 2008)

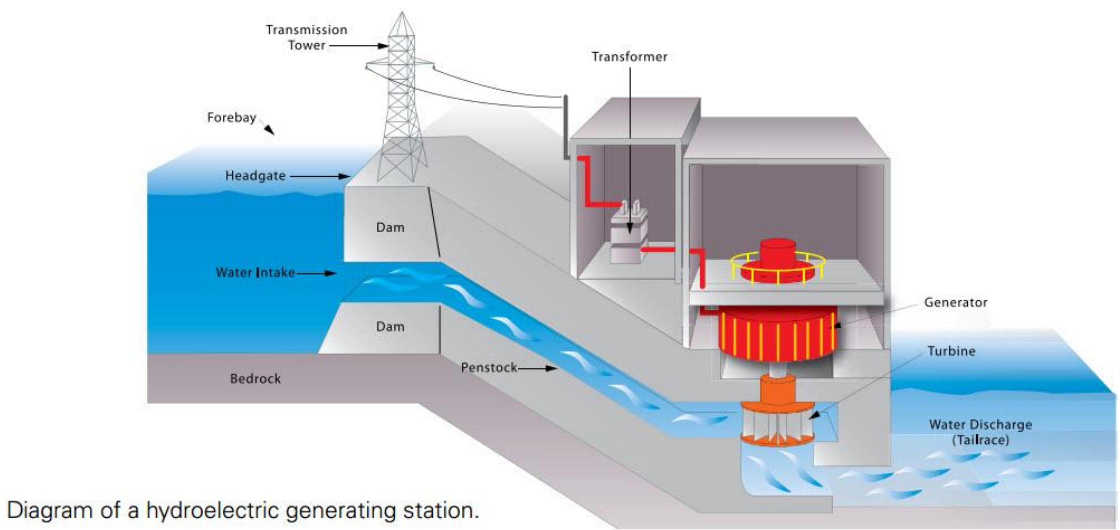


Figure 2.3. Diagram of a hydroelectric generating station. Source: (CERI, 2008)

As a sub-classification to the PHS systems described above, there are other types of storage by pumping.

- Open-loop pumped storage with sea water. The lower reservoir is fed with seawater, for this purpose it requires a steep orography near the coast to reach large hydraulic loads. The main obstacle of this technology is the salt content of seawater. Due to salt corrosion, constant protection and maintenance is required, which makes this technology more expensive; nevertheless, studies have been carried out to use the large hydraulic loads and in this way cause the water to be potabilized and will subsequently be used for its electricity generation (Slocum, Haji, Trimble, Ferrara, & Ghaemsaidi, 2016).

- Closed-loop pumped storage in underground deposits. Water is stored in mines or caves that were abandoned. These deposits must meet sufficient geological properties to prevent infiltration and therefore, losses in storage capacity (Madlener & Specht, 2013).

Models of hydraulic turbines

For years, hydroelectric storage has offered a cost-effective way of providing balance and stability services in the large-scale grid, with better predictability in terms of cost and performance. New hydraulic storage technologies, such as variable speed, give plant owners even more flexibility and faster response times.

For a fixed-speed hydroelectric storage plant, there is a constant and fixed energy requirement to activate the unit and pump excess energy to the highest tank for storage. The pumps have a sense of reverse rotation to the turbines, it could be said that a pump consumes energy from the power grid, and by means of an internal rotation movement transfers it to the water in the form of a higher pressure. On the other hand, pumps such as turbines capture the hydraulic energy of the water by means of a rotation movement, to convert it into electrical energy.

However, pumps such as conventional turbines have a limitation: the power generation process is only efficient under constant operating conditions, thereby wasting great energy potential when fluctuations occur.

At a fixed speed, it is only possible to have one operating point for each hydraulic load and, therefore, its operational flexibility is limited, the pumps can only operate at full power or shut down. With variable operating conditions, both pressure and flow, an electronic turbine speed control system that increases efficiency and energy production is necessary.

In turbine mode, the unit cannot operate with maximum efficiency during partial loading, while variable speed machines allow varying the power consumed in the pumping mode over a range of outputs. The speed modification also allows the turbine to operate with maximum efficiency in a larger portion of its operating band. [Victor, 2019]. The speed is controlled by a frequency converter with a change in discharge or power.

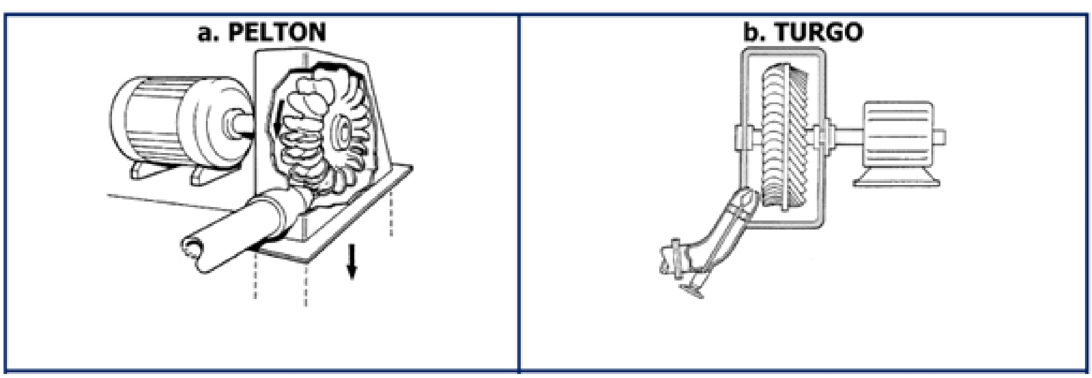
In this way, generating energy under variable hydraulic conditions produces energy for longer periods and a greater hydraulic potential is recovered, providing a more stable and robust electricity supply. In a conventional single-speed turbine pump, the magnetic field of the stator and the magnetic field of the rotor always rotate at the same speed and the two are coupled. In a variable speed machine, those magnetic fields are decoupled.

Hydro turbines are presented in different models; each type of turbine is used according to the need and the way in which the flow rate and the usable hydraulic load are presented as shown in the following table:

Table 2.2. Different models of conventional hydraulic turbines. Source: (RIVERS, 2019)

Types of turbines	Description
Pelton turbine	It is a turbine with transverse flow, with partial admission. It is said that it has spoons instead of shovels or blades. They are designed for large hydraulic

Types of turbines	Description
	loads, but small flows. It is considered an action turbine.
Turgo turbine	It is an impulse type turbine, designed for medium-level jumps. Water carries a low pressure when it passes through the turbine blades. The specific speed of the Turgo impellers is located between the Pelton and Francis turbines. One or more nozzles or injectors can be used.
Francis turbine	For mixed flow and reaction. There are elaborated designs that allow changing the angles of the pallets during operation. Work with jumps and medium flows.
Kaplan turbine	It is a turbine of the axial type that, in addition, has the particularity of varying the angle of the blades while operating. It has been designed to be used in small hydraulic loads, but with large flows. It is a reaction turbine
Propeller turbine	With adjustable valves, as in the previous case, but with the fixed vane angle. Instead of changing the angle, it is possible to change the speed of the impeller.
Banki-Michell or Ossberger turbine	It is a turbine with free deviation, partial and radial admission. It is considered a slow speed turbine by the number of specific revolutions. It has been designed for medium jumps. Unlike most hydraulic turbines, which have an axial or radial flow, in the transverse flow turbine the fluid crosses the blades diagonally. As in a hydraulic wheel, water enters the edge of the turbine leaving inside. After crossing the central opening, it leaves on the opposite side. It is an action machine. When passing twice, a high efficiency is obtained for variable flows, in addition to cleaning the waste rotor. The machine is low speed, suitable for low heights but high flow rates. Thanks to their constructive simplicity, they are usually low-cost machines. All this makes it suitable for small-sized plants (mini-hydraulics).



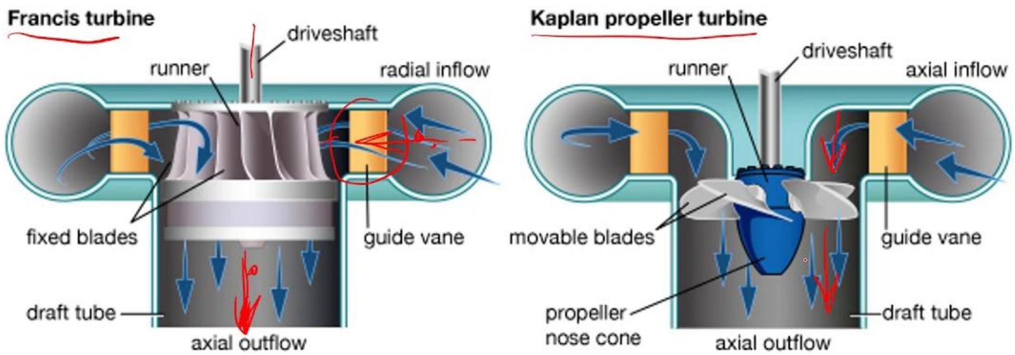


Figure 2.4. Types of hydraulic turbines. Source: (ED, 2019)

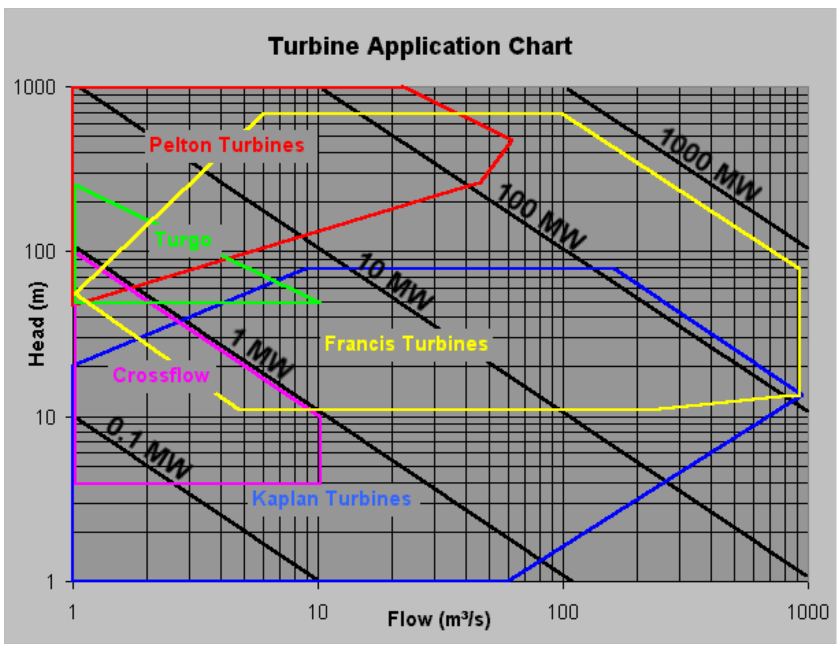


Figure 2.5. Selection of turbine based in head. Source: (RIVERS, 2019)

Typical storage period

When there is a low demand for energy in the electrical system or the production from variable renewable energy sources is high, the excess electricity in the grid is consumed by the pumping system with the aim of bringing water to the highest tank. At periods where the residual demand is the highest, i.e. demand is high and/or production from variable renewable energy sources is low, the water that was stored in the upper tank is released again to the lower tank through a turbine, thus generating the electricity required by the system. A pumped storage project would typically be designed to have 6 to 20 hours of hydraulic reservoir storage for operation.

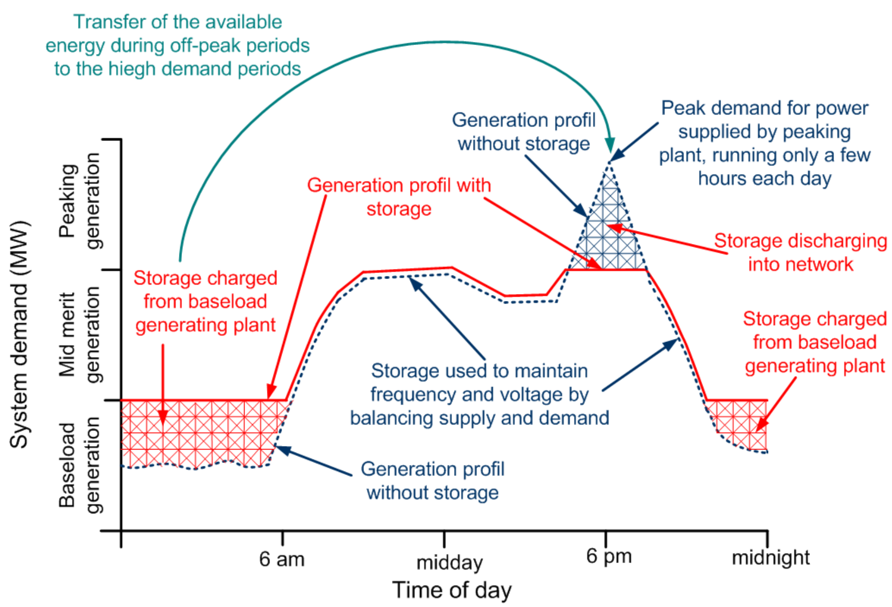


Figure 2.6. Example of a pumped storage operation. Source: (Ibrahim & Ilinc, 2013)

Temporal scales of operation of PHS systems

With respect to very short time scales, from seconds to minutes, there might be needed to compensate for an imbalance of the system and return the frequency and voltage of the grid to its optimum range.

This may include automated responses at the individual turbine scale, but also includes active responses by adjustable generators and fast dispatch. Variable speed units offer faster and wider response ranges in both generation and pumping mode and contribute to better frequency regulation (NGH, 2017).

Whereas synchronous generators are directly and electromechanically coupled to the power grid, modern Variable Renewable Energy sources use software-controlled power electronics to connect to the grid.

Variable Renewable Energy are generally deployed asynchronously, and their displacement of synchronous generators can have an impact on the very short-term (sub-second) stability of the grid.

Synchronous generators, by virtue of their physical spinning mass, provide a natural mechanical inertia that counteracts sudden changes to the grid. Thus, systems with less inertia will exhibit faster rates of frequency change during a perturbation.

The medium scale varies from hours to days and refers to the ability to use alternative modes of production to respond to a transient shock such as the unexpected interruption of a generator. It is often referred to as peaking support or system reserves.

Reserves are used utilized after the automatic frequency response has been used and covers unexpected losses or forecasting errors on the system. This timescale is often dependent on the technical availability and redundancy of alternative options, as well as having the relevant market conditions in place. PHS systems tend to hold large volumes of water and have very high energy-to-power ratios and are thus also well suited to provide long-term services.

The long-time scale extends from days to weeks and is mainly driven by weather system patterns. For example, this includes one-week periods of heating or cooling demands with little wind or weather-driven.

Finally, the very long-time scale encompasses intra and inter-seasonal variability in both energy demand and resource availability. Variable Renewable Energy sources, well as hydroelectric power, exhibit strong seasonal patterns that can result in a mismatch with demand.

For this reason, it is a challenge to foresee the energy resources that can cope with long-term variability, such as during prolonged periods of low winds, prolonged droughts or simply seasonal dry and wet periods.

Both Variable Renewable Energy and hydroelectric power can also have significant inter-annual variations, for example, as a result of the El Niño phenomenon (Hunt, Byers, Riahi, & Langan, 2018). Seasonal pumping storage has been proposed in Brazil to balance seasonal variations and increase total storage efficiency by coupling with conventional cascade systems. In cases where seasonal pumping storage projects reduce spillage or evaporation in cascade systems, it can result in a general energy gain rather than a loss to the system (Hunt, Freitas, & Pereira Junior, 2014).

Regulation ability

PHS is useful for maintaining control in the electricity grid, such as frequency regulation and grid decongestion. Depending on capacity and needs, some hydroelectric plants have functioned as synchronous capacitors to absorb energy from transmission lines that only saturates the grid, since they are not absorbed by the consumer. This operation causes wear on machinery that was not designed for this purpose. PHS adapts to the arbitrage or time shifting, which consists of storing energy at a given time for later use. This service supports the integration of variable renewable energies, since these cannot be programmed to meet demand and their production depends on external and uncontrollable factors, such as weather conditions. The time shift operation also reduces the need for “peak” capacity that is generally more expensive and polluting, such as gas turbine plants.

Demand fluctuates not only in daily or weekly periods, but also seasonally. Until now, the only storage technology capable of providing this service is hydraulic pumping and, potentially, hydrogen storage. According to an IRENA report, 89 percent of the world's pumped hydroelectric capacity is used for time shifting purposes (IRENA, 2017).

Variable renewable power plants, such as solar and wind, can also use storage to keep their production at a compromised level for a specific period (that is, “firm” or constant delivery over a period of time), which allows them to offer capacity-based products. Increasing the capacity (MW) value of renewable projects through energy storage could level the way towards greater matrix diversification and less dependence on fossil fuel generation for reliability purposes.

Table 2.3. Type of services can be provided by PHS. Source (Schmidt, Melchior, Hawkes, & Staffell, 2019)

Service	Can be provided
Energy arbitrage	√
Secondary response	√
Tertiary response	√
Peaker replacement	√
Black start	√
Seasonal storage	√
T&D investment deferral	√
Congestion management	√

As variable renewable energies continue to grow and, in some systems, begin to displace conventional generators, system operators face the challenge of effectively managing the growing uncertainty and variability. As a result, the planning and operations of the energy system are being adapted and updated to add "flexibility" to the system.

Conventional hydropower has traditionally provided flexible power generation, as well as most of the large-scale energy storage through storage of water in tanks. Hydroelectric facilities that incorporate deposits (without pumping capacity) have always provided significant flexibility to the power grid by modulating the output according to demand fluctuations and other generations.

The pumped storage provides a dynamic response by matching the demand curve with the supply of intermittent power plants (dispatch capacity) thus integrating variable renewable power plants into the electricity grid.

Pumping storage is a major consumer of energy; this can help solve the frequency problems associated with other technologies, as well as grid congestion relief.

The operations and technology of pump storage are adapting to the changing requirements that the energy system incurs due to the penetration of variable renewable resources. Variable speed hydraulic pumping systems allow for faster and wider operating ranges, which provides additional flexibility in all time scales, allowing greater penetration of renewable energy and often lowers system costs.

Another benefit of pumped hydro storage arises from the improvement in the profitability of transmission and distribution (T&D) systems, since integrated storage in the grid can lead to greater use of assets. When large amounts of energy are transmitted during periods of less activity for storage purposes, the total energy transmission increases; i.e. more energy transported (kWh) for the same T&D capacity (kVA). Greater use of assets, in turn, can lead to lower T&D rates for the benefit of taxpayers.

By temporarily relieving grid congestion, mitigating equipment overload and extending the useful life of existing T&D equipment, storage helps to defer (and possibly even minimize) intense grid updates and capital expansions. This benefit, in the form of avoided investments, could be quite important since sometimes a relatively small amount of modular energy storage can be used and strategically placed to defer (or completely avoid) a rather expensive and large incremental transmission investment. In summary, pumping storage hydropower might play a key role in the transition to clean energy by supporting intermittent renewable energy, reducing greenhouse gas emissions and providing stability to power grids.

Variable speed pump turbines and ternary systems offer additional grid flexibility by allowing power regulation and load tracking when pumped compared to more conventional fixed speed units, operating at a constant speed and power input for pumping.

The advantage of variable speed over fixed speed pump turbines is that PHS variable speed projects can operate in a wider range, greater efficiency and faster response time. In addition, the variable speed PHS can also adjust its energy consumption during pumping, allowing for better frequency control (Manwaring, 2018).

Ternary pumping storage machines are a unit configuration where pumps and turbines are separate machines connected to the same axis. This means that these units do not need to reverse their direction of rotation to switch between pumping and generation, which allows the turbine and pump to run in parallel, also known as 'hydraulic short circuit'. This offers faster response times and more flexible operations in terms of faster mode times, i.e. the time it takes to move from pumping to generation modes (Pérez-Díaz, Sarasúa, & Wilhelmi, 2014).

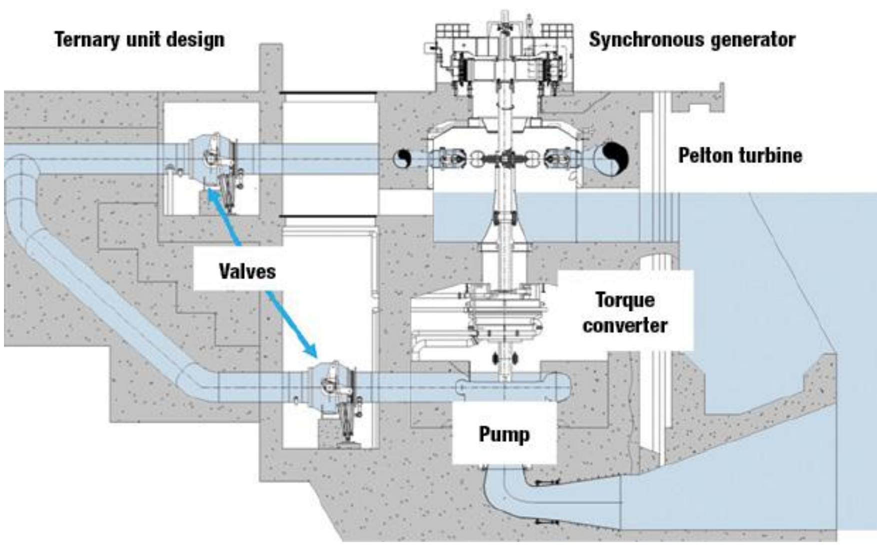


Figure 2.7. Illustration of ternary unit design. Source: (Borgquist, Hurless, & Padula, 2017)

Operation under hydraulic short circuits may also be possible with reversible pump turbines of variable and fixed speed and essentially reduces the time required for the system to return to the optimum frequency (Pérez-Díaz et al., 2014). In terms of discharge time, in reference to how long energy production can be maintained while releasing stored energy, PHS projects can generally generate up to 12 hours (or more in some cases) if the plant is loaded and unloaded for a period of 24 hours for example (day cycle) (EASE, 2016). PHS technology can ramp up to full production capacity within minutes, providing a quick response for peak-load energy supply and making it a useful tool for the following services:

Table 2.4. Applications PHS technology. Source: (EASE/EERA, 2017)

Services of a PHS	Description
Provision of contingency reserve to restore the balance of supply and demand	In generation mode, when one or more generating units of the normal electric supply resources become unavailable unexpectedly. In pumping mode, when there is a sudden drop of load. Requested response time: within 10 minutes. Requested reserve: generally, at least as large as the single largest generation unit.
Provision of regulation reserve	PHS is ready to increase or decrease pumping and generating power as needed and it is used to maintain the grid system frequency at a narrow band around the nominal value by balancing supply and demand. Frequency response is very similar to regulation, but it requires a shorter response time. Since frequency containment or primary control reserve must be capable of being activated within seconds, normally pumped storage plants cannot be applied unless they are already in operation or they are specifically designed for fast activation times. Requested response time: seconds to a few minutes.
Load following	The PHS provides fast ramping capacity in order to respond to a rapid or randomly fluctuating load profile. Expected up- and down-ramp rate: MW/minute. Timeframe: minutes.
Load shifting (energy arbitrage)	The PHS increases the efficiency of system operation by increasing the generation of base load units and decreasing the operation of expensive peaking units.
Black start	The PHS provides an active reserve of power and energy within the grid. It can be used to energize transmission and distribution lines and to provide station power to bring power plants on-line after a catastrophic failure of the grid.
Voltage support	The PHS can provide reactive power to maintain grid voltage within specific limits in order to operate the transmission system in a stable manner.

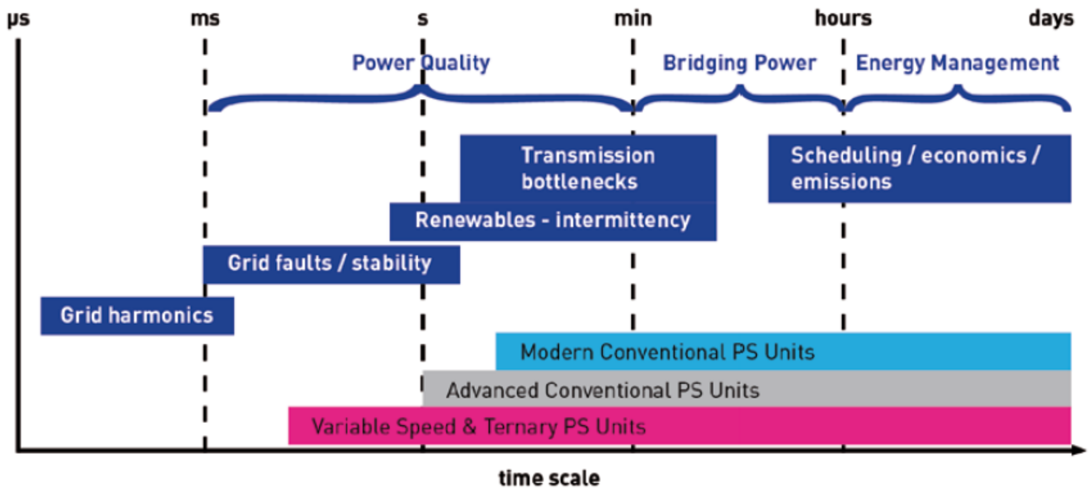


Figure 2.8. Time frames for modern advanced PHS unit regulation. Source: (EASE/EERA, 2017)

While PSH is a proven, reliable technology that currently represents more than 97% of all ES solutions globally, the overall technology continues to advance, and now includes improved efficiencies with modern reversible pump-turbines, adjustable-speed pumped turbines, advanced equipment controls such as static frequency converters and generator insulation systems, as well as innovative underground construction methods and design capabilities. The benefit of these advances is faster response time of which to load follow intermittent renewables more efficiently and cost effectively.

Examples of market standard technologies

Some identified operational projects show us the variability of the application of this technology:

Table 2.5. Comparison of pumped hydroelectric storage. Source: (Development by authors)

Name	Liyang	Veytaux	Iowa Hills	Valhalla	Cultana
Capacity (MW)	1500	480	400	300	225
Storage volume (MWh)	2007	1000		1500	1770
Capital cost (MUSD)	1200		520	543	477
Storage duration (hrs)				5	8
Round-trip efficiency (%)				77	72
Design head (m)	165	56		165	260

Name	Liyang	Veytaux	Iowa Hills	Valhalla	Cultana
Working fluid	Sweet water	Sweet water	Sweet water	Seawater	Seawater
Country	China	Switzerland	USA	Chile	Australia
Status	Operational	Operational	Operational	In construction (2019)	Design (2017)
Reference	("Liyang pumped storage power station," 2020)	(IWP, 2017)	(Ingram, 2016)	(Colthorpe, 2016)	(ARENA, 2017)

Advantage/disadvantage

Energy storage, especially in the form of PHS, has a crucial role in enabling higher levels of variable wind and solar penetration, by adding wide-ranging flexibility services on multiple time scales. The level of carbon-free generation necessary to meet the ambitious climate goals means that PHS will be required to work together with other energy storage technologies, especially batteries, as well as other grid flexibility resources.

By storing electricity, PHS facilities can protect the electrical system from power outages. Together with advanced power electronics, PHS systems can also reduce harmonic distortions and eliminate voltage drops and surges. It is important to remember the definition of harmonic as a sinusoidal component of a periodic wave or quantity (for example, voltage or current) that has a frequency that is an integral multiple of fundamental frequency (IEEE Power and Energy Society, 2014), which for the particular case of Mexico it is 60 Hertz.

Of all types of power generators, peak charge generators typically produce electricity at much higher costs than base charge ones. PHS provides an alternative to peak power by storing cheap base charge electricity and releasing it during peak hours.

PHS facilities provide large electricity capacities, with low operating and maintenance costs, and high reliability.

There are several disadvantages to PHS technology. PHS deployment requires adequate land with a significant elevation difference between the two reservoirs and a significant amount of water resources. Typical PHS installations have a hydraulic height of 200–300 m with volume deposits of the order of millions of m3. The construction of a PHS station generally takes many years, sometimes more than a decade, such as large-scale projects that require of large civil works. Although the cost of operation and maintenance is very low, there is a large initial capital investment in civil construction, which can only be recovered for decades.

Theoretically, both PHS and battery storage can provide similar balancing and auxiliary services, but ultimately, due to their technical characteristics, they are implemented and used differently. The advantage of PHS is cost-effective charging and releasing large amounts of energy, while batteries, flywheels or capacitors are more suitable for short-term incremental balance due to their ability to send energy stored in milliseconds. This highlights its complementarity and the coupling of PHS plants with batteries is also a future path of potential growth.

Environment

Many of the environmental impacts of the construction and operation of a PHS facility can be mitigated, although they have associated cost implications. The use of existing reservoirs or the use of closed-loop systems outside the river can further reduce impacts, as well as the use of other innovative configurations, including the use of oceans/seawater such as the lower reservoir or underground reservoirs (Rogner & Troja, 2018).

Environmental impacts have caused many cancellations of proposed PHS projects. The conventional construction of PHS sometimes involves damming a river to create a reservoir. The blockage of natural water flows disrupts the aquatic ecosystem and flooding of previously dry areas can destroy terrestrial wildlife habitats and significantly change the landscape.

Pumping can also remove sediments at the bottom of the deposits and deteriorate the water quality. The PHS operation can also catch and kill fish. There are technologies to mitigate ecological impacts. Fish detection systems could be installed to minimize fish entrapment and reduce fish death. Water inlet and outlet could be designed to minimize turbulence.

An oxygen injection system could also compensate for the potential loss of oxygen due to water heating due to pumping. In some cases, the PHS system can serve to stabilize the water level and maintain water quality (Yang & Jackson, 2011). The possible impacts of PHS projects are site specific and should be assessed on a case-by-case basis. Governments generally require an environmental impact assessment before approving a PHS project.

Any potential environmental impacts associated with construction and operation need to be considered and mitigated, including those immediately associated with the site, as well as downstream.

Environmental impacts during operation of pumped hydro are minimal. However, the ecology within the reservoirs will need to adapt to frequently changing water levels, reducing diversity in the system especially within fringing communities.

In all pumped hydro systems, water is re-used repeatedly, extracting maximum value from the resource. Nevertheless, depending on the configuration of the pumped hydro project, there may be an ongoing demand for water to top up the storages to counter evaporation.

Research and development

Fixed speed pump turbines machines. Most of the pumping storage projects under development worldwide are of this kind. There are several reasons for this, including the costs of additional equipment for variable speed, as well as the lack of recognition of the additional services provided by the equipment upgrades i.e. the opportunity to provide ancillary services to the market (EC, 2016).

The traditional design of the fixed speed machines is the reversible Francis pump turbine of one stage, which acts as a pump in one direction and as a turbine in the other. Although this technology is proven and has worked well for decades, there are limitations to its performance. While design improvements over the years have improved unit efficiency and output power, frequency regulation in pump mode is not possible with single speed equipment. In turbine mode, the unit cannot operate with maximum efficiency during partial loading. Pure reversible turbine equipment requires stopping and reversing the flow of water, this can take 20 to 30 minutes per cycle.

Reversible machine sets consist of a motor-generator and a reversible pump-turbine that functions as a pump or as a turbine, depending on the direction of rotation. With a wide range of specific speeds, pumping turbines can be installed at sites with heights of less than 50 to more than 800 m, and with unit capacities ranging from less than 10 to more than 500 MW (VOITH, 2013). At a fixed speed it is only possible to have an operating point for each hydraulic load and therefore its operational flexibility is limited, the pumps can only run at full power or shut down.

Variable speed pump turbines machines allow varying the power consumed in the pumping mode in a range of outputs. The speed modification also allows the turbine to operate with maximum efficiency in a larger portion of its operating band (Victor, 2019).

The key to the flexibility of the pumped storage hydroelectric power plant is the speed at which the installation can go from energy storage to power generation. Variable speed units can increase the weighted efficiency in turbine mode by an average of 1% and the pumping power adjustment range by 30% (GE, 2019).

By variable speed pump turbines machines, start and stop switch of the pump unit is replaced by a regulator, which increases efficiency and flexibility, in this kind of machines the speed is controlled by a frequency converter, and therefore this kind of machines for hydroelectric storage, allows to store large amounts of available electricity immediately, giving the grid greater flexibility, predictability and efficiency.

Another important advantage of variable speed pump turbine machines for storage technology is the adjustment of the frequency of the power grid to provide grid stability and frequency regulation. Therefore, variable speed technology adapts well to the rapid growth of renewable energy sources by offsetting fluctuations and are among the most adaptable production systems.

The variable speed pump turbines equipment is designed in a ternary configuration that will consist of 3 pairs of units. Each pair will include a pump and a turbine with motor and a generator, respectively. Ternary assemblies consist of a motor-generator, a separate turbine (typically Francis or Pelton) and a pump assembly.

As separate hydraulic machines, the rotation direction of the motor-generator can be the same in both operating modes. This operation offers the best response in terms of the speed that is carried out with the torque converter that allows a rapid change between the turbine and pump mode. There is a total regulation capacity both in the operation of the turbine and in the pump mode from 0% to 100% of the output of the unit (EC, 2016). By using hydraulic short circuit, the unit can generate energy while pumping water for storage. This provides an immediate response to changing energy needs.

By using this arrangement on reversible machines, almost the entire power range of the plant is available. In addition, this application helps to control the flow of energy to the grid. The principle of this mode of operation is based on the idea that only the difference between the constant load of the pump and the flexible output of the turbine, both rotating on a common axis, in this case the power generation should be consumed by the grid.

A major advantage of the ternary design is that the direction of rotation of the motor-generator is the same for both operating modes (that is, there is no change in the direction of the water flow to change from pumping to generator). The impacts of hydraulic transients are significantly reduced, and the machine can quickly move from full pumping mode to full generation mode, unlike a reversible machine, which must stop before restarting in the opposite direction (Koritarov & Guzowski, 2013).

Another advantage of a ternary unit is its ability to use different turbine technologies for the pump and the turbine; in particular, use a Pelton turbine for high-rise installations.

On the other hand, there are also some disadvantages of ternary design. In general, it will have a higher first cost because the hydraulic design is more complex and because more equipment is required. The hydroelectric plant will also be larger due to the additional equipment and that additional equipment will likely result in higher operating and maintenance costs.

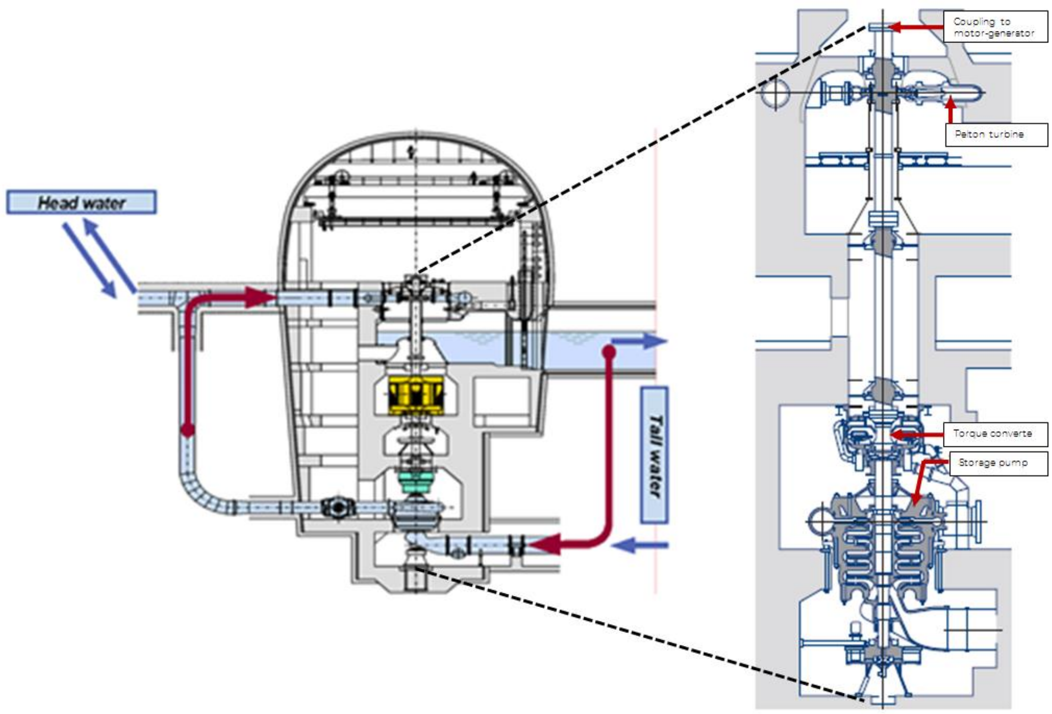


Figure 2.9. Ternary units demonstrating hydraulic short-circuit operation. Source: (Koritarov & Guzowski, 2013)

Prediction of performance and costs

Modern pumped storage hydropower project costs will vary based on site-specific conditions such as site geology, water availability, access to the transmission grid, and overall construction cost.

A feasible project site would include an approximate cost estimate range from $1,500/kilowatt (kW) to $2,500/kW, based on an estimated 1,000 MW sized project.

A smaller project typically does not have the same economies of scale and could result in higher unit costs (in $/kW) than a large project. These costs are representative for all project aspects except transmission interconnection charges, which can range from very minor charges to several hundred million dollars, based on factors such as existing line capacity or size and distance of new lines (Manwaring, 2018).

Although PHS projects can take 3 to 6 years from the beginning of construction to commissioning, they last long in terms of useful life, approximately 60 to 100 years (Koritarov et al., 2014).

Looking towards 2030, the installed capacity of PHS is expected to increase by about 78,000 MW, and much of the expansion is predicted to take place in China (up to 50,000 MW) (Rogner & Troja, 2018).

The main driver of the PHS expansion in China is the increased need of flexibility of the system, particularly the need to integrate photovoltaic wind and solar energy as well as the displacement of coal-based plants.

In Europe, PHS capacity is expected to grow modestly, between 8,000-11,000 MW by 2030, driven by the need for greater flexibility due to the growth of Variable Renewable Energy. However, in many regions, the PHS growth barriers are the sources of uncertain income since the long-term commercial argument for energy arbitration is uncertain and the alternative income sources of the markets for capacity, balance and auxiliary services develop slowly (Masiello, Roberts, & Sloan, 2014; West & Vaughan, 2018).

Non-powered dams also represent great untapped potential. It is estimated that 12,000 MW of capacity from this source could be added in the USA, some of which could be used for PHS. It would allow developing projects at a lower cost, with less risk and in a shorter term and without some of the environmental challenges previously affected. This type of conversion also works with conventional hydroelectric plants. The Los Angeles Department of Water and Energy is considering equipping the Hoover Dam with a pipe and a pumping station that would help regulate the flow of water through the dam's generators, sending water to the top to help manage electricity in times of greatest demand (Blakers, Stocks, Lu, Anderson, & Nadolny, 2017; Penn, 2018).

The PHS is considered to have technological maturity. Consequently, the performance and costs of PHS will not have a variation in the period 2020-2050.

Uncertainty

The round-trip efficiency, energy losses during storage, and the total number of cycles will have uncertainty due to the physical properties of water and electromechanical characteristics of PHS. The other technical data of PHS will not have uncertainty because PHS has technological maturity.

Conversely, the costs of lead-acid batteries will have uncertainties due to the oil price, investment or solar plants, plant size, and storage capacity.

The capital costs of PHS system depend on the hydrological basin and upper and lower reservoir. The account is to be taken of the capacity of reservoirs and the high between both, too. When the PHS system is applied in hydroelectric dams, the uncertainty is reduced significantly.

Data for the quantitative description

PHS contains a variety of ranges and applications, because the amount of energy stored is directly proportional to the size of the reservoir, and the difference in heights between reservoirs. These can vary significantly depending on the characteristics on the ground for their construction, to reduce costs in the construction of the reservoirs for example, however many design possibilities are technically possible, either with man-built reservoirs or by taking advantage of other reservoirs not created for that purpose such as mines or natural caves.

In the past, most PHS plants were used to balance the discrepancy between generation and load during times of high and low demand in power systems with many base load power plants. With the penetration of variable renewable energies in electrical systems this traditional form of operation must be adapted to provide additional flexibility options to balance the operation of the system.

For this situation a wide range of capacity is found in the literature, although in general its application refers to medium and long period storage and discharge times that range from hours to days.

Table 2.6. Features of pumped hydroelectric storage. Source: (EASE/EERA, 2017)

<table>
<tr><td rowspan="6">General performances</td><td>Output/Input</td><td>50 to 500 MW</td></tr>
<tr><td>Most Typical values</td><td>200 to 350 MW</td></tr>
<tr><td>Storage capacity</td><td>>> 8 hours full load</td></tr>
<tr><td>Head Range</td><td>75 to 1500 m</td></tr>
<tr><td>Single stage reversible pump-turbine</td><td>~100 to ~600 m</td></tr>
<tr><td>Cycle efficiency</td><td>> 80%</td></tr>
<tr><td rowspan="4">Reaction Time</td><td>50% to 100% Generation</td><td>~15 s</td></tr>
<tr><td>0% to 100% Generation</td><td>< 2 min</td></tr>
<tr><td>0% to 100% Pumping</td><td>~ 1 min (TS) / ~4 min (VS)</td></tr>
<tr><td>100% Generation to 100% Pumping</td><td>~ 1 min (TS) / ~8 min (VS)</td></tr>
<tr><td rowspan="3">Ancillary Services</td><td>Production adjustment range</td><td>15% (TS) / 25% (VS) to 100%</td></tr>
<tr><td>Pumping power adjustment range</td><td>~0% (TS) / 70% (VS) to 100%</td></tr>
<tr><td colspan="2">Reactive power, Primary frequency response, Black start capability</td></tr>
</table>

VS = variable-speed, TS = Ternary Set

Table 2.7. Quantitative description. Source: Own elaboration.

PARAMETERS\REFERENCE	(Victor, 2019)	(Manwaring, 2018)	(EC, 2016)	(EASE, 2016)	(Lazard, 2016)
Energy storage capacity for one typical unit (MWh)	4000		3000	100	800

PARAMETERS\REFERENCE	(Victor, 2019)	(Manwaring, 2018)	(EC, 2016)	(EASE, 2016)	(Lazard, 2016)
Output capacity for one unit (MW)	500	1000	600	10 – 3000	100
Input capacity for one unit (MW)	500	1000	600	10 – 3000	100
Power generation time (hrs)	8		5	10	8
Round trip efficiency AC-AC (%)	77		75	70 – 85	80 – 82
- Charge efficiency (%)	75 – 85				75 – 85
- Discharge efficiency (%)	75 – 85				75 – 85
Energy losses during storage (%/period)	10 – 15				15 – 25
Forced outage (%)	10%	3.0%	4.5%		5%
Planned outage (weeks per year)	5.2	1.56	2.34		2.5
Technical lifetime (years)	40 - 100	25 – 100		> 80	20 – 100
Construction time (years)	5 – 10	3 – 10			3 – 7
Lifetime (total number of cycles)					7000
Specific energy (Wh/kg)				0.5 – 3	
Specific investment (M$/MWh)	0.285 – 0.452	0.170 – 0.250	0.201	0.446 – 1.674	0.238 – 0.350
- capacity component (M$/MW)				0.400 – 1.500	
Fixed O&M ($/MWh/year)	5,700				2000 - 4000

Data sheet

	Pumped Hydro Storage								
	2020	2030	2050	Uncertainty (2020)		Uncertainty (2030)		Note	Ref
Energy/technical data				Lower	Upper	Lower	Upper		
Form of energy stored	Mechanical / hydraulic								
Application	Energy Shifting/ 8h								
Energy storage capacity for one unit (MWh)	8500	8500	8500	8500	8500	8500	8500		[1]
Output capacity for one unit (MW)	1060	1060	1060	1060	1060	1060	1060		[1]
Input capacity for one unit (MW)	1060	1060	1060	1060	1060	1060	1060		[1]
Round trip efficiency AC-AC (%)	78	80	80	68	82	68	82	A	[2], [3], [4], [5], [6], [7]
- Charge efficiency (%)	88	89	89	83	90	83	90		
- Discharge efficiency (%)	88	89	89	83	90	83	90		
Energy losses during storage (%/day)	0.01	0.01	0.01	0.00	0.02	0.00	0.02		[5]
Auxiliary electricity consumption (% of output)	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01		
Forced outage (%)	2	2	2	2	2	2	2		[3]
Planned outage (weeks per year)	1	1	1	1	1	1	1		[3]
Technical lifetime (years)	60	60	60	60	60	60	60	A	[2], [4], [6]
Construction time (years)	5	5	5	5	5	5	5	A	[3], [7]
Lifetime (total number of cycles)	33250	33250	33250	26100	40300	26100	40300		[7]
Regulation ability									
Response time from idle to full-rated discharge (sec)	120	120	120	120	120	120	120		[8]
Response time from full-rated charge to full-rated discharge (sec)	300	300	300	300	300	300	300		[8]
Financial data									
Specific investment (MUSD 2020 per MWh)	0.128	0.128	0.128	0.070	0.349	0.070	0.349	B	[1]
-Energy component (MUSD/MWh)	0.023	0.023	0.023	0.005	0.1	0.005	0.1	C	[1]
-Capacity component (MUSD/MW)	0.84	0.84	0.84	0.525	2	0.525	2	D	[1]
Fixed O&M (kUSD2020/MW/year)	5.1	5.1	5.1	2.2	10.2	2.2	10.2		[9]
Variable O&M (USD2020/MWh/year)	0.242	0.242	0.242	0.209	0.924	0.209	0.924		[9]
Technology specific data									
Specific investment (USD2020/MW)	1.02	1.02	1.02	0.57	2.80	0.57	2.80		[1]

Notes

A. Data average with data of the references
B. This data is interpreted within the IRENA tool as: "Total Invest per usable kWh storage", and is verifiable as a result of: Energy Storage + Power Conversion/Usable Storage Capacity
C. This data is interpreted within the IRENA tool as: "Energy Installation cost". But also estimated by: Total Storage Invest/Usable Storage Capacity
D. This data is interpreted within the IRENA tool as: "Power Installation cost". but also estimated by: Total conversion Invest/Installed Conversion Power

The references in data sheet can be found in the quantitative data sheet file that supplements the qualitative technology description ("PHS.xlsx" file) as well as in "Appendix B references of datasheets"

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2.2 Lithium-ion batteries

Brief technology description

"First introduced by Sony Corporation in the early 1990s, rechargeable Li-ion batteries have rapidly become the most important technology for mobile consumer electronics" (IRENA, 2017). A lithium-ion battery or Li-ion battery (LIB) can store electric energy as chemical energy, and non-rechargeable and rechargeable LIBs are commercially available. The non-rechargeable LIBs have long shelf-life and low self-discharge rates and are typically fabricated as small button cells for e.g. portable consumer electronics, arm watches and hearing aids. Rechargeable LIBs are applied in all kinds of consumer electronics and is currently entering new markets such as electric vehicles and large-scale electricity storage. (Danish Energy Agency-ENERGINET, 2019). The rechargeable LIBs can be used to supply system level services such as a variety of operations including frequency regulation, load following, voltage support, time shifting, capacity firming of renewables etc., as well as for local electricity storage at individual households. For this reason, this section only focuses on rechargeable LIBs to supply system level services.

A LIB contains two porous electrodes separated by a porous membrane. A liquid electrolyte fills the pores in the electrodes and membrane. By convention, the negative and the positive electrodes are also called the anode and the cathode respectively. Most common lithium ion batteries (LIB) contains a graphitic anode (mesocarbon micro beads, MCMB), a cathode (lithium metal oxide or phosphate e.g. LiCoO2) and the electrolyte consisting of a solution of a lithium salt (e.g. LiPF6) in a mixed organic solvent (e.g. ethylene carbonate–dimethyl carbonate, EC–DMC) embedded in a separator felt (Scrosati & Garche, 2010)

Li-ion batteries exchange lithium ions (Li+) between the anode and the cathode, which are made from lithium intercalation compounds. Both the positive and negative electrode materials can react with the Li+ ions. As the lithium ions move from one host to another upon charge and discharge.

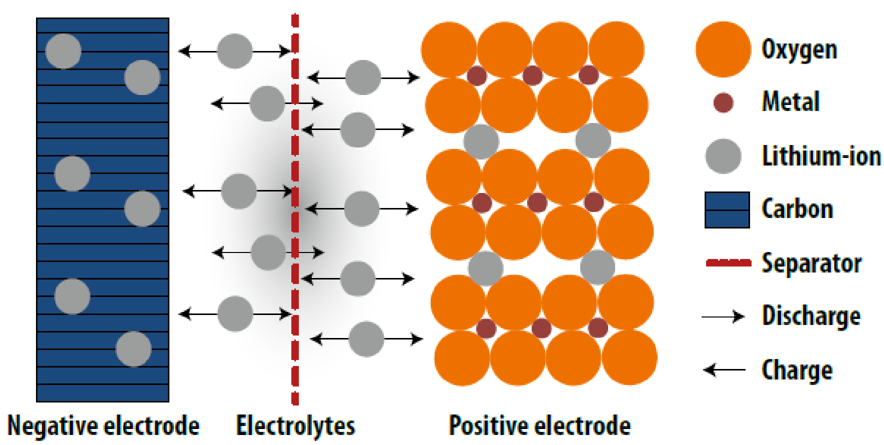

Figure 2.10. Operating principle of a lithium metal oxide cathode and carbon-based anode lithium-ion cell. Source: (IRENA, 2017)

When the two electrodes are connected via an external circuit the battery starts to discharge. During the discharge process electrons flow via the external circuit from the negative electrode to the positive, at the same time lithium ions intercalated in graphite anode ($LixC_6$) is taken out, moved through the electrolyte and finally intercalated in the host material in the cathode (lithium metal oxide, here Li(1-x) CoO_2). The chemical bond between the cathode material and lithium is stronger than that between anode material and lithium. Thus, the chemical energy stored in the battery is reduced. The excess energy is released as electrochemical potential during discharge. It drives one electron for each Li+ ion moved from anode to cathode, through the external circuit. On the contrary, during the charging process, electrical energy is provided to drive lithium ions from cathode to anode, increasing the chemical energy of the system (DTU Energy, Department of Energy Conversion and Storage, 2019).

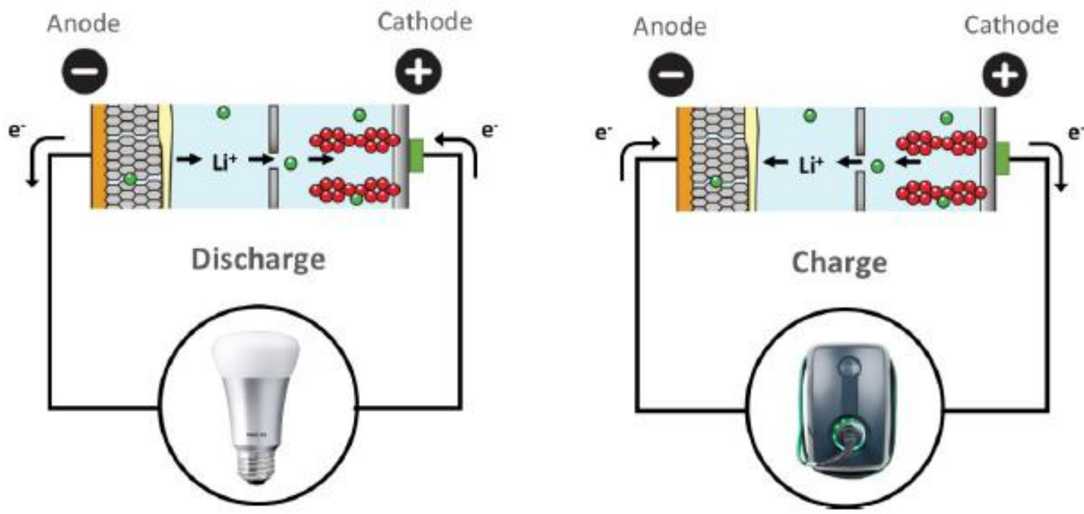

Figure 2.11. Schematic diagram of a LIB system in charge and discharge mode. During discharge the green Li+ ions moves the negative electrode (left side) to the positive electrode. The process is reversed during charge mode (right side). Source: (Danish Energy Agency-ENERGINET, 2019)

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 (also known as the electromotive force: EMF) that is 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) (Danish Energy Agency-ENERGINET, 2019).

The extent to which lithium ions can migrate from one electrode to another during charge/discharge processes is often referred to as state of charge (SOC)/depth of discharge (DoD). This is often controlled during battery operation to maintain structural stability of electrode materials i.e. maintain the cyclability (DTU Energy, Department of Energy Conversion and Storage, 2019). In other words, 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 (Ah) and depends on the type and amount of material in the electrodes. Overcharging, or prolonged storage at high SOC also accelerates degradation (Danish Energy Agency-ENERGINET, 2019).

Li-ion batteries have the advantage of high specific energy, as well as high energy and power density relative to other battery technologies. They also exhibit a high power discharge capability, high round-trip efficiency (more than 90%) , a relatively long lifetime and a low self-discharge rate (IRENA, 2017). Issues relating to the thermal stability and safety of Li-ion batteries relate to chemical reactions that release oxygen when lithium metal oxide cathodes overheat. This "thermal runaway" may cause leaks and smoke gas venting and may lead to the cell catching fire. While this is an inherent risk of Li-ion batteries, it can be triggered by external non-design influences such as external heat conditions, overcharging or discharging or high-current charging. Therefore, Li-ion Battery energy storage systems (BESS) contain integrated thermal management and monitoring processes, and much effort is being placed on their improvement (IRENA, 2017).

Lithium-ion chemistries

While Li-ion batteries are often discussed as a homogeneous group, this is far from reality. The various material combinations (i.e. chemistries or sub chemistries) of Li-ion BESS yield unique performance, cost and safety characteristics. The chemistry choice often relates to the desire to optimize the BES system to meet various performance or operational objectives, and such considerations may lead to a different electrode (or electrolyte) material selection. For example, some Li-ion BES systems may be designed for applications where high power or high energy density is required, while for other applications prolonged life or the lowest capital cost possible may be the goal (IRENA, 2017).

A wide range of materials and combinations has been researched for application in anode, cathode or electrolytes of BES systems, and research activities are ongoing. Each set-up has its own economical, electric performance and safety characteristics.

Table 2.1. Comparison of lithium-ion chemistry properties. Source: (IRENA, 2017)

Key active material	Lithium nickel manganese cobalt oxide	Lithium manganese oxide	Lithium nickel cobalt aluminum	Lithium iron phosphate	Lithium titanate
Technology short name	NMC	LMO	NCA	LFP	LTO
Cathode	$LiNi_xMn_yCo_{1-x-y}O_2$	$LiMn_2O_4$ (spinel)	$LiNiCoAlO_2$	$LiFePO_4$	Variable
Anode	C (graphite)	C (graphite)	C (graphite)	C (graphite)	$Li_4Ti_5O_{12}$
Safety	3	3	2	4	4
Power density	3	3	4	3	3

Key active material	Lithium nickel manganese cobalt oxide	Lithium manganese oxide	Lithium nickel cobalt aluminum	Lithium iron phosphate	Lithium titanate
Energy density	4	3	4	2	2
Cell costs advantage	3	3	2	3	1
Lifetime	3	2	4	4	4
BES performance	2	2	2	4	4

1. Regular, 2. Good, 3. Very good, and 4. Excellent

Nickel-manganese-cobalt (NMC) cells are a common choice for stationary applications and the electromobility sector. These types of cells emerged from research, which, for cost reasons, aimed to combine cobalt with other less expensive metals while retaining structural stability (Yabuuchi & Ohzuku, 2003). The NMC cathode material provides a good combination of energy, power and cycle life. NMC cells have better thermal stability than LCO cells due to their lower cobalt content (IRENA, 2017).

Lithium manganese oxide (LMO) cells have high power capabilities and have the advantage of relying on manganese, which is about five times less expensive than cobalt. LMO cells has high-current discharging capabilities; LMO cells, however, have a lower energy performance and only moderate life cycle properties (Thackeray, 2004) These disadvantages may have an impact on the attractiveness for stationary applications, and the BES systems often apply a blend of NMC and LMO cells. The NMC/LMO-combined BES system provides a balance between performance and cost (IRENA, 2017).

Lithium nickel cobalt aluminum (NCA) battery chemistries have an increased use in the mobility market (e.g. notably, in Tesla Motors EVs). NCA cells and their BES systems feature a higher energy density than NMC-based Li-ion batteries, with the additional advantage that aluminum increases performance and is more cost effective than cobalt. Higher voltage operation of NCA cells leads to the degradation of electrolytes, and research continues to tackle this challenge (Krause, Jensen, & Chevrier, 2017).

The olivine crystalline structure of the lithium iron phosphate (LFP) chemistry ensures that it has better thermal stability compared to other Li-ion cells, and, while they still require single-cell management systems, LFP cells may be marketed as “inherently safe”. The technology possesses relatively high-power capability, the environmental advantage of an inexpensive and non-toxic cathode material and a long lifetime. These characteristics, as well as the relative low self-discharge rate, makes the LFP BES system a very attractive technology for stationary applications (Stan, Stroe, Swierczynski, & Teodorescu, 2014). The LFP BES system has the disadvantage, however, of a lower-rated cell voltage and, hence, lower achievable energy density due to the lower electrical and ionic conductivity of the material structure (IRENA, 2017).

Even though graphite remains the most common anode material in Li-ion cells, the utilization of the spinel structure of lithium titanate (LTO) is gaining traction due to some advantages over graphite that may be relevant to stationary applications. LTO cells exhibit benefits in terms of power and chemical stability, while the increased ion agility in the LTO structure enables fast charging (i.e. high rate operation). LTO cells are very stable thermally in the charge and discharge states (Scrosati & Garche, 2010). Due to the higher reference potential of titanate compared to graphite, the cell voltage is reduced to approximately 2-2.5 volts, thus lowering its maximum energy density, although it is still higher than batteries of lead acid and nickel-cadmium. LTO is inherently safer compared to other Li-ion technologies. The LTO anode high potential prevents issues that relate to electrolyte material decomposition, which can result in the growth or breakdown of the solid electrolyte interphase and its related tendency to overheat and see capacity fade and other ageing issues. Their properties make LTO the most durable Li-ion technology so far, and extremely high cycle lifetimes of 20,000 equivalent full cycles or more can be reached. Due to a low worldwide production volume, however, cell prices remain high (IRENA, 2017).

Components in a lithium-ion battery energy storage system

In LIB storage systems battery cells are assembled into modules that are assembled into packs. The battery packs include a Battery Management System (BMS). The BMS is an electronic system that monitors the battery conditions such as voltage, current, and temperature and protects the cells from operating outside the safe operating area. A Thermal Management System (TMS) regulates the temperature for the battery and storage system. The TMS depends on the environmental conditions. Further an Energy Management System (EMS) controls the charge/discharge of the grid-connected LIB storage from a system perspective. Depending on the application and power configuration the power conversion system may consist of one or multiple power converter units (DC/AC link). Value generation and profit is created by selling the services to grid Transmission System Operators (TSOs). 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.

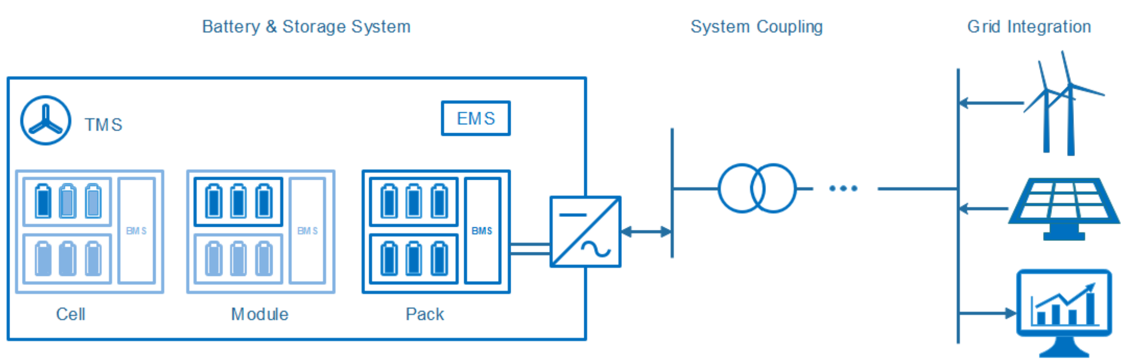

Figure 2.12. Schematic drawing of a battery storage system, power system coupling and grid interface components. Source: (Danish Energy Agency-ENERGINET, 2019)

The advantageous characteristics and the promising avenues to further improve the key characteristics of Li-ion batteries have made them the dominant battery technology of choice for the portable electronics and electromobility markets. As the costs of Li-ion BES systems decline, they are increasingly becoming an economic option for stationary applications, and their presence in that segment is increasing (IRENA, 2017).

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 described in the section: "Brief technology description"

Energy efficiency and losses

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/passing the internal resistance Ri in the LIB. The voltage change ΔU can be described using Ohms law:

$$\Delta U = U - EMF = R_i I$$

and the loss in the internal resistance is defined as:

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

This Equation 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% (Schimpe, et al., 2018).

Unwanted chemical reactions 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. The standby loss is the sum of the energy losses during standby due to self-discharge and power consumption in the balance of plant (BOP) components (Danish Energy Agency-ENERGINET, 2019).

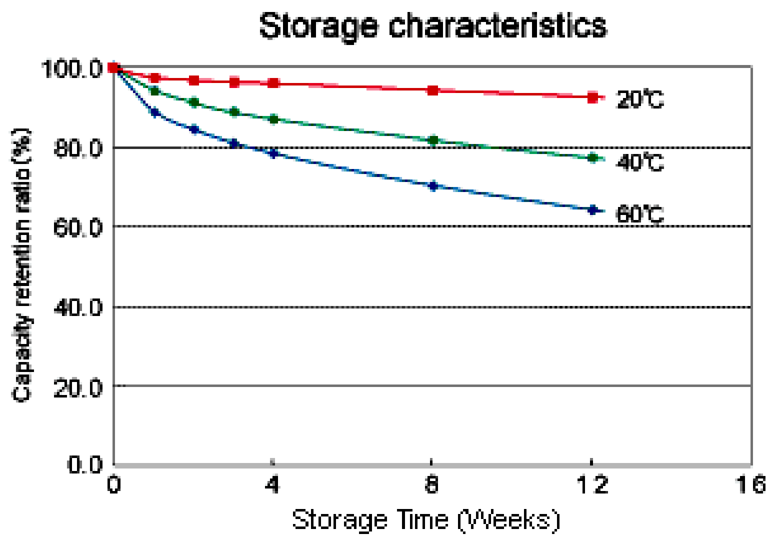

Figure 2.13. Remaining charge capacity for a typical LIB as function of storage time. Source (Danish Energy Agency-ENERGINET, 2019)

Besides the self-discharge in the cell, a LIB electricity storage system requires power to operate the auxiliary BOP components. The BOP components include the inverter, BMS, EMS and TMS. The relative energy loss to the BOP components depends on the application, and operation strategy, and it is important to minimize their power consumption. The standby loss is the sum of the energy losses during standby due to self-discharge and power consumption in the BOP components (Danish Energy Agency-ENERGINET, 2019).

The conversion roundtrip efficiency of the LIB cell is the discharged energy divided with the charged energy.

$$\eta_{Conversion} = \frac{E_{Discharge,AC}}{E_{Charge,AC}}$$

The battery conversion efficiency decreases with increasing current since the P_{loss} increases, as shown in the figure below. 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.

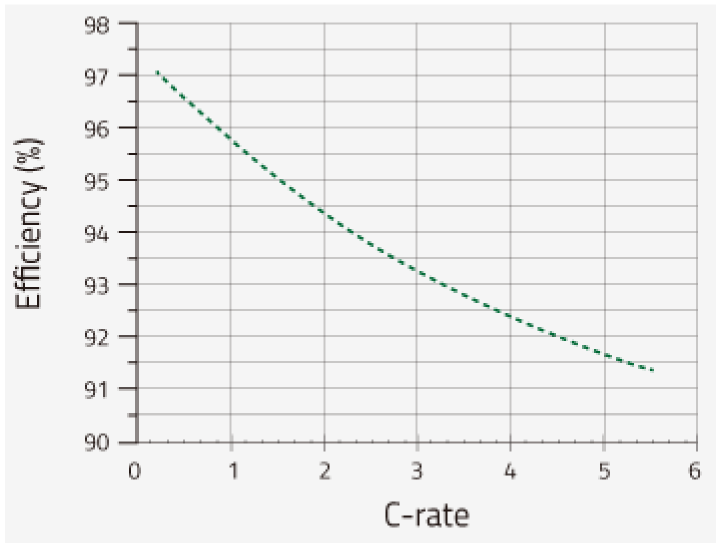

Figure 2.14. Conversion round trip efficiency vs C-rate for one of Kokam's NMC-based lithium polymer batteries. Source: (L. Kokam Co.)

The total roundtrip efficiency η_{Total} further includes the standby losses:

$$\eta_{Total} = \frac{E_{Discharge,AC}}{E_{Charge,AC} + E_{stb}}$$

Here E_{stb} denotes the energy required from the grid to continuously operate BOP and maintain state of charge. The various types of losses heavily dependent on the application.

The total roundtrip efficiency for a typical Li-ion BESS is around 80 % (Fathima & Palanisamy, 2018). Lazard uses an estimate of 85% (Lazard, 2017). 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. (Danish Energy Agency-ENERGINET, 2019).

While the central round-trip efficiency estimate of Li-ion technologies (i.e. a key advantage) ranges between 92% and 96% for IRENA in its 2017 report (IRENA, 2017).

Typical characteristics and capacities

In general, batteries have advanced technologically features to be able to offer adequate capacities for various services of the electrical network in capacity ranges of several MW. An advantage due to the modularity of the technology that gives it flexibility to adapt to a wide range of capacities and operating conditions.

The battery pack without the BMS, that holds the batteries is called a rack. The energy per rack is typically 60-166 kWh and the size is e.g. 415mm x 1067 mm x 2124 mm (W x D x H) for a 111kWh rack from Samsung SDI and 520 mm x 930 mm x 2200 mm (W x D x H) for a 166.4 kWh rack from LG Chem . The weight of the Samsung SDI rack is 1170 kg. For the LG Chem system the weight is 1314 kg. This gives an 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 (Danish Energy Agency-ENERGINET, 2019).

Typical storage period

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. 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 (Danish Energy Agency-ENERGINET, 2019).

Until now the majority of the current LIB systems have been deployed to provide frequency response with a service duration ranging from seconds to minutes, battery 'plants' have grown big enough to deliver time-shift of energy on a bulk scale, this application requires batteries to handle long discharges at lower power levels (<0.5C). Li-ion technology is a good match for renewable power generation. The main reason – because it's extremely flexible. Initially, they were deployed to perform the fast reactive renewables smoothing and firming (short term response; seconds-minutes) (Researchinterfaces, 2018).But more recently, the systems are increasingly used for long scheduled storage in renewables, like a time shifting with typical storage periods of a few hours (long term response) (Schimpe, et al., 2018) (Researchinterfaces, 2018).

Regulation ability

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

The competitive installation cost (outlined below) makes grid-connected LIB BESS (Battery Energy Storage System) suitable for a broad range of applications and the fast response time enables the use of BESS for a broad range of primary control provisions (Danish Energy Agency-ENERGINET, 2019):

- 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 according to data recorded in the United States Department of Energy (US DOE., 2019).
- Deferred or avoided substation upgrade, in this way the BESS can help defer expensive upgrades of the transmission and distribution network.
- Peak load shaving, where the BESS provides or consumes energy to reduce peaking in a power system.
- Renewable integration, e.g. time or load shifting of intermittent renewable power.
- Energy cost savings e.g. reduce peak energy generation/purchases or shift off-peak wind generation to peak.

- Transmission congestion relief, where locally deployed BESS reduces the load in the transmission and distribution system.
- Black start
- Regulation and voltage control are suitable for reducing voltage deviations in distribution networks and regulate active and reactive power thereby improving the network voltage profile.
- Power quality and network reliability, by reacting immediately after a contingency.
- Spinning reserves, this can improve the integration of renewable energy because it reduces the events triggering the protections of the inverters.

Table 2.2. Type of services probably can be provided by Li-ion battery. Source: (Schmidt, Melchior, Hawkes, & Staffell, 2019)

Service	Can be provided
Energy arbitrage	√
Primary response	√
Secondary response	√
Tertiary response	√
Peaker replacement	√
Black start	√
T&D investment deferral	√
Congestion management	√
Bill management	√
Power reliability	√

Examples of market standard technologies

Several companies have experience in using Li-ion batteries in the utility-scale level and grid scale turnkey systems are commercially available from a wide range of suppliers.

Upon completion by December 2017, the largest grid-scale LIB storage system identified was the Neoen's Hornsdale Wind Farm which features a 100MW/129MWh, providing peak shaving. And was supplied by Tesla (Tesla, 2017).

Toshiba Corporation announced in 2106 that a battery energy storage system (BESS) the company has supplied to Tohoku Electric Power Company started operation as scheduled. The 40MW-40MWh lithium-ion BESS is one of the largest in the world. The BESS will manage and improve the balance of renewable energy supply and demand, which is subject to weather-influenced output fluctuations, by storing surplus renewably electricity when supply exceeds demand and releasing stored electricity at times of high demand (Toshiba, 2016).

Figure 2.15. Render of Tesla Powerpack System to be paired Neoen's Hornsdale Wind Farm near Jamestown, South Australia. Source: (Tesla, 2017)

Figure 2.16. Minima-Soma storage system of Tohoku Electric Power Company. Source: (Toshiba, 2016)

Other of the most largest systems is grid-scale LIB storage system Mira Loma Substation, in California which features 20MW/80MWh in 2016 using 400 Tesla Powerpack to provide peak shaving (electrek, 2017) and The Laurel Mountain, West Virginia, USA grid-scale LIB storage system at 32MW/8MWh (AES), it was installed in 2011 by AES and is designed for frequency regulation and for supporting a 98MW wind generation plant 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 (Figure 2.17). Also, the U.S. based AES Energy Storage has been commercially operating a Li-ion BES system (8 MW/2MWh in 2010, enlarged 16MW in 2011) in New York for supplying frequency regulation.

Mexico has a utility-scale electricity storage project was built in La Paz, in Baja California Sur, constructed by Elmya for Gauss Energy as part of the 32 MW solar park Aura solar III power plant which includes storage system of lithium-ion batteries with 10.5 MW of charge/discharge capacity and 7 MWh of stored energy (pv magazine, 2019). And was constructed aimed at the PV plant for stabilization of the grid (Figure 2.18).

Figure 2.17. LIB System of the Laurel Mountain wind generation plant. Source: (AES)

Figure 2.18. Solar plant Aura III in La Paz, Mexico. Source: (pv magazine, 2019)

Advantage/disadvantage

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 (Danish Energy Agency-ENERGINET, 2019).

Containers come in standard sizes. For small systems this impacts the LIB system CAPEX, however when the system size exceeds several container units, the price can be considered linear. Compared to e.g. fuel cell technology the CAPEX per storage capacity is relatively high. This is because the electricity is stored in the battery electrodes whereas for fuel cells the electricity is stored as a separate fuel. Adding incrementally more energy capacity to a battery system is therefore relatively expensive. The relatively high energy specific CAPEX combined with the gradual self-discharge and parasitic losses in the BOP make the technology less attractive for long-term storage beyond a few days (Danish Energy Agency-ENERGINET, 2019). Due to the great variation between the possible chemistries, these also differentiate certain advantages and disadvantages with respect to their composition:

Table 2.3. Comparison of lithium-ion chemistry advantages and disadvantages. Source: Adapted from (IRENA, 2017)

Key active material	NMC	LMO	NCA	LFP	LTO
Advantages	Can be tailored for high power or high energy Stable thermal profile Can operate at high voltages	Low cost due to manganese abundance Very good thermal stability Very good power capability	Very good energy and good power capability Good cycle life in newer systems Long storage calendar life	Very good thermal stability Very good cycle life Very good power capability Low costs	Very good thermal stability Long cycle lifetime High rate discharge capability No solid electrolyte interphase issues
Disadvantages	Patent issues in some countries Cobalt relates to ethical issues and price/abundance issues Low Co content and high Ni content present instability	Moderate cycle life, insufficient for some applications Low energy performance	Moderate charged state thermal stability which can reduce safety Capacity can fade at temperature 40-70 °C Cobalt relates to ethical issues and price/abundance issues	Lower energy density due to lower cell voltage	High costs of titanium Reduced cell voltage Low energy density

NMC: Lithium nickel manganese cobalt oxide; LMO: Lithium manganese oxide; NCA: Lithium nickel cobalt aluminum; LFP: Lithium iron phosphate; LTO: Lithium titanate

Environment

Current lithium reserves are estimated at approximately 14 million t, while the world's total resources owing to continuing exploration, lithium resources have increased substantially worldwide and total about 62 million tons (USGS, 2019). Despite the fact that overall Li-ion material resources and reserves are sufficiently abundant to support the expected increased uptake of the technology, aggressive demand scenarios could pose challenges for the mining industry to react sufficiently rapidly given that the uncertainty in demand growth makes supply planning difficult (IRENA, 2017).

A review on life-cycle analysis (LCA) of Li-Ion battery production estimates that "on average", producing 1 Wh of storage capacity is associated with a cumulative energy demand of 328 Wh and causes greenhouse gas (GHG) emissions of 110 g CO_2 eq" (Peters, Baumann, Zimmermann, Braun , & Weil , 2017); and A US-EPA report stated in 2013 that across the battery chemistries, the global warming potential impact attributable to LIB production including mining is substantial- The study showed that the batteries that use cathodes with nickel and cobalt, as well as solvent-based electrode processing, have the highest potential for environmental impacts. These impacts include resource depletion, global warming, ecological toxicity, and human health impacts.

A recent analysis by Germany's DERA suggests total demand for lithium content could increase to 80,150 tones (t) per annum by 2025, a 9.2% compounded annual growth from 2015. At the same time, their conservative supply scenario indicates total lithium extraction growing from 33,011 t in 2015 to 88,000 t by 2025. This assumes 2015 supply capacity is maintained and that planned expansions to existing capacity will be realized at a rate of 70%. Under a more optimistic supply scenario the surplus of supply over demand in 2025 of 8,000 t for the central demand estimate could rise five-fold to around 40,000 t in 2025, or 50% higher than projected demand. However, uncertainty continues regarding the actual development of demand (IRENA, 2017).

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 (The Washington Post, 2018)

Although supply risks for lithium and cobalt for BES systems do not appear sufficiently threatening to endanger the future uptake of the technology, they do point to the growing importance of sustainable end-life management strategies for BES systems that include effective recycling (IRENA, 2017).

Research and development

Many research lines are currently being developed to improve the materials, cells, and systems of lithium-based batteries. Due to the economic and technological impact, a wide range of government and industry sponsored research is taking place across the world towards the improvement of LIB. Great progress has been made in the direction of new cathode materials and significant improvement has been achieved in terms of voltage and energy density, but a complimentary electrolyte is not available, this limitation is for overall battery chemistry (DTU Energy, Department of Energy Conversion and Storage, 2019). Therefore, some points of attention are:

- Enhancing the energy density of LIB cells by developing high-voltage electrolytes allowing charging voltages of up to 5 volts (given current systems often capped at 4.4 volts in order to limit electrolyte oxidation and protect cell lifetime), (Petibon, Xia, Ma, Bauer, Nelson, & Dahn, 2016). Ionic liquids still researched upon for safer high potential operation (Armand, Endres, MacFarlane, Ohno, & Scrosati, 2009)
- Increasing battery power capability by developing advanced electrode materials; for example with the use of nanoscale materials like silicon nanoparticle based anodes (Casimir , Zhang, Ogoke, Amine, Lu, & Wu, 2016) , or the develop of nickel phosphate based cathode which can operate at 5.5 V (compared to 3.7 V of cobalt oxide cathodes) (Wolfenstine & Allen, 2004)
- Improving the cycle lifetime; several research and development activities focus on improving the rechargeable lithium metal batteries lifetime, especially focus on LMO cells (Lee, Kim, Lee, & Oh, 2014) (Saulnier, Auclair, Liang, & Schougaard, 2016). Since manganese is a low-cost and abundantly available basic cathode material, but during cycling, manganese leaches out of the cathode and dissolves in the electrolyte, thus destabilizing the solid electrolyte interface on the anode and decreasing the available battery capacity. Some approaches to stop the dissolution process include a coating of the cathode, as well as cationic doping. And a new coating could make lightweight lithium metal batteries safe and long lasting, a boon for the development of next-generation electric vehicles

New approaches towards lithium as a material for energy storage have been explored in past years.

- Lithium Sulphur batteries. That uses Sulphur as an active material which is abundantly available at a reasonable price and allows for very high energy densities of up to 400 Wh/kg and its chemical composition offers an inherent protection against overcharging, making it considerably safer. A range of challenges (including a high self-discharge rate, a low internal conductivity and a very low cycle lifetime of only 50 to 100 full cycles) maintain it in the early stage of development, and can't be considered a commercial opportunity yet (IRENA, 2017)
- Lithium air batteries. 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 (IRENA, 2017).

Although LIB systems for electricity storage are now commercially available and have increased deployment and improved economies of scale from a larger manufacturing base, continuous innovation and technological improvements are likely to have a large impact on the cost decline potential of Li-ion BES systems.

Prediction of performance and costs

BES system costs are experiencing a downward trend in recent years, nevertheless, detailed cost breakdowns for battery ESSs are often scarce or difficult to obtain due to confidentiality restrictions and consistent time-series data for Li-ion BES systems are typically not readily available.

However, according to the U.S. Energy Storage Monitor, Lithium-ion battery rack prices declined by more than 20% every year in 2015 and 2016, and in 2017 prices came down by almost 15%. Growing demand from the EV industry and stationary energy storage market, as well as improvements in energy density, drove the bulk of these historical price declines (Wood Mackenzie, 2019).

The recent cost forecast from Bloomberg's New Energy Outlook 2018 for industry average LIB pack shows that LIB price is close to US$ 200/kWh (as can also be seen above, where indicates a US$ 225 /kWh) and the forecast predicts a battery price of US$ 70 /kWh by 2030 (figure 2.20). Further, the forecasted added installed capacity between now and 2050 is estimated to 1,291 GW (Bloomberg NEF, 2018). Using Bloomberg's forecast results with an 18% learning rate and the predicted capacity growth, this results in a forecasted US$ 50/kWh in 2040 and US$ 40 /kWh in 2050. Although this may be too optimistic.

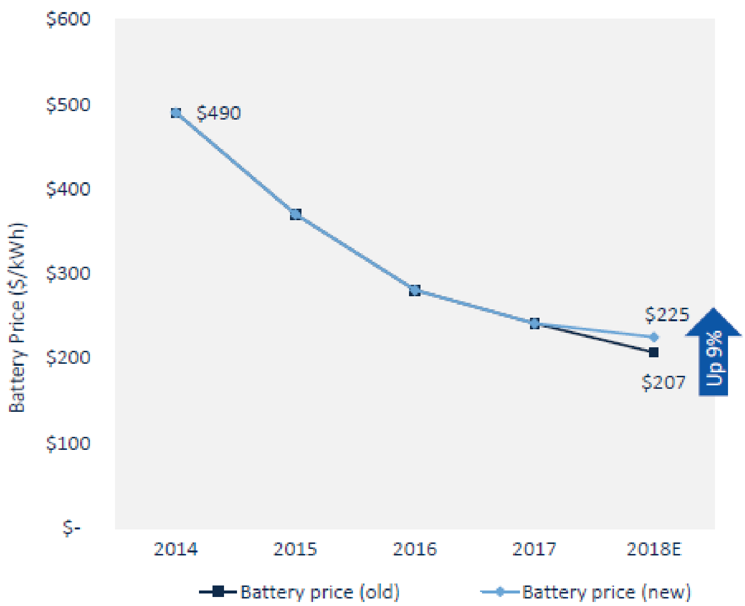

Figure 2.19. Lithium-ion battery prices. Source: (Wood Mackenzie, 2019)

The projection method in the data sheet deviates a little from this as it is considered that Bloomberg New Energy Finance (BNEF) could be too optimistic in its forecast, and the methodology should be consistent with the information sources, hence the approach for projection in this Catalog considers a more conservative scenario based on the experience of the Danish Energy Agency and its forecast.

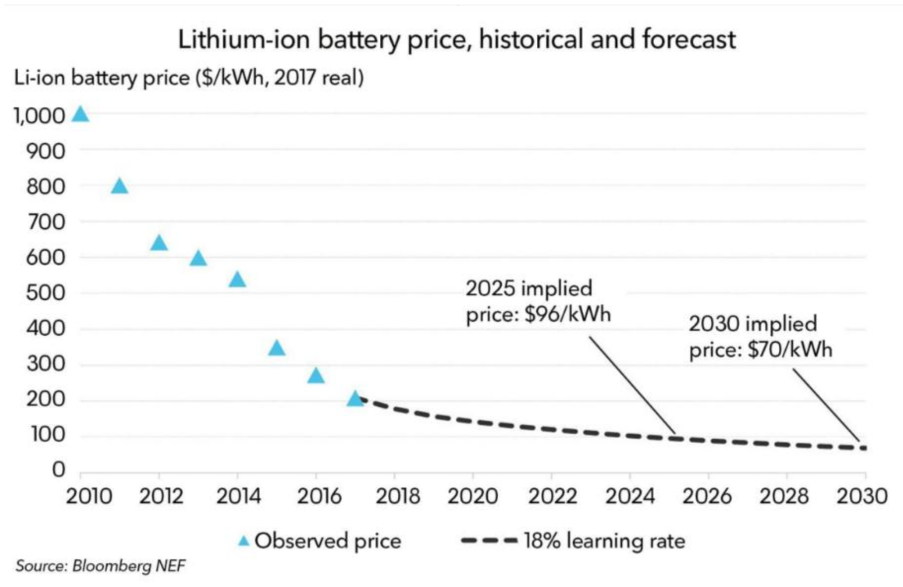

Figure 2.20. Historical and forecasted lithium-ion battery pack cost. Source: (Bloomberg NEF, 2018)

Tesla is still both well ahead of the competition on costs today and still on track to keep improving costs at around 15% per year. With a pack cost level of US$190/kWh already in 2016 and indications have been reported of US$ 100/kWh before 2020 (CleanTechnica, 2018). Showing significant cost advantage over the industry average, which is regularly tracked by Bloomberg New Energy Finance (BNEF).

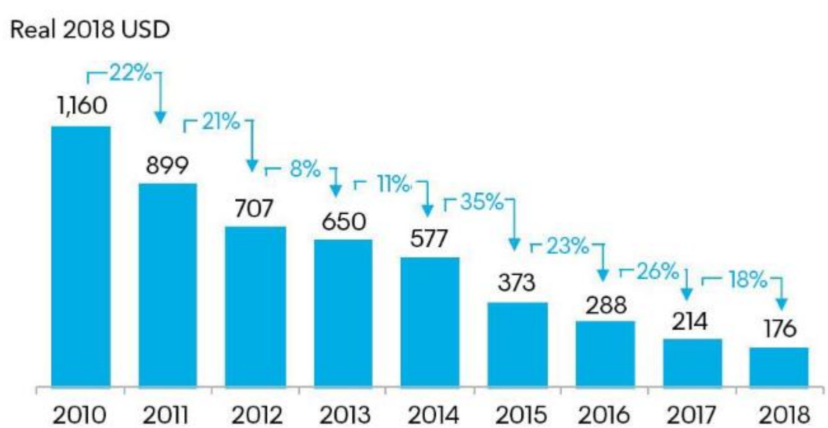

Figure 2.21. Volume weighted average lithium-ion pack price. Source: (Bloomberg NEF)

The cost reductions are backed up by a rapid increase in the LIB production capacity. Global manufacturing for Li-ion cells has ramped up considerably and plans to further expand capacities continue. Li-ion production capacity expansion is underway from current established players and some new entrants, primarily driven by Chinese stakeholders. Apart from so-called mega factories, an impressive five-fold growth can be seen in the figure 2.22, with the increase from approximately 29 GWh in 2016 to 174 GWh by 2020 (Desjardins, 2017).

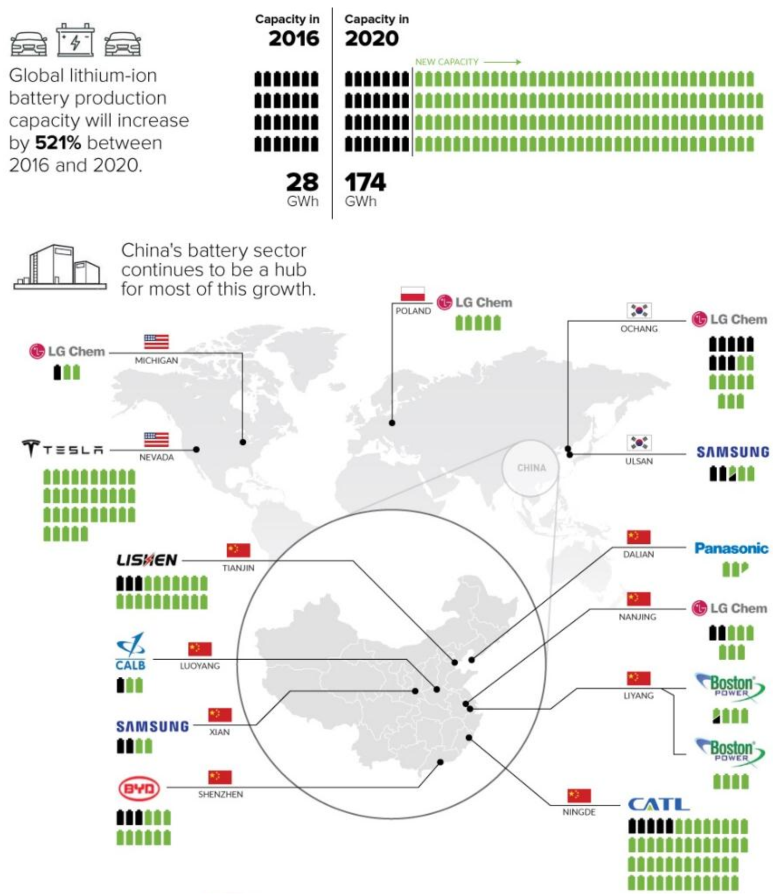

Figure 2.22. Projected growth in LIB manufacturing capacity total and divided on technology producers. Each battery represents a production capacity of one GWh per year. Source: (Desjardins, 2017)

Uncertainty

The LIB price forecast depends on improving the competitiveness of Li-ion battery systems and will require a combination of improvements in performance and installed cost reductions. Therefore price forecasts imply a broad range of uncertainties since the different chemistries used and the avenues in the fields of technological improvements such as the enhanced of energy densities or achieving higher lifetimes, the improvement of the round trip efficiency and material improvements represent a much amplified range of variables for the forecast. Therefore, if the learning rate is not 18% as estimated in Bloomberg's New Energy Outlook 2018 (Bloomberg NEF, 2018) but rather 12-16% as estimated by IRENA (IRENA, 2017), the forecasted price reductions will have price ends at 70 US$/kWh for a 12% learning rate in 2050 instead of 40 US$/kWh for the 18% forecast. With a 14% and 16% learning rate the 2050 price ends respectively at 60 US$/kWh and 50 US$/kWh.

For IRENA overall, the central projection for costs of each of these technologies between 2016 and 2030 represent a decline of between 54% and 61% (Figure 2.23) (IRENA, 2017). Setting decline from between 200 and 1 260 USD $/kWh in 2016 to between 77 and 574 USD $/kWh by 2030, for Energy installation costs for utility-scale applications.

The central estimate for each Li-ion sub technology is expected to decline from between 350 to 1,050 USD $/kWh in 2016 to between 145 to 574 USD $/ kWh by 2030, although the low end of that range reflects the current less-expensive NCA chemistry. By 2030, NCA, NMC/LMO and LFP battery chemistries are projected to have costs that fall within roughly the same range of from 80 to 340 USD $/kWh. The central estimates for their costs in 2030 are also similar, with NMC Li-ion technologies for stationary applications at 145 USD $/kWh, NMC/LMO at 167 USD $/kWh and LFP somewhat higher at 224 USD $/kWh. LTO technologies are expected to remain more expensive, with the central estimate for their energy installation costs falling to 480 USD $/kWh. However, LTO technologies also maintain a performance advantage over the other Li-ion battery chemistries (IRENA, 2017).

The energy density of Li-ion stationary systems is expected to range between 200 Wh/L and 735 Wh/L by 2030. The central estimate round-trip efficiencies (DC-to-DC) are expected to increase two percentage points from between 92% and 96% in 2016 to between 94% and 98% by 2030. The central estimates for self-discharge of Li-ion batteries range between 0.05% and 0.20% a day in 2016 and are expected to stay flat to 2030 (Figure 2.23) (IRENA, 2017).

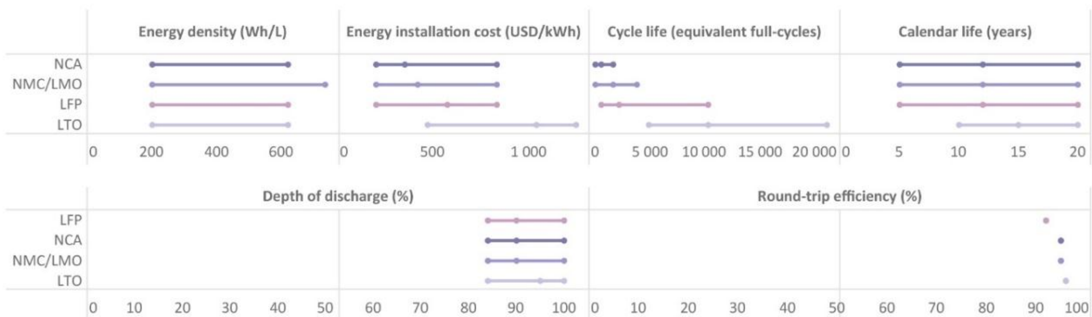

Figure 2.23. Projected properties of selected chemistries of lithium-ion battery electricity storage systems of 2016 and 2030. Source: (IRENA, 2017)

Data sheet

Technology		Lithium-ion NMC battery (Utility-scale, Samsung SDI E3-R135)							
	2020	2030	2050	Uncertainty (2020)		Uncertainty (2030)		Note	Ref
Energy/technical data				Lower	Upper	Lower	Upper		
Form of energy stored	Electrochemical								
Application	System, energy-intensive (2 h)								
Energy storage capacity for one unit (MWh)	6	7	8	5	9	6	11	A	[1, 6]
Output capacity for one unit (MW)	3	3.5	4	2.7	3.5	3.1	4.1	A	[1, 6]
Input capacity for one unit (MW)	3	3.5	4	2.7	3.5	3.1	4.1	A	[1, 6]
Round trip efficiency (%) AC	92	93	93	91	93	92	94	B	[2, 8, 9, 17]
Round trip efficiency (%) DC	96	97	97	96	97	97	98	B	[2, 8, 9, 17]
- Charge efficiency (%)	98	99	99	98	99	98	99	C	[1]
- Discharge efficiency (%)	98	99	99	98	99	98	99	C	[1]
Energy losses during storage (%/day)	0.1	0.1	0.1	0.05	0.20	0.05	0.18	D	[7, 16, 18]
Forced outage (%)	0.38	0.35	0.32	0.20	0.50	0.17	0.45	E	
Planned outage (weeks per year)	0.2	0.10	0.05	0.10	0.25	0.05	0.15	E	
Technical lifetime (years)	20	25	31	15	25	18	33	F	[2, 4, 5, 6]
Construction time (years)	0.2	0.2	0.2	0.2	0.3	0.17	0.25		[11]
Lifetime in total number of cycles	14000	30000	50000	10000	16000	18200	36800	P	[2-4, 6]
Regulation ability									
Response time from idle to full-rated discharge (sec)	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	G	[19]
Response time from full-rated charge to full-rated discharge (sec)	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	G	[19]
Financial data									
Specific investment (M$2020 per MWh)	0.41	0.26	0.17	0.32	0.55	0.20	0.51	H	[14, 15]
- energy component (MUSD/MWh)	0.15	0.09	0.05	0.08	0.21	0.05	0.18		[14]
- capacity component (MUSD/MW) PCS	0.30	0.18	0.11	0.27	0.57	0.15	0.48		[23]
- other project costs (MUSD/MWh)	0.11	0.09	0.07	0.10	0.12	0.07	0.15	J	[9, 12, 20]
Fixed O&M (kUSD2020/MW/year)	0.54	0.54	0.54	0.45	0.54	0.43	0.54	K	[23]
Variable O&M (USD2020/MWh)	2.22	2.00	1.80	0.44	6.22	0.39	4.77	L	[21]
Technology specific data									
Energy storage expansion cost (M$2020/MWh)	0.26	0.17	0.12	0.18	0.33	0.12	0.32	M	[14, 15]
Output capacity expansion cost (M$2020/MW)	0.30	0.18	0.11	0.27	0.57	0.15	0.48	N	[20-22]
Alternative Investment cost (M$2020/MW)	0.37	0.22	0.13	0.31	0.64	0.17	0.55	O	[13, 14, 15, 20-22]
Specific power (W/kg)	58	67	77	57	60	61	72	Q	[1, 10]
Power density (kW/m3)	69	80	92	68	82	72	96	Q	[1, 10]
Specific energy (Wh/kg)	115	135	154	107	154	115	184	Q	[1, 10]
Energy density (kWh/m3)	138	161	184	128	212	135	247	Q	[1, 10]

Notes:

A. One unit defined as a 40 feet container including LIB system and excluding power conversion system. Values for 2015-2030 are taken from Samsung SDI brochures for grid-connected LIBs from 2016 and 2018. This unit of 6MWh/3MW (0.5C) is a typical size grid scale battery for energy shift and peak shaving. The Specific investment cost under financial data is provided for a 1MWh: 0.5 MW (0.5C) battery.

B. The AC roundtrip efficiency includes losses in the power electronics and is 2-4% lower than the DC roundtrip efficiency. The total roundtrip efficiency further includes standby losses making the total roundtrip efficiency typically ranging between 80% and 90%.

C. The C-rate is 0.5 during charge and can be up to 6 during discharge for the Samsung SDI batteries. The presented conversion efficiencies assume average charge and discharge C-rates in 2015-2020 around 0.5. Higher C-rates during discharge will slightly decrease the efficiency.

D. Lithium-ion battery daily discharge loss. The central estimates for self-discharge of Li-ion batteries range between 0.05% and 0.20% a day in 2016 and are expected to stay flat to 2030.

E. It is expected not to have any outage during lifetime of the grid-connected LIB. Only a few days during the e.g. 15 years lifetime is needed for service and exchanging fans and blowers for thermal management system and power conversion system. Forced outage is expected to drop with increasing robustness following the learning rate and cumulated production. Planned outage is expected to decrease due to increased automation.

F. Current state-of-the-art NMC LIB has 20 years lifetime. The NMC lifetime is expected to have LTO lifetime by 20 and 30 years lifetime for grid-connected LIBs in 2040 and 2050 as photovoltaic power systems have today.
G. The response time is obtained from simulated response time experiments with hardware in the loop.
H. The system specific forecasts include rack, TMS, BMS, EMS and PCS. The forecast is calculated as the sum of the PCS, the battery cell, and other costs. The system specific forecast is exclusive power cables to the site and entrepreneur work for installation of the containers. The specific investment cost is the total cost of a 1MWh: 0.5MW (0.5C) battery.
I. Power conversion cost is strongly dependent on scalability and application. The PCS cost is based on references and reflects the necessity for high 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. Inverter replacement is expected every 10 years. The bidirectional inverter given here has the same charge and discharge capacity (MW).
J. Other costs include construction costs and entrepreneur work. These costs heavily dependent on location, substrate and site access. Power cables to the site and entrepreneur work for installation of the containers are included in other costs. Therefore, other costs are assumed to – roughly – correlate with the system size. Automation is expected to decrease other costs from 2030 and onwards.
K. Fixed O&M is assumed to be constant, although the O&M may depend on the application.
L. Variable O&M is assumed to be 2.3 USD/MWh in 2015 with a range of 0.4 – 5.6.
M. Since multi-MWh LIB systems are scalar, the energy storage expansion cost is here estimated to be equal to the energy component plus the “other costs”.
N. Since multi-MW LIB systems are scalar, the capacity expansion cost equals the capacity component cost.
O. The alternative investment cost in MUSD2015/MW is specified for a 4C, 0.25 h system as for the Laurel Mountain, West Virginia, USA grid-scale LIB storage system. I.e. the alternative investment cost is 25% of the energy storage expansion cost plus the PCS cost.
P. Cycle life specified as the number of cycles at 1C/1C to 80% state-of-health. Samsung SDI 2016 whitepaper on ESS solutions provide 15 year lifetime for current modules operating at C/2 to 3C. Steady improvement in battery lifetime due to better materials and battery management is expected. Kokam ESS solutions are also rated at more than 8000-20000 cycles (80-90% DOD) based on chemistry. Thus, for daily full charge-discharge cycles, the batteries are designed to last for 15-50 years if supporting units are well functioning. Lifetimes are given for both graphite and LTO anode based commercial batteries from Kokam. Cycle lives are steadily increasing over last few years as reflected in 2020/2030 numbers.
Q. Specific power, power density, Specific energy and energy density is provided for 0.5C reflecting the energy and power capacity in the datasheet. The expected development depends on the successive R&D progress.

The references in data sheet can be found in the quantitative data sheet file that supplements the qualitative technology description (“Li_ion.xlsx” file) as well as in “Appendix B references of datasheets”

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2.3 Lead-acid batteries

Brief technology description

Lead-acid batteries were invented in 1859 (Zou et al., 2018) by Gaston Planté (Rand & Moseley, 2009). The concept of the pasted plate proposed it Camille Fauré (Rand & Moseley, 2009). Lead-acid is the most widely used rechargeable battery (Luo, Wang, Dooner, & Clarke, 2015).

The lead-acid batteries are a form to store electrical energy at local (Danish Energy Agency, 2019) and at utility scale. They are considered as an electrochemical technology (Deloitte, 2015) and operate at room-temperature (DNVGL, 2017). They may be flooded, or sealed valve regulated (VRLA) types. This technology can be recycled fully (May, Davidson, & Monahov, 2018) and they are the most common batteries on the market (DTU Energy, 2019).

Lead-acid batteries are used when the cost, reliability, and abuse tolerance are crucial (Zou et al., 2018).

Lead-acid chemistries

Lead-acid battery is an electrochemical cell. Consequently, they have a Pb negative plate (anode), a separator, and a PbO_2 positive plate (cathode) as shown in Figure 2.24.

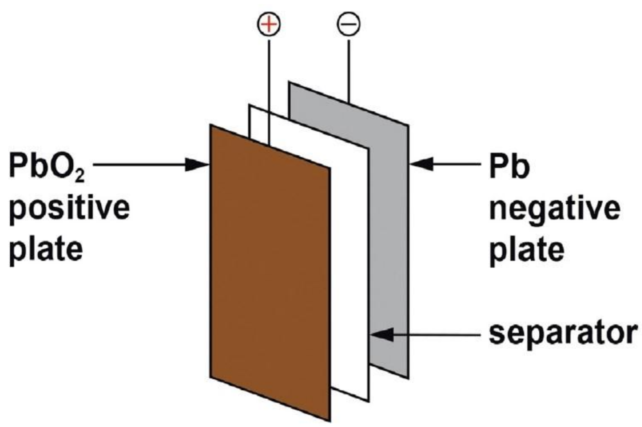

Figure 2.24. Principal components of lead-acid battery. Source: *(May et al., 2018)*

The electrolyte is dilute aqueous sulfuric acid. So, the overall discharge and charge reaction in a lead-acid battery is (May et al., 2018):

$$PbO_2 + Pb + 2H_2SO_4 \Leftrightarrow 2PbSO_4 + 2H_2O$$

The above chemical reaction is a reversible reaction because the reactants form products that, in turn, react together to give the reactants back. This chemical reaction takes place usually in a closed system and in a liquid medium (electrolyte). At the beginning of the reaction, the dilute aqueous sulfuric acid dissociates in H+ and HSO_4- ions. After this dissolution, the HSO_4- ions migrate to the negative electrode (Pb negative plate) producing H+ ions and lead sulfate ($PbSO_4$). This is the discharge process. At the positive electrode, the lead dioxide (PbO_2) reacts with dilute aqueous sulfuric acid (H_2SO_4) to form lead sulfate crystals ($PbSO_4$) and water (H_2O). In the charging process, the reverse reactions take place when energy is applied into the system. If there is further charging, it will result in water loss because it is electrolyzed to H_2 and O_2. The nominal cell voltage is 2.05 V (May et al., 2018).

The types of positive plate are flat pasted plates and tubular plates. The negative plates are flat pasted plates. The separator for the flooded pasted plate may be of microporous polyethylene, polyvinyl chloride (PVC), rubber or similar materials and needs to be protected with a sheet of glass fiber against loss of active material on cycling. The absorptive glass mat (AGM) separator is used for VRLA pasted place cell. They are made from glass microfibers by a paper-making process.

Components in lead-acid battery energy storage system

The main components are the following:

- Cells composed of an assembling or electrodes, electrolyte and separators
- Mono-blocks composed or serial assembling of cells
- Battery systems composed of a large assembling on cells modules
- Power conversion system (PCS)

Input/output

The input and output of lead-acid battery is electricity.

Energy efficiency and losses

The lead-acid battery has a round cycle efficiencies between 63 to 90 % (Nadeem et al., 2019). During high discharging rates, the efficiency is decreased because hydrogen is produced (Nadeem et al., 2019).

Typical characteristics and capacities

The typical characteristics and capacities for lead-acid battery are shown in Table 2.11.

Table 2.4. Typical characteristics of lead-acid battery for energy storage system. Source: (Koohi-Fayegh & Rosen, 2020)

Characteristic	Value
Power density (kW/m^3)	10 – 700
Energy density (kWh/m^3)	25 – 90
Energy density (Wh/kg)	10 – 50
Cycle efficiency (%)	60 – 90
Lifetime (cycles)	100 – 2000

Typical storage period

This technology is very flexible, consequently, the typical storage period is from seconds to 10 hours (Luo et al., 2015). The lead-acid battery has more tolerance for storage when the storage system is under subfreezing temperature compared with a lead-acid battery at a higher temperature (Nadeem et al., 2019).

Regulation ability

The lead-acid battery has a fast response time (Nadeem et al., 2019) and it is a very flexible technology. Therefore, it can provide the following applications to the grid mentioned below:

Table 2.5. Type of services can be provided by lead-acid battery. Source: (Schmidt, Melchior, Hawkes, & Staffell, 2019)

Service	Can be provided
Energy arbitrage	√
Primary response	√
Secondary response	√
Tertiary response	√
Peaker replacement	√
Black start	√
T&D investment deferral	√
Congestion management	√
Bill management	√
Power quality	√
Power reliability	√

Examples of market standard technologies

Table 2.13 summarizes some examples of Electrical Energy Storage System (EES). Additional examples will be presented with further information.

Table 2.6. Lead-acid battery energy storage facilities. Source: (Luo et al., 2015)

Name/Locations	Characteristics	Application area
BEWG, Berlin	8.5 MW/8.5 MWh	Spinning reserve, frequency control

Name/Locations	Characteristics	Application area
Chino, California	10 MW/40 MWh	Spinning reserve, load leveling
Kahuku Wind Farm, Hawaii	15 MW/3.75 MWh	Power management, load farming, grid integration
Metlakatla, Alaska	1 MW/1.4 MWh	Enhancing stabilization of island grid
Notrees EES project, US	36 MW/24 MWh	Solving intermittency issues of wind energy
PREPA, Puerto Rico	20 MW/14 MWh	Spinning reserve, frequency control

Lerwick, Shetland Islands, Scotland

The Shetland Islands has an electricity supply network with a 66 MW diesel generating plant and 11 MW of wind power. The system was installed in 2013 and has operated successfully since that time providing a 20 % reduction in peak demand for diesel generation with savings in fuel costs and improvement in power quality in the network (May et al., 2018).

The basic building block of the energy storage system installed at Lerwick Power Station is a 2-volt advanced lead-acid battery manufactured by GS Yuasa. The following tables below present battery characteristics, battery systems configuration data, and power infrastructure data (GS Battery Inc., 2016).

Table 2.7. Battery characteristics of advanced lead-acid battery. Source: (GS Battery Inc., 2016)

Battery Specification Data	
Batteries voltage	2 VDC
Cells per battery	1
Battery chemistry	Advanced (carbon enhanced) lead-acid, AGM
Battery AH rating	1,000 AH @ 10 HR
Battery cycle life	3,000 cycles at 50 % depth of discharge (DOD)

Table 2.8. Battery system of advanced lead-acid battery. Source: (GS Battery Inc., 2016)

Battery System Configuration Data	
Battery per rack	24
Racks per string	11
Cells per string	264
Nominal voltage	528 VDC
Parallel strings	12
Total cell count	3,168

Battery System Configuration Data	
System power	1 MWAC
System energy	3 MWh

Table 2.9. Power infrastructure of advanced lead-acid battery. Source: (GS Battery Inc., 2016)

Power Infrastructure Data	
Transformer room	11 kV grid connection
Power conversion room	2 x 500 kW AC-DC converters
Battery room	1 MW / 3 MWh VRLA storage
Storeroom	Fire suppression and spares

The lessons learnt from this installation are (May et al., 2018):

- Current sharing between strings
- Recharge factor uniformity are useful parameters to identify the proper functioning of the battery system
- High level of measurement of voltage and temperature is useful to ensure efficient maintenance activity
- Overall efficiency was measured as 84 %
- Recharge factor was 105 %

Figure 2.25. Battery room at Lerwick Power Station. Source: (GS Battery Inc., 2016)

Lyon Station, Pennsylvania

Since 1946, East Penn has developed quality products made in state-of-the-art manufacturing facilities and operates the world's largest, single-site lead-acid battery manufacturing facility. The facility has over 3.7 million sq. feet under roof on a 520-acre plant site. These facilities include a modern US EPA permitted lead smelter, refinery, and recycling center where virtually 100 % of every used lead-acid battery returned to East Penn is recycled (DOE, 2015).

In 2012, a large lead battery/supercapacitor hybrid system for frequency regulation was installed. The following tables below present battery characteristics, battery systems configuration data, and power infrastructure data (May et al., 2018).

Table 2.10. Battery specification of hybrid lead battery/supercapacitor. Source: (DOE, 2015)

Battery Specification Data	
Batteries voltage	2 VDC
Cells per battery	1
Battery chemistry	VRLA cells

Table 2.11. Battery system configuration of hybrid lead battery/supercapacitor. Source: (DOE, 2015)

Battery System Configuration Data	
Battery per rack	4
Cells per string	480
System power	3.6 MW
DC/DC efficiency	92 – 95 %
AC to AC efficiency	80 %

Table 2.12. Power infrastructure of hybrid lead battery/supercapacitor. Source: (DOE, 2015)

Power Infrastructure Data	
Transformer room	13.8 kV grid connection
Power conversion room	4 x 900 kW inverters

Figure 2.26. Three strings of batteries installed. Source: (DOE, 2015)

The lessons learnt from this installation are (DOE, 2015):

- The range of individual cell SOCs was found to be larger than expected during operation
- The 2V cells installed had trouble operating continuously at the high rates demanded by the dynamic frequency regulation application
- Cell temperatures were observed to have a larger than desired range over a stack while operating in the frequency regulation market
- Some issue was experienced with incorrect temperature and voltage readings being reported to the battery management system

Aachen, Germany

In 2016, a large battery was installed as a pilot plant to evaluate various battery technologies for energy storage application called Modular Multi-megawatt, Multi-technology Medium-Voltage Battery Storage System (M5BAT) (May et al., 2018). Table 2.20 shows the battery types for this system.

Table 2.13. Battery types and sizes in the M5BAT storage system. Source: (Münderlein, Steinhoff, Zurmühlen, & Sauer, 2019)

Battery type	Power (MW)	Energy (MWh)	Number of Strings
Lead-acid OCSM	1.21	1.36	2
Lead-acid OPzV	1.00	1.00	2
Lithium-ion LMO	2.35	2.35	4
Lithium-ion LFP	0.60	0.70	1
Total	5.16	5.41	9

M5BAT can supply power to 10,000 households for about 60 minutes (Meyer, 2017). The experience from this project is (May et al., 2018):

- Battery energy storage can control reactive power in a network, maintain stability and provide useful support to the network
- It is intended to evaluate the economic aspects of different methods of operation
- It has been confirmed that batteries can be installed and put into service quickly close to consumers

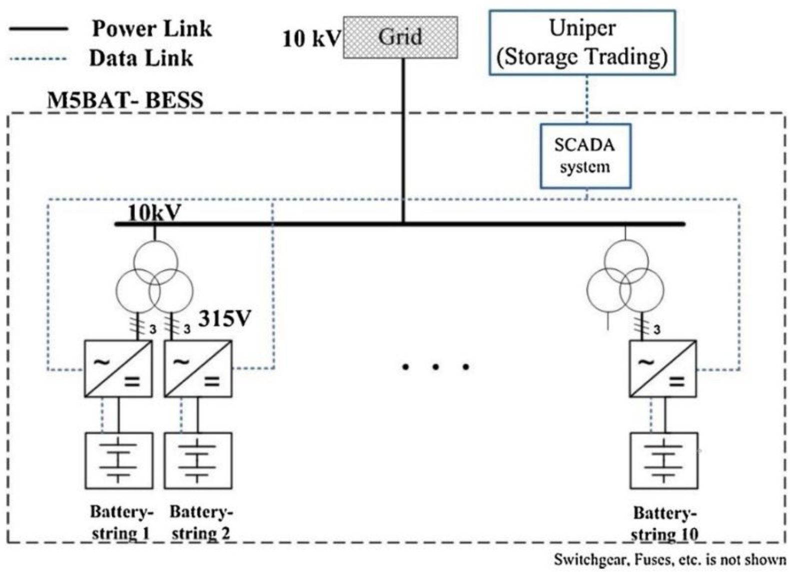

Figure 2.27. Setup of the M5BAT battery system. Source: (Münderlein et al., 2019)

Although there are no grid-scale lead-acid battery systems in Mexico, some applications have been used mainly for isolated systems such as the tiny village of San Juanico in Baja California, which is isolated from the national transmission grid, installed a hybrid electricity project in 1999. The system is comprised of 17kW photovoltaic cells, ten wind turbines with a total capacity of 70 kW, and an 80-kW diesel generator. The hybrid system includes flooded lead-acid battery bank with a nominal capacity of 2,450 Ah (Corbus, 2004).

Advantage/disadvantage

The advantages and disadvantages of lead-acid batteries are shown in Table 2.21.

Table 2.14. Advantage and disadvantage of lead-acid batteries. Source: (Koohi-Fayegh & Rosen, 2020)

Factor	Advantage	Disadvantage
Positive Electrode	• The battery is held at the charging voltage when it is immersed in sulfuric acid • High corrosion resistance when the material of positive electrode is lead-antimony, lead-calcium-tin, lead-tin or pure lead	• When the top-of-charge voltage is reached, it will corrode throughout the life of the battery • Grid corrosion is accelerated by higher charging voltages and is sensitive to temperature • Grid resistance increases during

Factor	Advantage	Disadvantage
	• Grid design parameters provide enough electrode metal for the life of the battery • The voltage is set to achieve a fully charged battery without excessive water loss and corrosion is kept at a level to attain the design life	the life of the battery, accelerating towards end-of-life • When the battery ages, the changes in active material volume and the volume of the corrosion product place stress on the grids • Short circuits when the grids grow to contact the negative group
Sulfation	• Easy to recover lead sulfate by recharge	• Capacity loss of recharge when over time and on cycling • Sulfation will increased when the battery is left in a partially or fully discharged state for extended periods
Active material softening	• For positive plates it can be reduced using higher density pastes	• It will be more rapid if the battery is deeply discharged cycled
Hydrogen production	• If use flame-retardant vents not it will have ignition	• External ignition by hydrogen
Technical characteristics	• Low cost • Technical maturity	• Low energy density • Low power density • Short life cycle

Environment

Lead-acid batteries contain dilute sulfuric acid, which may cause severe chemical burns and when in a fire, it can lead to sulfuric acid gas and other sulfur-based compounds. They may develop hydrogen gas and oxygen during charge or operation, which may result in an explosive mixture. So, they can be both very environmentally damaging and unsafe when not treated in a proper way.

In the EU and USA, lead is collected and recycled more than 99 %, whereas the recycling rate in Mexico is lower because there is no culture of recycling. The bulk of the scrap collected is from used automotive batteries (May et al., 2018). The recycling efficiency by average weight of lead-acid batteries acceptable is between 65-99 % (DNVGL, 2017).

Research and development

For years, this battery has been for years the most diffused and applied storage system in the world, for its commercial and technological availability. Low cost and abundant raw materials with a well-organized recycling chain have been winning aspects for the technology. Lead-acid batteries have been used for more than a century in grid applications. (EASE-EERA, 2017)

There are researches and new developments for lead-acid batteries such as carbon-enhanced designs, carbon negative current collectors, carbon negative electrodes, supercapacitor/battery hybrids, and bipolar lead-acid batteries. An end-of-line credit will be provided for lead batteries with battery recycling carried out in full compliance with environmental regulations (May et al., 2018).

There are several advanced lead-acid batteries that have fast response comparable to flywheels and supercapacitors (Luo et al., 2015).

Even after a hundred years as a commercial product there remains extensive potential for advanced lead-acid battery technology. Specific power is being improved with advanced active materials and lower resistance designs. Further cost reductions are being achieved through automation and process improvement. Cycle life will be doubled through design enhancements and intelligent battery management. Complete turnkey systems up to the MW size are being developed, and lead acid batteries will be integrated into hybrid systems in combination with other power and storage technologies to maximize benefits and minimize costs. Through these improvements, additional cost savings in the range of 40% for RES systems are expected. (EASE-EERA, 2017).

Carbon-enhanced designs

In a lead-acid battery, the carbon can modify the performance of the negative plate. Table 2.22 summarizes the carbon-enhanced designs.

Table 2.15. Types carbon-enhanced designs. Source: (May et al., 2018)

Enhanced designs	Description
Capacitive effects	They are favored by carbons that have large specific surface. They have good contact with the grid as the current collector and the spongy lead matrix of the active mass
Surface area effects	The surface area can be less than the capacitive process because the carbon promotes bulk rather than surface processes
Physical processes	The carbon does not have to be conductive, but it does have to be very intimately mixed with the sponge lead and the particle size enough for its function not to be reduced over time. These requirements will lead to further improvements in lead batteries for energy storage applications

Carbon negative current collectors

There are many carbon materials to replace some or all the metallic parts of the negative electrode. This material can be rigid carbon foams, lead electroplated graphite foil, and flexible carbon felts. The table 2.23 summarizes the carbon negative current collectors.

Table 2.16. Carbon materials for carbon negative current collectors. Source: (May et al., 2018)

Carbon material	Description
Rigid carbon foams	They have outstanding life and active mass utilization, but these materials made manufacture problematic
Lead electroplated graphite foil	They had a low-level utilization but high durability in PSoC cycling suggesting that lead sulfate formation was inhibited

Carbon material	Description
Flexible carbon felts	It is a carbon felt activated by treatment with an electric arc, after that, it is impregnated with active material and attached to lead alloy current collectors. This construction has good potential for energy storage applications in larger scale

Carbon negative electrodes

The Pb negative electrode is replaced by carbon-negative active. The energy density is low compared to a lead-acid battery and offers a very long cycle life. This technology is still being developed (May et al., 2018).

Supercapacitor/battery hybrids

The Pb negative plate is replaced by a carbon-based supercapacitor combined with a conventional negative electrode. Both negative electrodes are connected in parallel, consequently, the capacitor part acts as a buffer to share current with the negative plate and reduce the rate of charge and discharge. This combined negative electrode and a standard positive electrode offers substantially improved behavior in deep cycling.

This technology offers advantages over lead-acid batteries, such as (May et al., 2018):

- The avoidance of irreversible sulfation of the negative plate in PSoC cycling
- The need for intermittent conditioning cycles where the battery is charged for an extended period
- Improved high-rate charge acceptance
- Better self-balancing of cells in series strings
- An energy density and voltage profile on discharge in line with a lead-acid battery

Bipolar lead-acid batteries

The bipolar lead-acid battery is composed of plates that have one side operating as the positive and the other as the negative separated by a membrane that is electronically conductive and corrosion-resistant. If a successful bipolar lead-acid design was available, this technology would offer an attractive energy storage battery. The key to this technology is the selection of membrane. Table 2.24 summarizes the membrane materials used on bipolar lead acid batteries.

Table 2.17. Membrane materials for bipolar lead-acid battery. Source: (May et al., 2018)

Membrane material	Description
Conductive titanium suboxides incorporated in resin fabricated into thin sheets	They have been extensively examined but have not been commercialized
Polymer sheets conductive with metallic fibers	It is under study, but no battery performance data has been published
Porous alumina impregnated with lead	Unsuccessful attempt
Silicon	It can be made sufficiently conductive to operate as a membrane

Prediction of performance and costs

The lead-acid battery is considered to have technological maturity. Consequently, the performance of lead-acid battery will not have a variation in the period 2020-2050.

In the past two decades, the costs of lead-acid batteries have had smaller variations (Koohi-Fayegh & Rosen, 2020). The prediction of costs was obtained and estimated from IRENA for energy and capacity components. The fixed and variable O&M was obtained from (Zakeri & Syri, 2015).

Uncertainty

The round-trip efficiency, energy losses during storage, and the total number of cycles will have uncertainty due to the electrochemical properties of water of lead-acid battery. The other technical data of lead-acid battery will not have uncertainty because lead-acid battery has technological maturity.

Conversely, the costs of lead-acid batteries will have uncertainties due to the oil price, investments of solar photovoltaic systems, plant size, and storage capacity. These uncertainties was obtained and estimated from (EASE/EERA, 2013; IRENA, 2017; Schmidt, Melchior, Hawkes, & Staffell, 2019; Zakeri & Syri, 2015)

Data sheet

Technology	Lead Acid battery								
	2020	2030	2050	Uncertainty (2020)		Uncertainty (2030)		Note	Ref
Energy/technical data				Lower	Upper	Lower	Upper		
Form of energy stored	Electro-chemical								
Application	Frequency Restoration Reserve (2h)								
Energy storage capacity for one unit (MWh)	30	30	30	30	30	30	30		[1]
Output capacity for one unit (MW)	15	15	15	15	15	15	15		[1]
Input capacity for one unit (MW)	15	15	15	15	15	15	15	A	
Round trip efficiency - DC (%)	82	85	85	76	93	78	96	B	[2], [3], [7]
- Charge efficiency (%)	91	92	92	87	96	88	98		
- Discharge efficiency (%)	91	92	92	87	96	88	98		
Energy losses during storage (%/day)	0.3	0.3	0.3	0.1	0.4	0.1	0.4		[6]
Forced outage (%)	0	0	0	0	0.1	0	0.1	C	
Planned outage (weeks per year)	0.2	0.1	0.1	0.1	0.3	0	0.2	D	
Technical lifetime (years)	13	13	13	4	22	4	22	average	[3],[4], [6], [7]
Construction time (years)	1	1	1	1	1	1	1		[3]
Lifetime in total number of cycles	1900	3200	9600	300	3100	1000	5000		[1]
Regulation ability									
Response time from idle to full-rated discharge (sec)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	E	
Response time from full-rated charge to full-rated discharge (sec)	0.001	0.001	0.001	0.001	0.001	0.001	0.001		[4]
Financial data									
Specific investment (MUSD$2020 per MWh)	0.554	0.332	0.120	0.385	0.764	0.230	0.461		
- energy component (MUSD/MWh)	0.216	0.132	0.049	0.086	0.388	0.053	0.237	F	[1]
- capacity component (MUSD$/MW)	0.675	0.401	0.141	0.597	0.753	0.355	0.447	G	[3], [1]
- other project costs (MUSD$/MWh)	0	0	0	0	0	0	0		
Fixed O&M (kUSD2020/MW/year)	3.77	3.77	3.77	3.55	14.43	3.55	14.43		[5]
Variable O&M ($USD2020/MWh/year)	0.41	0.41	0.41	0.17	0.58	0.17	0.58		[5]
Technology specific data									
Alternative Investment cost (M$USD2020/MW)	1.107	0.664	0.240	0.770	1.529	0.460	0.921		
Specific power (W/kg)	22	30	53	15	29	24	36	H	[8], [9]
Power density (kW/m3)	56	108	214	33	78	78	139	H	[8], [9]
Specific energy (Wh/kg)	44	59	105	29	59	47	71	H	[8], [9]
Energy density (kWh/m3)	111	217	428	67	156	156	278	H	[8], [9]

Notes:

A. Assumed to be the same as output.
B. IRENA has a slightly increasing projection, but only starts at 82%. Several studies mention a range between 84% to 86%, an average of 85% is commonly assumed for today.
C. It is assumed that no forced outage is necessary due to the maturity level of the technology.
D. Flooded lead-acid batteries require refilling, for which the outage however could be reduced over time due to automation. The bigger valve-regulated lead-acid batteries do not require refilling. Values are assumed based on comparison with Li-Ion battery sheet.
E. Assumed to be in the range of full-rated response time.
F. This data is interpreted within the IRENA tool as: "Energy Installation cost". But also estimated by: Total Storage Invest/Installed Storage Capacity.
G. The central data is based on values from [3], while uncertainty ranges correspond to the relative span of values from [1].
H. Array 1660 Ah, 48 VDC, 79,68 kWh (8x4)

The references in data sheet can be found in the quantitative data sheet file that supplements the qualitative technology description ("Lead_Acid.xlsx" file) as well as in "Appendix B references of datasheets"

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2.4 Sodium sulfur batteries

Brief technology description

The interest in research on sodium sulfur (NaS) battery began when Warburg showed the Na+ conductivity (1884). High-temperature batteries utilize liquid active materials and a solid ceramic electrolyte made of beta-aluminium (β-Al_2O_3 sodium-ion-conducting membrane). They are called high-temperature batteries, because high temperatures are required to keep the active materials in a liquid state (IRENA, 2017). The Na+ diffusion process in crystalline structure of β-Al_2O_3 occurs because it is a hexagonal system with two spinel blocks separated by a mirror plane, which contains one oxygen and one vacancy (Figure 2.28). In 1937, Beevers and Ross proposed the nomenclature BR (Beevers-Ross) and aBR (anti-Beevers-Ross), which it describes that plane is not compact and contain many empty sites where the Na+ ions are delocalized at high temperature leading a behavior similar to a bidimensional liquid.

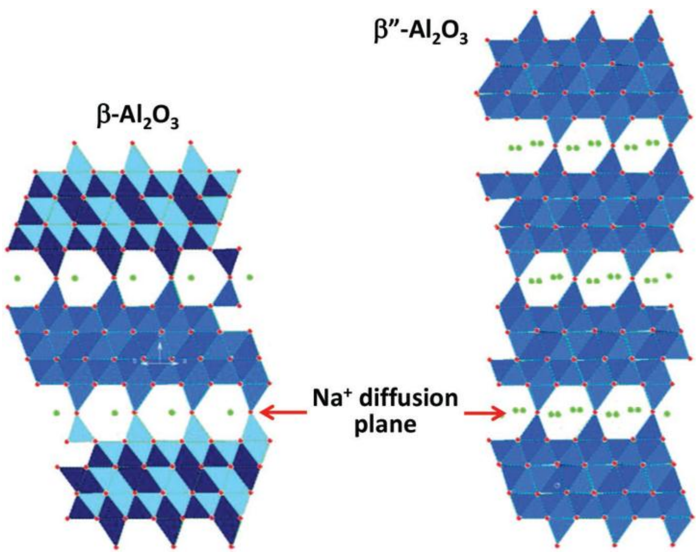

Figure 2.28. Sodium diffusion plane in the β-Al2O3 and β''-Al2O3. Source: (Delmas, 2018)

The table 2.25 shown a brief history of sodium technology in energy storage.

Table 2.18. Brief history of sodium technology in energy storage. Source: (Delmas, 2018)

Year	Description
1839	Faraday observed the ionic conductivity in the PbF2 and Ag2S
1884	Warburg showed the Na+ conductivity in Thüringer glasses
1897	Nernst developed the first application in zirconia filament lamp and proposed the Nernst equation
1930's	Frenkel, Krüger, Schottky, and Wagner contribute to laying the foundations of the solid-state electrochemistry Beevers and Ross proposed the nomenclature BR (Beevers-Ross) and aBR (anti-

Year	Description
	Beevers-Ross), where Na+ ions are delocalized at high temperature leading to a behavior like a two-dimensional liquid
1967	Takahashi introduces the concept solid state ionics Kummer and Yao discovered the high Na+ ion conductivity at intermediate temperatures
1969	Ford Company used liquid sulfur in the sodium-sulfur battery for electrical vehicles
1970	NGK company developed a system for stationary applications (peak leveling)
1973	Fouassier published the phase diagram of the NaxMnO2 and NaxCoO2 systems
1976	The intercalation of TiS2 and WO3 was considered in Na battery
1978	Hong and Kafalas proposed a Na Super Ionic Conductor (NASICON), which is a derivate of the NaZr2(PO4)3 phase Bordeaux began to research on the NaxMO2 layered oxides with special focus on the relationship between electrochemical intercalation and structural modifications Takeda studied the NaxFeO2 system
1982	Delmas et al. synthesized a new variety of O2-$LiCoO_2$ by Li^+/Na^+ exchange from P_2-Na_xCoO_2
1986	Bones, Coetzer, Galloway, and Teagle invented ZEBRA (Zeolite Battery Research Africa Project) batteries, in which sulfur is replaced by NiCl2
1987	Delmas et al. synthesized the $Na_3M_2(PO_4)_3$ phases which were potential electrode materials in the reduced state
2001	Dahn et al. studied layered $Na_x(Mn,Ni)O_2$ materials as precursors to obtain new lithium materials by exchange and also as positive electrodes for Na-batteries
2000 – 2008	The research on Na-batteries material was slowly increasing

NaS batteries are considered as secondary batteries (i.e. rechargeable) (DTU Energy, 2019) with solid electrochemical cell. So, the main components in NaS battery cell are Na electrode (anode), β''-alumina solid electrolyte (BASE), and sulfur electrode (cathode). The figure 2.29 shows a schematic of NaS battery cell.

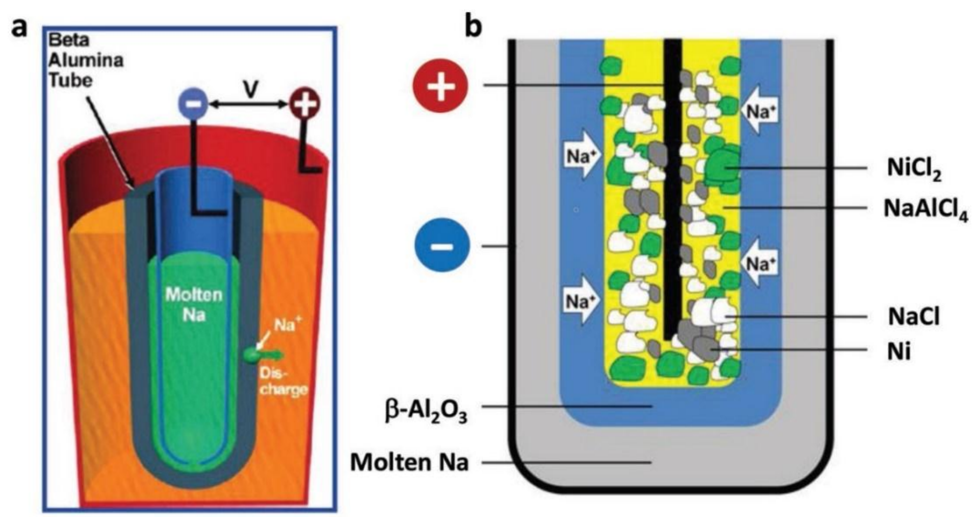

Figure 2.29. Schematic representation of NaS battery (a) and of ZEBRA battery (b). Source: (Delmas, 2018)

Sodium sulfur battery chemistries

The chemical reaction is a reversible reaction because the reactants form products that, in turn, react together to give the reactants back. This chemical reaction takes place usually in a closed system.

During the discharging process, the sodium electrode (anode) loses two electrons and produces Na+. The Na+ travels through the solid electrolyte and reacts with sulfur electrode (cathode) and two electrons to produce Na_2Sx. This process occurs at a potential of 1.78 – 2.08 V at 350 °C because the ionic resistance of β-alumina is then low like liquid aqueous electrolyte solutions (Holze, 2009). In the charging process, the reverse reactions take place when we apply energy into the system (Figure 2.30).

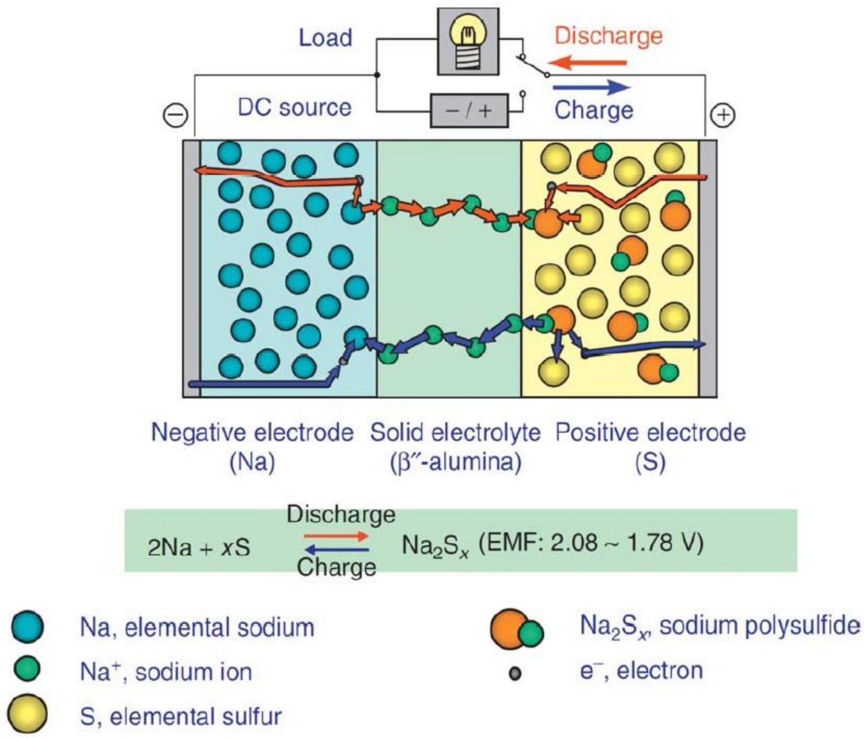

Figure 2.30. Discharge and charge reaction in NaS battery cell. Source: (DTU Energy, 2019)

Components in sodium sulfur battery energy storage system

The NaS battery energy storage system consists of three main components:

1. Battery modules (series-parallel array between NaS cells)
2. Power conversion system
3. Thermal management systems

In the first case, its components are sodium electrode, β-alumina, and sulfur electrode, mainly. In the last case, its components are (Holze, 2009):

- Active and/or passive cooling system
- Heat distribution system inside the cell
- Heater to maintain temperature in cold environments
- Thermal insulation system

Input/output

The input and output of sodium-sulfur battery is electricity.

Energy efficiency and losses

The daily self-discharge of NaS battery is 0.05 – 1 % when the NaS battery has an efficiency of 75 – 90 % (Nadeem, Hussain, Tiwari, Goswami, & Ustun, 2019). The energy efficiency in a battery depends on charge and discharge cycle (Koohi-Fayegh & Rosen, 2020). According to Figure 2.31, the sodium-sulfur battery has an energy efficiency around 80 – 90 % and a lifetime in terms of total number of cycles of approximately 1000 – 5000.

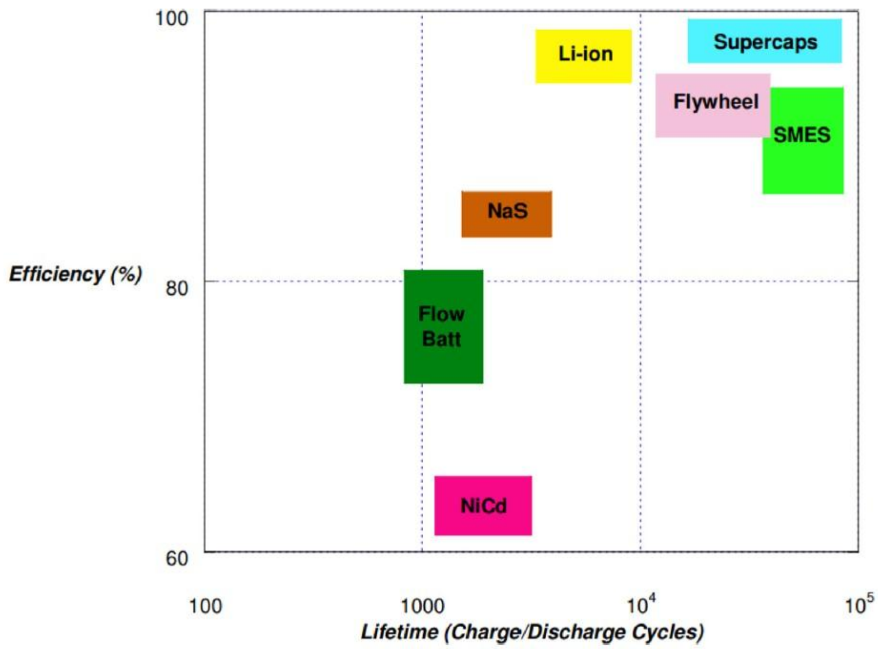

Figure 2.31. Efficiency and lifetime properties of energy storage technologies. Source: (Koohi-Fayegh & Rosen, 2020)

Typical characteristics and capacities

The typical characteristics and capacities of sodium-sulfur batteries are shown in Table 2.26.

Table 2.19. Principal characteristics for a sodium-sulfur battery. Source: (Koohi-Fayegh & Rosen, 2020)

Characteristics	Value
Power density (kW/m^3)	1 – 180
Energy density (kWh/m^3)	150 – 350
Energy density (Wh/kg)	100 – 250
Cycle efficiency (%)	65 – 90
Lifetime (cycles)	1000 – 4500

Typical storage period

This technology has a typical storage period from minutes to hours.

Regulation ability

The response time of a NaS battery since milliseconds, therefore it has a wide application on the grid (Nadeem et al., 2019). Consequently, its applications on the grid are:

Table 2.20. Type of services can be provided by NaS battery. Source: (Schmidt, Melchior, Hawkes, & Staffell, 2019)

Service	Can be provided
Energy arbitrage	√
Primary response	√
Secondary response	√
Tertiary response	√
Peaker replacement	√
Black start	√
T&D investment deferral	√
Congestion management	√
Bill management	√
Power quality	√
Power reliability	√

Examples of market standard technologies

Today, the applications are stationary like load-leveling, power quality management, peak shaving and localized storage at sites of wind or solar energy conversion systems (Holze, 2009).

Fumata, Japan

Fluctuating power generation is one of the principal problems for wind energy. In Futamata, there is a 51 MW wind farm supplemented with a constant-output stabilization system using 34 MW NaS batteries in 2008. The main features of NaS battery system are compactness, high efficiency, large capacity, long-term durability and preservation on the environment (Kawakami et al., 2010). The system configuration of this plant is shown in Table 2.28 and Table 2.29.

The voltage of common coupling point (CCP) is stepped down to 22 kV and 6.6 kV by three-winding transformer. The 17 sets of 2 MW NaS batteries (Figure 2.32) are connected to the 6.6 kV bus.

Table 2.21. System ratings. Source: (Kawakami et al., 2010)

Items	Ratings
Wind turbine	1.5 MW – 34 units
Total WT generation capacity	51 MW
NaS battery system	2 MW – 17 units
Total NaS battery storage capacity	244.8 MWh
Contracted generation capacity	40 MW
Voltage of common coupling	154 kV

Table 2.22. PCS specifications. Source: (Kawakami et al., 2010)

Items	Ratings
Rated capacity	2,400 kW – 17 units
Grid voltage	6600 V @ 50 Hz
Transformer voltage ratio	6600 V / 290 V
DC voltage (Battery voltage)	470 V □ 750 V
Converter type	Voltage source self-commutated converter
Converter configuration	2 level – 3 phases
Switching method	Pulse Width Modulation (PWM)
Switching frequency	2 kHz
Power device	Insulated Gate Bipolar Transistor (IGBT), (1200 V – 1400 A)
Cooling method	Forced air cooling

This system started commercial operation from September 2009.

Figure 2.32. 17 sets of 2 MW NaS batteries. Source: (Kawakami et al., 2010)

Advantage/disadvantage

The key advantages of NaS batteries are (Kumar, Kuhar, & Kanchan, 2018):

- High energy and power density
- High natural abundance of materials
- Low cost material
- Low rate of self-discharge

On the other hand, the disadvantages or limitations are (Kumar et al., 2018):

- Capacity fading
- Low discharge capacity
- Shuttle-mechanism[4]
- High annual operating cost. (IRENA, 2017).

Environment

All components in the NaS batteries are 98 % recoverable and eco-friendly. However, the local environmental impacts due to its manufacture, such as air pollution with graphite dust, local water contamination with acids in the immediate vicinity of factories, are an issue to be considered in a complete life cycle (Florin & Dominish, 2017).

[4] This phenomenon occurs during charging if polysulfides are reduced at the negative electrode, where electrons are readily available. The shorter polysulfides migrate back to the positive electrode where they are oxidized again. The current associated with these reactions does not contribute to charging the electrodes, causing a low coulombic efficiency. In addition, this effect contributes to commonly observed shortcomings of liquid-electrolyte cells like poor cyclability and high self-discharge rates.

Research and development

Several MWh systems have been demonstrated on the electrical grid, being the NaS battery the most used electrochemical storage system currently used in electricity grid. The largest system currently under construction is a 34-MW/238-MWh (7 hours) Na-S storage for the Rokkasho wind farm in northern Japan, while another one, for daily storage, has been built in a Hitachi factory with an energy content of 57 MWh. Other demonstration plants are built or under construction in the rest of the world (50 MW in Abu Dhabi, 1.2 MW in Charleston, USA), but an unclear recent accident in a storage system in Japan has temporarily stopped installation and production to clarify the safety aspects of the technology (EASE-EERA, 2017). Soon, the NaS battery could be considered as a mature technology.

Corrosion issues are a major ageing mechanism of high temperature cells. It can especially affect the larger cells that are preferred for stationary storage applications. To achieve lower cost of service from these batteries, it is therefore essential to continue developing robust materials, coatings and joints to address corrosion so as to increase the lifetime of the batteries (IRENA, 2017).

Another avenue of research includes the lowering of the high operating temperatures necessary to achieve satisfactory, electrochemical activity in sodium beta battery energy storage systems. Efforts center on improving ion transfer through the BASE ceramic electrolyte. The solid electrolyte interphase (SEI) is qualitatively recognized to be a dynamic structure, so it requires methods that can “see-through” model half-cells. It needs studies for determining the rate of parasitic Na loss, cycling Coulombic efficiency, solid-state electrolyte-Na metal interactions, as well as on coupled ex situ, in situ, and operando studies to probe bulk structural changes in the Na-metal anode (Lee, Paek, Mitlin, & Lee, 2019).

Prediction of performance and costs

The most data presented for NaS battery were obtained from (IRENA, 2017) and (Danish Energy Agency, 2019) because the design is based on the same operational capacities of the energy storage system.

The round-trip efficiency and technical lifetime were obtained for the average the several authors. The fixed and variable O&M were obtained from (Zakeri & Syri, 2015).

The NaS battery will not have a variation in this period due to its technological maturity. The technical lifetime and lifetime in total number of cycles have a similar trend that as(Danish Energy Agency, 2019). The specific investment, energy and capacity component have the same trend that as (IRENA, 2017).

Uncertainty

The most uncertainties for Nas battery were obtained from (IRENA, 2017) and (Danish Energy Agency, 2019) because the design is based on the same operational capacities of the energy storage system.

The uncertainty for round-trip efficiency has a similar numerical behavior from (Danish Energy Agency, 2019). The uncertainty for fixed and variable O&M is the same as (Zakeri & Syri, 2015) to keep the consistency between data.

Data sheet

Technology	NaS battery								
	2020	2030	2050	Uncertainty (2020)		Uncertainty (2030)		Note	Ref
Energy/technical data				Lower	Upper	Lower	Upper		
Form of energy stored	Electro-chemical								
Application	Frequency Restoration Reserve (2h)								
Energy storage capacity for one unit (MWh)	30	30	30	30	30	30	30		[1]
Output capacity for one unit (MW)	15	15	15	15	15	15	15		[1]
Input capacity for one unit (MW)	15	15	15	15	15	15	15	A	[1]
Round trip efficiency - DC (%)	81	83	83	69	90	72	93	average	[2], [3], [4], [5]
- *Charge efficiency (%)*	90	91	91	83	95	85	96	E	
- *Discharge efficiency (%)*	90	91	91	83	95	85	96	E	
Energy losses during storage (%/day)	0.1	0.1	0.1	0	1	0	1		[1], [2]
Forced outage (%)	0	0	0	0	2	0	2	B	[2]
Planned outage (weeks per year)	0	0	0	0	0	0	0	C	[2]
Technical lifetime (years)	19	24	24	10	28	13	36	average	[2], [4], [5]
Construction time (years)	0.5	0.5	0.5	0.2	2	0.2	2		[2]
Lifetime in total number of cycles	5600	7500	7500	1100	11200	1500	15000		[2]
Regulation ability									
Response time from idle to full-rated discharge (sec)	0.001	0.001	0.001	0.001	0.02	0.001	0.02	D	[2]
Response time from full-rated charge to full-rated discharge (sec)	0.05	0.05	0.05	0.001	0.05	0.001	0.05	D	[2]
Financial data									
Specific investment (MUSD2020 per MWh)	0.38	0.22	0.09	0.28	0.76	0.16	0.43		[1]
- energy component (MUSD/MWh)	0.291	0.162	0.050	0.208	0.582	0.116	0.324		[1]
- capacity component (MUSD/MW)	0.085	0.051	0.018	0.060	0.153	0.035	0.091		[1]
- other project costs (MUSD/MWh)	0.05	0.03	0.03	0.04	0.10	0.02	0.06		[2]
Fixed O&M (kUSD2020/MW)	4.0	4.0	4.0	2.2	19.2	2.2	19.2		[7]
Variable O&M (USD2020/MWh)	2.0	2.0	2.0	0.3	6.2	0.3	6.2		[7]
Technology specific data									
Alternative Investment cost (MUSD2020/MW)	0.767	0.435	0.178	0.555	1.517	0.312	0.852		[1]
Specific power (W/kg)	28	28	28	21	35	21	35	F	[2]
Power density (W/m3)	13000	13000	13000	9750	16250	9750	16250	F	[2]
Specific energy (Wh/kg)	56	56	56	42	70	42	70	G,H,I	[2]
Energy density (Wh/m3)	26000	26000	26000	19500	32500	19500	32500	G,H,I	[2]

Notes:

A. Assumed to be the same as output
B. Forced outage is minimal. Only reported case is a 2011 fire incident
C. On the order of 1 h per year
D. Due to absence of predictions in literature, no development is assumed as an estimate
E. In the absence of data, it is inferred from the round-trip efficiency which is assumed as the product of charge and discharge efficiency and is considered equal, also due to the lack of data
F. Specific power and power density were upscaled from [2] taking into account the different energy to power ratio
G. Data for standard NGK container unit, based on NGK Insulators LTD, "Structure of NAS Energy Storage System," 2016. [Online]. Available: https://www.ngk.co.jp/nas/specs/
H. Not the technological maximum values, i.e., the density of single cells, but the specifications for a full market-standard commercial product
I. Uncertainties are based on a qualified guess

The references in data sheet can be found in the quantitative data sheet file that supplements the qualitative technology description ("NaS.xlsx" file) as well as in "Appendix B references of datasheets"

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2.5 Vanadium redox flow batteries

Brief technology description

In the early 1970s, NASA developed the vanadium redox flow (VRF) battery for long-term space missions (L'Abbate, Dassisti, & Olabi, 2019). It is considered like an electrochemical system, a secondary battery, and is applicable at grid-scale and local user levels (DTU Energy, 2019; Tossaporn Jirabovornwisut & Arpornwichanop, 2019). The basic components of a VRF battery are shown in Figure 2.33.

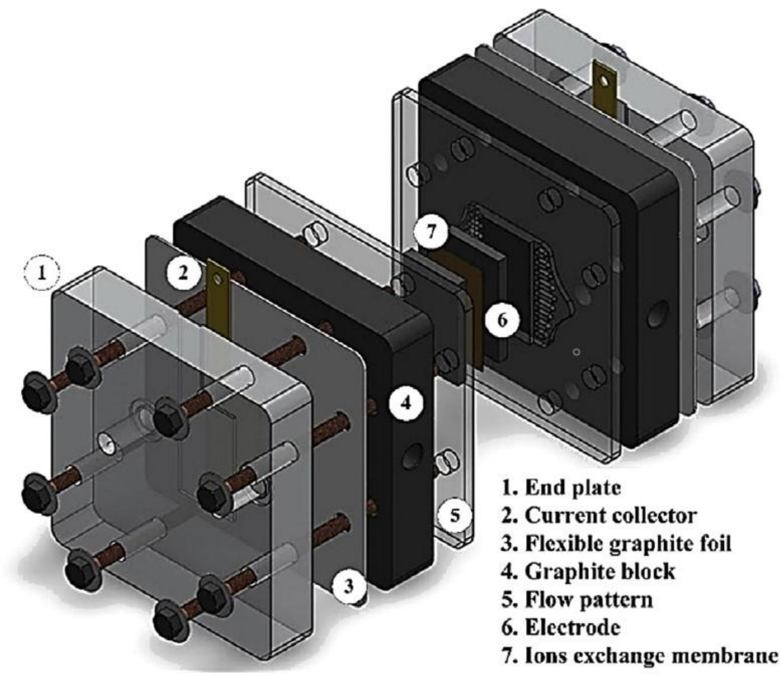

Figure 2.33. Cell components of single VRF battery cell. Source: (Tossaporn Jirabovornwisut & Arpornwichanop, 2019)

Electrolyte is made by dissolving vanadyl sulfate in sulfuric acid, which is corrosive to metals during VRF battery operation (Tossaporn Jirabovornwisut & Arpornwichanop, 2019). It is stored in two separate tanks, and pumped into the cells where the oxidation reaction occurs (L'Abbate et al., 2019). The analyte is in a tank and the catholyte is in another tank. During charging operation, the analyte is oxidized, the catholyte is reduced, and both electrolytes are stored in different tanks. The discharging process is when the oxidized analyte is reduced, the reduced catholyte is oxidized and then they are stored in the same tanks at the beginning.

The membrane can be an ions exchange membrane. Its main role is to prevent a short circuit between electrode and transfer of proton or sulfate ions for balancing the charge. It is important to have to good stability under highly oxidizing environment, low permeability of vanadium ions, and low resistivity (Tossaporn Jirabovornwisut & Arpornwichanop, 2019).

A VRF battery is an energy storage system being for use in a large-scale electric utility service (Tossaporn Jirabovornwisut & Arpornwichanop, 2019). But VRF is also capable for sessional storage. VRF battery technology is most frequently used for (L'Abbate et al., 2019):

- Electrical energy storage applications in industry
- Large fixed electrical storage systems
- Peak shifting

VRF battery consists of a reaction cell stack, at least one storage tank filled with electrolyte (anolyte) consisting of reactants in solution for the negative battery electrode (anode), at least one storage tank filled with electrolyte (catholyte) consisting of reactants in solution for the positive battery electrode (cathode), piping connecting the storage tanks with the reaction cell stack, and mechanical pumps to circulate the electrolytes in the system (DTU Energy, 2019) (Figure 2.34).

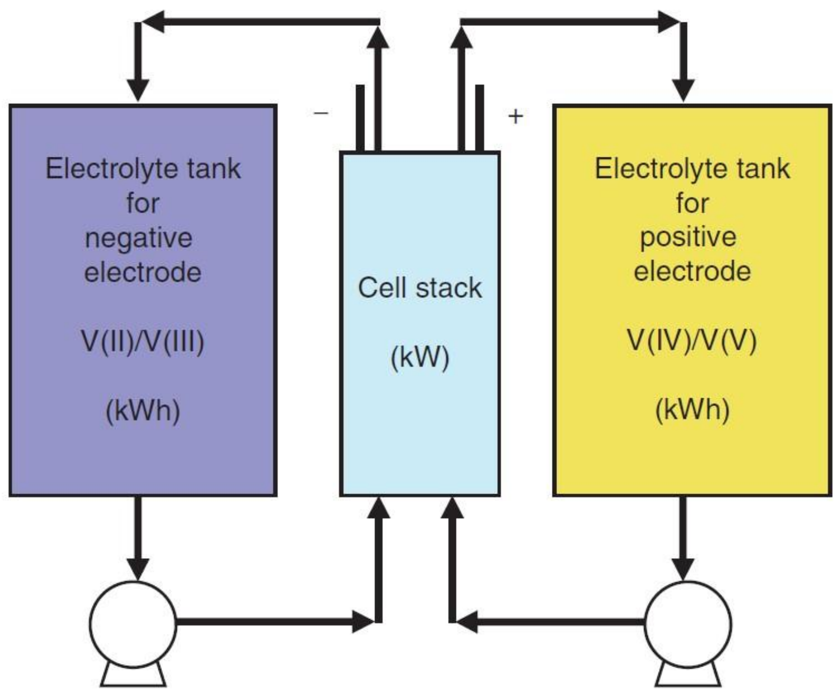

Figure 2.34. Redox flow concept. Source: (Skyllas-Kazacos, 2009)

VRF battery chemistries

Both positive and negative half-cells utilize redox coupled reactions in all VRF batteries, as reactions shown following (Tossaporn Jirabovornwisut & Arpornwichanop, 2019):

$$VO^{2+} + H_2O \xrightarrow{charge} VO_2^{+} + 2H^{+} + e^{-}$$

$$V^{3+} + e^{-} \xleftarrow[discharge]{} V^{2+}$$

Figure 2.35 shows four reaction mechanisms from the charging process. The anolyte reactive species are V2+ and V3+ ions. The catholyte reactive species are VO2+ and VO2+ ions with the V atom in oxidation state +V and +IV respectively. 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. When pumped into the reaction cell, the anolyte and catholyte will be separated by a proton conducting (polymer) membrane (DTU Energy, 2019).

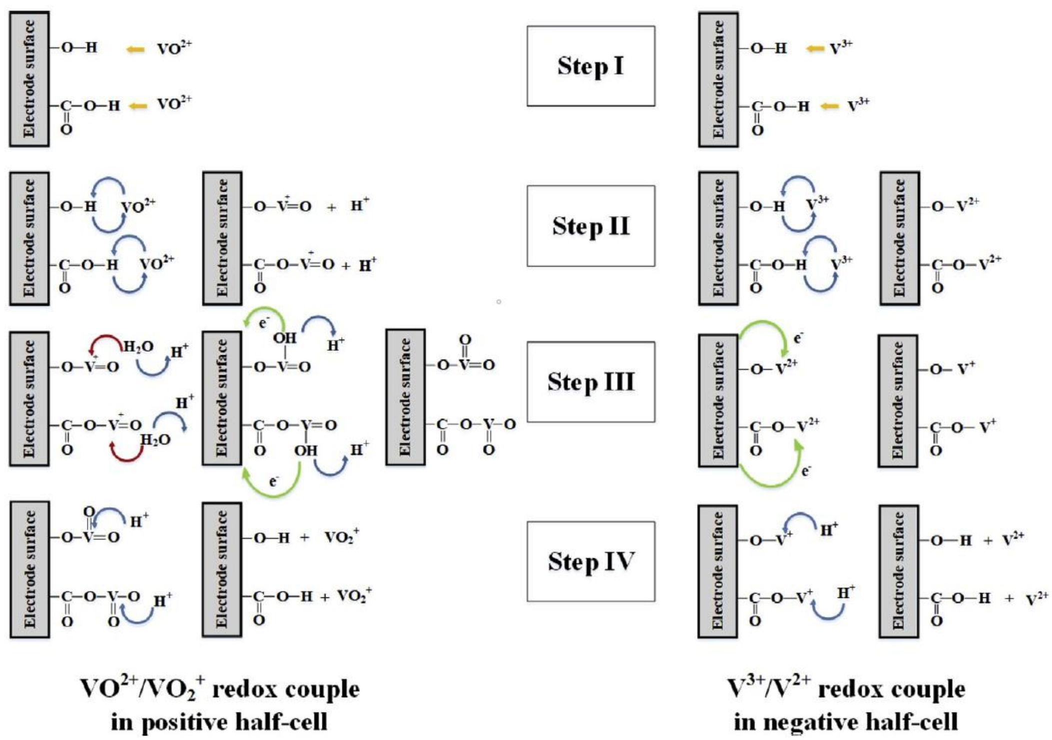

Figure 2.35. Reaction mechanism for VO^{2+}/VO_2^+ redox couples. Source: (DTU Energy, 2019)

Step one, the V^{3+} and VO^{2+} diffuse from bulk electrolyte to electrode surface and absorb on the oxygen functional groups. Step two, the ion exchange process between V^{3+} and VO^{2+} ions and the H^+ ions on C–OH and COOH functional groups takes place on the carbon surface. Step three, at the positive half-cell, one oxygen atom from H_2O transfers from hydroxyl functional groups (^-OH) to the electrode. Step four, the ion exchange between V ions attached on the electrode surface, H^+ ions in the electrolyte occurs and produces the VO_2^+ and V^{2+} ions as products in the charging process. During discharge, the reaction mechanism occurs in a reverse manner of the charging process (DTU Energy, 2019; Tossaporn Jirabovornwisut & Arpornwichanop, 2019).

Components in VRF battery energy storage system

A VRF battery installation consists of a VRF battery unit as described above, a battery management system, and a power conversion system connecting the battery unit to grid (see the Encyclopedia of Electrochemical Power Sources). Grid scale battery operation depends on the application. Batteries used for time shifting will generally complete a single charge/discharge cycle over 24 hours. Batteries used for various other grid services including stabilization of input from renewables will often not undergo traditional battery cycling but frequently switch between being charged and discharged according to demand (DTU Energy, 2019).

Due to its short response time combined with the ability to independently vary installation size of energy storage capacity and power capacity, VRF battery installations can be designed to provide a range of system services. The manufacturer UniEnergy Technologies lists the following applications for grid and utility installations: T&D deferral, flex capacity/ramping, load shifting, and ancillary services (DTU Energy, 2019).

Input/output

Input and output from a VRF battery are both electrical energies. The electrical energy input is provided by a power generation plant that can be based on either fossil fuels or renewable energy. This electrical energy is stored in chemical energy inside the VRF battery during the charging process. The electricity output is generated by conversion of this chemical energy from an electrochemical reaction during the discharge process.

Energy efficiency and losses

The capacity losses for a VRF battery can be caused by the following reasons (Tossaporn Jirabovornwisut & Arpornwichanop, 2019):

1) Capacity loss by self-discharging when the interface of the electrolyte encounters the air.
2) Diffusion of vanadium ions through the membrane caused by concentration gradient between half-cells.
3) Hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) can occur at the electrode surface when the electrode potential is higher, and it causes the consumption of applied current for battery charging.
4) Ohmic loss in the cells by high resistivity of membrane.
5) The electrolyte can be transferred across the membrane and cause an inequality of electrolyte volume and vanadium concentration.

The relation between cell voltage and current density during the charging-discharging process depends on the operating temperature as shown in Figure 2.36.

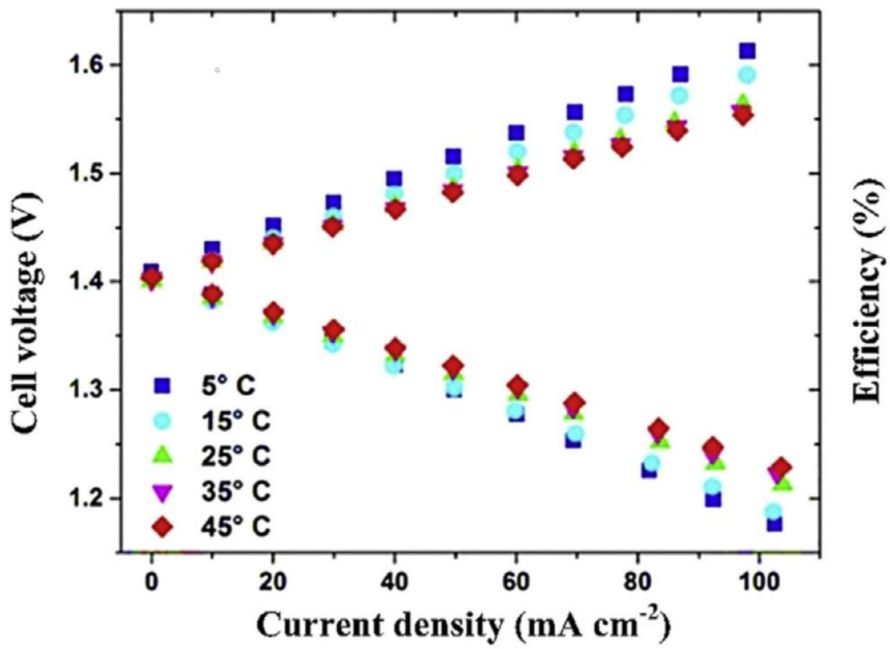

Figure 2.36. Effect of operating temperature on the charge-discharge battery voltage at 50 % SoC. Source: (T. Jirabovornwisut & Arpornwichanop, 2019)

The battery discharge capacity happens when the charging-discharging process has a current density of 40 mA ·cm^{-2} and the electrolyte tank is exposed to air oxidation. The VRF battery has very low parasitic and standby losses.

The performance of a VRF battery is characterized by its discharge capacity (DC), energy efficiency (EE), coulombic efficiency (CE), system efficiency (SE), and voltage efficiency (VE). The coulombic efficiency is a function of temperature as shown in Figure 2.37.

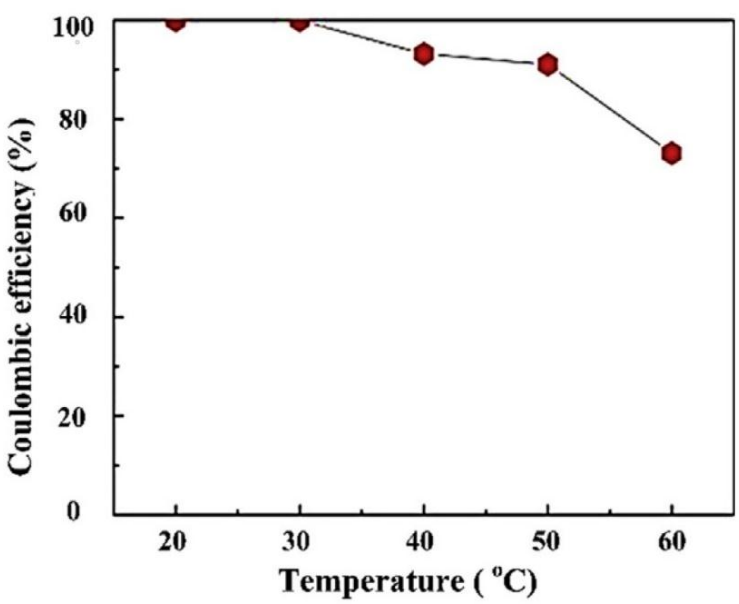

Figure 2.37. Correlation between CE and operating temperature for a solution 2 M H_2SO_4 + 2 M $VOSO_4$ with graphite electrode. Source: (Tossaporn Jirabovornwisut & Arpornwichanop, 2019)

The coulombic efficiency decreases with the increasing operating temperature as shown Figure 2.38. The reason is because the current applied for charging the battery is consumed by the hydrogen evolution reaction.

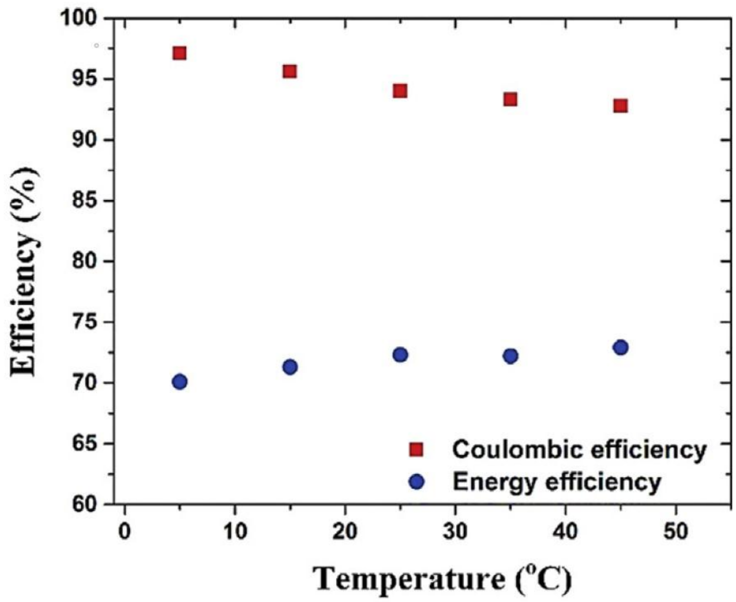

Figure 2.38. Coulombic and energy efficiency. Source: (Tossaporn Jirabovornwisut & Arpornwichanop, 2019)

The maximal energy density of a VRF battery is only 30 Wh/l (Ye et al., 2017). The efficiency and life cycle of the VRF battery are affected by membrane and electrode materials (Tossaporn Jirabovornwisut & Arpornwichanop, 2019). Table 2.30 shows cell efficiencies depending on different current densities.

Table 2.23. Cell efficiencies at different discharge currents. Source: (Skyllas-Kazacos, 2009)

Current density ($mA \cdot cm^{-2}$)	Voltage efficiency (%)	Coulombic efficiency (%)	Energy efficiency (%)
20	93	97	90
40	90	97	87
60	85	98	83
80	82	98	80
100	76	97	74

Typical characteristics and capacities

A VRF battery cell voltage is 1.26 V when operated at ambient temperatures (DTU Energy, 2019) and can typically store between 20 and 30 Wh/l of electrolyte (Lourenssen, Williams, Ahmadpour, Clemmer, & Tasnim, 2019).

Flow batteries are different from other batteries by having physically separated storage and power units. The volume of liquid electrolyte in storage tanks dictates the total battery energy storage capacity, while the size and number of the reaction cell stacks dictate the battery power capacity. The energy storage capacity and power capacity can thus be varied independently according to desired application and customer demand (DTU Energy, 2019). In Table 2.31 some characteristic features of VRF battery are shown.

Table 2.24. Characteristic features of VRF battery. Source: (Tossaporn Jirabovornwisut & Arpornwichanop, 2019)

Characteristic feature	Description
Flexibility in design	Power and energy capacity of the system can be separated
Power output	It is defined by the number of cells in the stack
Stored energy capacity	It is limited by the size of the electrolyte tank
Electrode material	Good electrochemical activity for the active species in a redox reaction, good stability during occasional overcharge, and low electrochemical activity for gas-make by side reactions.

When a VRF battery is operated a different temperature, this it will have different charge-discharge characteristic voltage as shown in Figure 2.39. For example, when the VRF battery is operated to 40 °C, the charge characteristic voltage at the beginning is 1.1 – 1.28 V and, then, it is moved gradually to 1.7 V. The discharge characteristic voltage has a similar behavior that the charge characteristic voltage but the other way around. At the beginning the voltage is 1.7 – 1.52 V, and it decrease gradually to 1.1 V. This is repeated in every cycle.

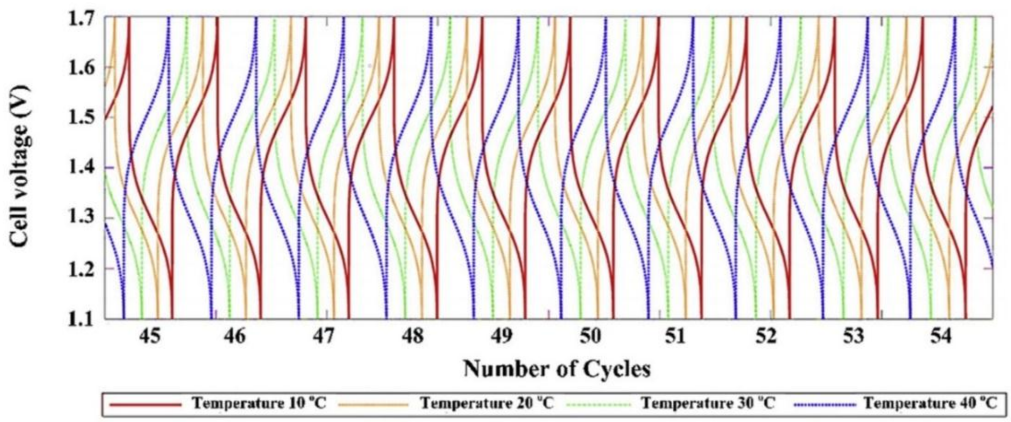

Figure 2.39. Charge-discharge characteristic voltage at different temperatures. Source: (T. Jirabovornwisut & Arpornwichanop, 2019)

Typical storage period

The self-discharge process occurs during storage period and was found that ionic species are ordered as follows V^{2+} > VO^{2+} > VO_2^{+} > V^{3+}. The self-discharge process is classified into five regions, according to variation in the open circuit voltage, as shown in Figure 2.40.

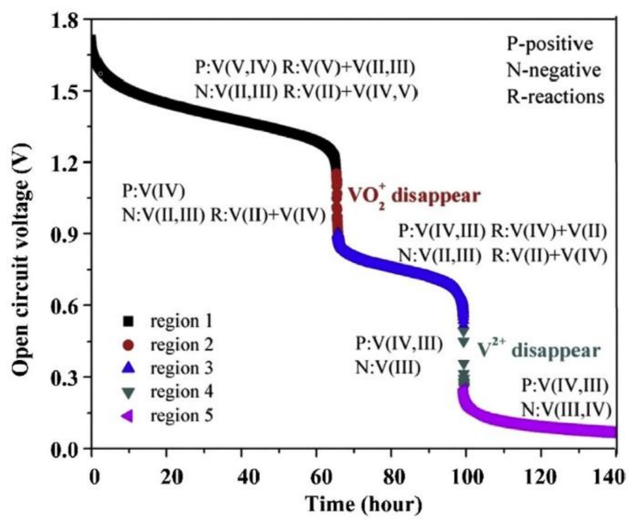

Figure 2.40. Open circuit voltage during the self-discharge process. Source: (Tossaporn Jirabovornwisut & Arpornwichanop, 2019)

Regulation ability

VRF can provide the following applications to the grid mentioned below:

Table 2.25. Type of services can be provided by VRF battery. Source: (Schmidt, Melchior, Hawkes, & Staffell, 2019)

Service	Can be provided
Energy arbitrage	√
Primary response	√
Secondary response	√
Tertiary response	√
Peaker replacement	√
Black start	√
Seasonal storage	√
T&D investment deferral	√
Congestion management	√
Bill management	√
Power quality	√
Power reliability	√
Seasonal storage	√

Examples of market standard technologies

At least 21 different installations of minimum 100 kW have been commissioned since 2011. The 21 installations have been supplied by at least 8 different manufactures. A 200 MW/800 MWh installation is currently under construction in Dalian in China.

Table 2.26. Examples of installations of VRF battery. Source: (Danish Energy Agency, 2019)

Location	Hokkaido, Japan	Pullman, USA	Braderup, Germany	Yokohama, Japan
Commissioning (year)	2016	2015	2014	2012
Energy storage capacity (MWh)	60	4	1	5
Power capacity (MW)	15	1	0.325	1
Technology provider	Sumitomo Electric Industries	UniEnergy Technologies	UniEnergy Technologies	Sumitomo Electric Industries

The following examples were the first employed in Japan, such as (L'Abbate et al., 2019):

- Tomamae Wind Villa in Japan. Stabilize a 32 MW wind farm to provide a maximum power of 4 MW/6 MW units.
- Vanteck has installed the first major commercial VRF battery outside Japan.

Advantage/disadvantage

There are several advantages and disadvantages of VRF battery technology. Table 2.34 summarizes this advantages and disadvantages.

Table 2.27. Advantage and disadvantage of VRF battery. Source: (Lourenssen et al., 2019)

Advantage	Disadvantage
Lowers levels of gas evolution during quick charge cycles relative to other flow batteries	Battery charge depleted and electrode surface area reduced from gas evolution
No solution contamination with diffusion of vanadium ions across the membrane	Gas evolution can damage and lower cell efficiency
Efficiency (70 to 90 %)	High oxidation properties of V^{5+}
Potential for electrolyte recycling between applications	Thermal regulation (10 to 40 °C)
Regeneration of ion crossover occurs through normal battery operation	

Environment

VRF battery requires a large amount of space to operate but is considered an environmentally sustainable battery because its components can be regenerated or recycled. On the other hand, it can be slightly toxic when the vanadium electrolyte is prepared (L'Abbate et al., 2019) because of sulfuric acid is corrosive and vanadium is a heavy metal (Letcher, 2016).

Research and development

The electrolyte used in VRF battery cells is considered as an acidic electrolyte, consequently, the metal electrode can corrode during VRF battery operation. Therefore, the electrodes used in VRF battery are carbon electrodes such as graphene oxide, carbon nanofibers, carbon nanotubes, and carbon paper. Other development is introducing an active site in redox reactions by surface treatment methods, such as acid treatment, electrochemical activation, metal doping, and thermal activation (Tossaporn Jirabovornwisut & Arpornwichanop, 2019).

VRF battery are under rapid development. There is significant potential for R&D to reduce cost of all battery components. An example is research in use of non-aqueous electrolytes. The minimum cost will likely be limited by the vanadium resource cost. The vanadium cost is not fixed in the sense that there is a potential for use of lower cost vanadium sources in production than those traditionally used. There is significant potential for cost reduction of flow batteries by using alternative reaction chemistries. An alternative is to use organic compounds or zinc-bromide, bromide-polysulfide, iron-chromium, and zinc-chloride for grid-scale applications (DTU Energy, 2019).

Prediction of performance and costs

The most data presented for VRF battery were obtained from (IRENA, 2017) and (Danish Energy Agency, 2019) because the design is based on the same operational capacities of the energy storage system.

The round-trip efficiency and technical lifetime were obtained for the average the several authors. The planned outage was obtained from (Lazard, 2016) due we suppose there is no interruption in the storage system. The fixed and variable O&M were obtained from (Zakeri & Syri, 2015).

The VRF battery will not have a variation in this period due to its technological maturity. The specific investment, energy and capacity component have the same trend that (IRENA, 2017). The fixed O&M has similar numerical behavior to (Danish Energy Agency, 2019).

Uncertainty

The most uncertainties for VRF battery were obtained from (IRENA, 2017) and (Danish Energy Agency, 2019) because the design is based on the same operational capacities of the energy storage system.

The uncertainty for round-trip efficiency, technical lifetime, other project cost and fixed O&M have a similar numerical behavior from as (Danish Energy Agency, 2019). The uncertainty for variable O&M is the same as (Zakeri & Syri, 2015) to keep the consistency between data.

Data sheet

Technology	Vanadium Redox Battery (VRB)								
	2020	2030	2050	Uncertainty (2020)		Uncertainty (2030)		Note	Ref
Energy/technical data				Lower	Upper	Lower	Upper		
Form of energy stored									
Application	Frequency Containment Reserve (4h)								
Energy storage capacity for one unit (MWh)	6.65	6.65	6.65	6.65	6.65	6.65	6.65		[1], Table 3
Output capacity for one unit (MW)*	1.66	1.66	1.66	1.66	1.66	1.66	1.66		[1]
Input capacity for one unit (MW)*	1.66	1.66	1.66	1.66	1.66	1.66	1.66		[1]
Round trip efficiency (%)	73	73	73	58	82	60	84	average	[2], [3], [4], [5], [6]
- *Charge efficiency (%)*	85	85	85	76	91	77	92		
- Discharge efficiency (%)	85	85	85	76	91	77	92		[3]
Energy losses during storage (%/day)	0.2	0.2	0.2	0	1	0	1		[1]
Forced outage (%)	0.5	0.5	0.5	0	5	0	5	A	[2]
Planned outage (weeks per year)	0	0	0	0	0	0	0	A	[2], [4]
Technical lifetime (years)	14	14	14	4	16	5	18	average	[2], [3], [4]
Construction time (years)	1	1	1	0.2	2	0.2	2	B	[2]
Lifetime in total number of cycles	13000	13000	13000	12000	14000	12000	14000		[1]
Regulation ability									
Response time from idle to full-rated discharge (sec)	0.1	0.1	0.1	0.005	2	0.005	2	C	[2]
Response time from full-rated charge to full-rated discharge (sec)	0.07	0.07	0.07	0.004	1.4	0.004	1.4	C	[2]
Financial data									
Specific investment (MUSD2020 per MWh)	0.602	0.319	0.111	0.508	1.238	0.266	0.624		
energy component (MUSD2020 per MWh)	0.521	0.276	0.077	0.445	1.092	0.234	0.549	D	[1]
capacity component (MUSD2020 per MW)	0.085	0.051	0.018	0.060	0.153	0.035	0.091	E	[1]
- other project costs (MUSD/MWh)	0.06	0.030	0.030	0.05	0.11	0.02	0.05	F	[2]
Fixed O&M (kUSD/MW/year)	9.44	4.13	3.89	3.77	19.20	1.65	8.40	G	[8], [2]
Variable O&M (USD2020/kWh/year)	1.0	1.00	1.00	0.22	2.31	0.22	2.31		[8], [2]
Technology specific data									
Alternative Investment cost (M$USD2020/MW)	2.410	1.275	0.446	2.032	4.953	1.062	2.498		
Specific power (W/kg)	3.0	3.0	3.0	1.5	3.7	1.5	3.7		
Power density (W/m3)	2260	2260	2260	1130	2825	1130	2825	average	
Specific energy (Wh/kg)	11.8	11.8	11.8	5.9	14.75	5.9	14.75		[2]
Energy density (Wh/m3)	9040	9040	9040	4520	11300	4520	11300		[2]

Notes:

A. Some companies guarantee at least 99.5% uptime
B. Depends highly on the installation
C. Time is less than 100 ms for idle situation with electrolyte in reaction stack and pumps on. Less the 1 s if electrolyte must first be pumped. Less than 1 min if pumps are not on. PCS might be limiting the response time [2]
D. This data is interpreted within the IRENA tool as: "Energy Installation cost+(Power Installation Cost/4 hr)"
E. This data is interpreted within the IRENA tool as: "Power Installation cost"
F. Value for utility T&D installations with discharge time of 4 hours used
G. 2020 value is taken from [8], while the projections follow the relative decrease in costs from [2], based on the 2020 value

The references in data sheet can be found in the quantitative data sheet file that supplements the qualitative technology description (“VRB.xlsx” file) as well as in “Appendix B references of datasheets”

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2.6 Molten salt

Brief technology description

Molten salt is a technology for storing thermal energy sensible at high temperature and an electrochemical energy storage device that uses molten salts as electrodes and/or electrolytes (DTU Energy, 2019; Lu & Yang, 2015) in the known high temperature batteries, such as sodium sulfur (NaS) technology, or sodium nickel chloride ($NaNiCl_2$). Thermal energy storage by molten salts account for 75 % deployed thermal energy storage (TES) used for electricity applications and are commercial solution (Fernández et al., 2019).

It is heated sensibly and, then stored in large insulated tanks for later use. It is classified like thermal energy storage in liquids (DTU Energy, 2019).

The compounds used in molten salt are inorganic salts and their operating temperature is at 500 – 600 °C. With this temperature, they produce superheated steam via a heat exchanger to power a conventional steam turbine and then generate electricity. This technology offers high energy and power density (Lu & Yang, 2015). Consequently, it is used in stationary Concentrated Solar Power plants (CSP) (DTU Energy, 2019). A main component is CSP technology it shows in (Figure 2.41).

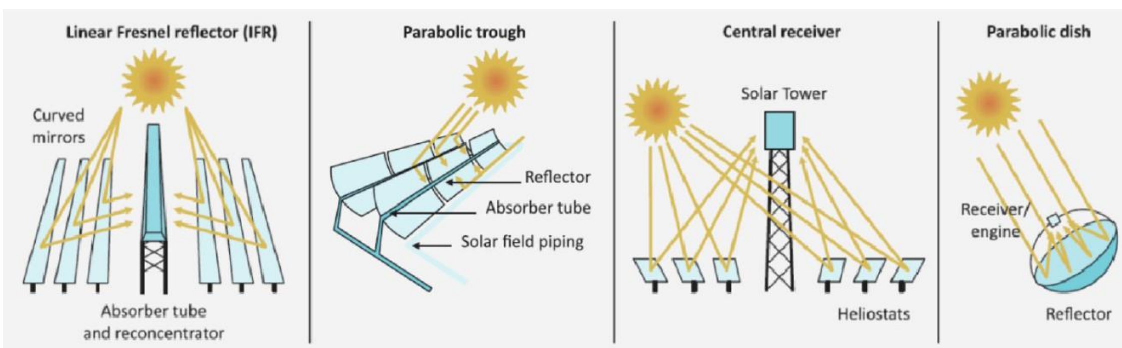

Figure 2.41. CSP technology types. Source: (Fernández et al., 2019)

Molten salt mixtures

Nitrates or nitrides salts are commonly used in molten salt storage technology but also carbonates, for example binary mixture of 60 % $NaNO_3$ and 40 % KNO_3 by weight, this material is called "solar salt". It has a fusion point around 222 °C. It is not aggressive in terms of corrosion of a variety of metals and alloys, including stainless steels and other ferrous alloys (DTU Energy, 2019). These salts have favorable thermophysical properties and low cost for TES (Bell, Steinberg, & Will, 2019). Some key properties of carbonate salt mixtures developed for CSP. Some key properties of carbonates salt mixture are shown in Table 2.35.

Table 2.28. Melting point and heat capacities of carbonate salt mixtures. Source: (DTU Energy, 2019)

System	Temperature (°C)	cp ($J \cdot g^{-1} \cdot °C^{-1}$ at 600 °C)
$LiF\text{-}K_2CO_3$	482	1.85
$LiF\text{-}Li_2CO_3$	608	1.88
$NaF\text{-}Na_2CO_3$	690	1.78
$Li_2CO_3\text{-}K_2CO_3$	503	2.03
$Li_2CO_3\text{-}Na_2CO_3\text{-}K_2CO_3$	398	1.70
$LiF\text{-}Na_2CO_3\text{-}K_2CO_3$	389	1.74
$LiF\text{-}NaF\text{-}K_2CO_3$	422	1.81
$LiF\text{-}KF\text{-}K_2CO_3$	438	-
$LiF\text{-}NaF\text{-}Na_2CO_3\text{-}K_2CO_3$	423	1.85
$LiF\text{-}NaF\text{-}Li_2CO_3\text{-}Na_2CO_3$	444	1.88

Components in molten salt energy storage system

There are many types of molten salt storage system, such as molten salt steam-accumulator, two tanks direct, two tanks indirect, and concrete storage.

The typical configuration for Parabolic Trough Systems (PTCs) the molten salt two tank indirect system with synthetic oil heat-transfer fluid (HTF) (Figure 2.42).

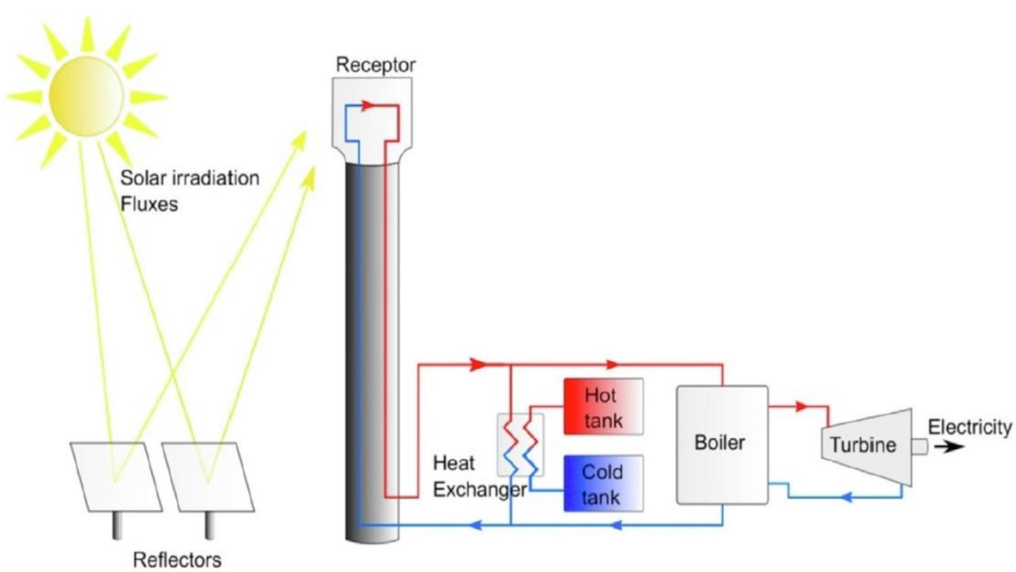

Figure 2.42. Molten salt two indirect concept. Source: (Fernández et al., 2019)

Therefore, the components in molten salt storage system are:

- Concentrated solar power, mainly reflectors and receptors
- Heat exchanger
- Hot tank
- Cold tank
- Boiler
- Turbine

Input/output

The input of energy storage is thermal energy. The output of energy storage is electricity. The temperature of solar salt for energy storage is between 200 – 250 °C. The mixture suggested for energy storage is of 40% KNO_3 and 60% $NaNO_3$ by weight.

Energy efficiency and losses

The thermal efficiency of solar power tower is between 30 to 40 % (Islam, Huda, Abdullah, & Saidur, 2018). There is little information about energy efficiency, energy, and operational losses because of the molten salt energy storage system always is associated with CSP.

Typical characteristics and capacities

Molten salt is a technology for storing thermal energy sensible at high temperatures and is used in CSP. In the world, just there are two CSP with molten salt. Consequently, the typical characteristics and capacities will depend on plant size and the location.

Typical storage period

The typical storage period of molten salt storage in usage with CSP is between 6 to 10 h (Islam et al., 2018).

Regulation ability

The thermal energy storage is not applicable for rapid response requirements (Luo, Wang, Dooner, & Clarke, 2015). Consequently, the molten salts can provide the following applications on the grid such as:

Table 2.29. Type of services can be provided by molten salt. Source: (Luo et al., 2015)

Service	Can be provided
Energy management	√
Peak shaving	√
Seasonal storage	√

Examples of market standard technologies

Agua Prieta II, Mexico

This plant it was design to use parabolic trough collectors (PTCs) but it does not use molten salt TES, whereas it could use it. The project is an integrated solar combined cycle (ISCC) called "Agua Prieta II" (Figure 2.43) and began operations on July 1, 2018. It is considered such as the first ISCC in Latin America.

Figure 2.43. Agua Prieta II combined cycle power station. Source: (SENER, 2016)

The Table 2.37 shown Agua Prieta II project overview.

Table 2.30. Agua Prieta Project overview. Source: (CENACE, 2019; NREL, 2013)

Owner	Federal Electricity Commission	Land area	60 ha
Turbine capacity (Net)	12 MW	Electricity generation	34,000 MWh/year
Turbine capacity (Gross)	14 MW	Project type	Commercial
Developer	Abengoa Solar	Solar field aperture area	85,000 m2
# Solar collector assemblies (SCA)	104	# of loops	26
# SCA's per loop	4	SCA length	150 m

Mirror manufacturer	Rioglass	Heat-transfer fluid type	Thermal oil
Output type	Steam rankine	Estimated investment	560,700,000 USD

Agua Prieta II has a capacity factor close to 0.3 (Figure 2.44).

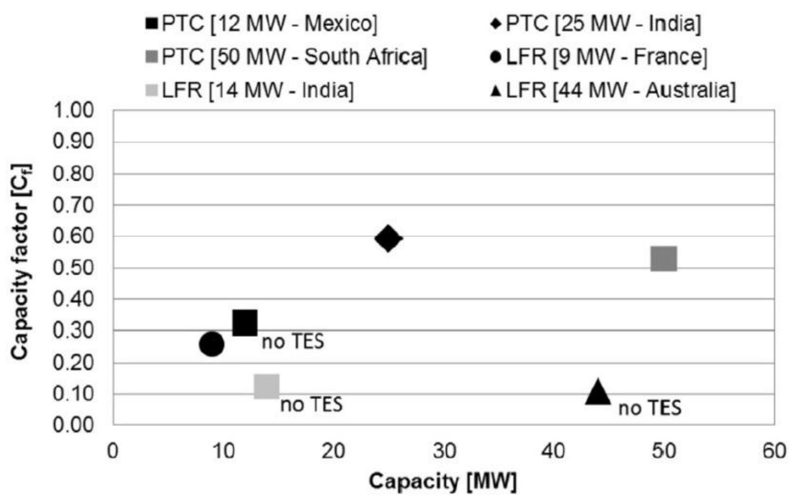

Figure 2.44. Capacity factor for PTCs and Linear Fresnel Reflectors (LFRs) technology CSP plants. Source: (Fernández et al., 2019)

Solana Solar Generating Plant, US

The Solana Generating Plant is a concentrating solar power project in Arizona. It began its construction in 2010 and started operation in 2013. It has a power capacity of 280 MW with a duration of 6 h (Koohi-Fayegh & Rosen, 2020) from the energy produced by a 780-ha solar field formed by 3232 PTC's (Figure 2.45). Its application principal is for renewable energy time-shifting (Koohi-Fayegh & Rosen, 2020).

Figure 2.45. Solana Solar Generating Plant. Source. (NREL, 2015)

Ain Beni Mathar, Morocco

The Ain Beni Mathar solar-gas hybrid power plant is the first in the world and the largest capacity – 470 MW – to provide services. 20 MW of its capacity is obtained from the energy produced by a 62-hectare solar field formed by 224 PTCs. The remaining 450 MW is from a conventional combined cycle comprising a steam turbine (150 MW) and two gas turbines (150 MW x 2).

Figure 2.46. Ain Beni Mathar power plant. Source: (ABENGOA, 2019)

The Table 2.38 shows Solana Solar Generating Plant project overview.

Table 2.31. Solana Solar Generating Plant project overview. Source: (NREL, 2015)

Owner	Atlantica Yield & Liberty Interactive Corporation	Land area	780 ha
Turbine capacity (Net)	250 MW	Electricity generation	900,000 MWh/year
Turbine capacity (Gross)	280 MW	Project type	Commercial
Developer	Abengoa Solar	Solar field aperture area	2,200,000 m2
# Solar collector assemblies (SCA)	3232	# of loops	808
# SCA's per loop	4	# of modules per SCA	10
Mirror manufacturer	Abengoa Solar (E2)	Heat-transfer fluid type	Therminol VP-1
Output type	Steam rankine	Estimated investment	2,000,000,000 USD
Storage type	2-tank indirect	Storage capacity	6 h
Storage description	Molten salt		

Advantage/disadvantage

The main advantages are (Fernández et al., 2019; Yang, Weng, & Xiao, 2020):

- Cutback in real time net power variability in the event of pool solar radiation
- Extension of the whole production period
- High faradaic efficiency
- High reaction rate
- Low temperature (< 500 °C)
- Rearrangement of production toward high-price periods

The main disadvantage are (Yang et al., 2020):

- Corrosive medium
- Low stability of electrode materials

Environment

In general, this type of storage is associated with the generation of electrical energy through CSP. It is considered a high impact on the use of land associated with solar concentration fields, although storage is not in itself the cause of this impact.

Research and development

Since the technology depends on insulation to keep the temperature above the melting point of the used salt, improved insulation techniques and materials are required. Furthermore, the high temperature in combination with salts may set tough requirements on materials used in pipes, valves, fittings and containments in general. The research for this technology is to operate at the best performance with temperatures above 560 °C and the phase change materials (PCMs) in their thermal storage systems (Bell et al., 2019).

Other challenges are (Islam et al., 2018):

- Thermal performance and economics of storage medias
- Impact of different types of TES systems could reduce cost and increase CSP efficiency

Prediction of performance and costs

The most data presented for molten salt were obtained from (Epp, 2018) and (Fedato et al., 2019) because the design is based on the same operational capacities of the energy storage system. The round-trip efficiency and energy losses throughout the storage process is the average value obtained from a small number of references reviewed by different authors.

It's supposed that the response time from idle to full-rated discharge of CAES is very similar for molten salt because the technical response of the technology is comparable because the energy generation equipment is similar. This data was obtained from (Danish Energy Agency, 2019). The specific investment, energy and capacity component was obtained from consultation with analyst of the GRIDSOL (See: https://www.gridsolproject.eu/) project through the Danish Energy Agency.

It is expected the molten salt will not have a significant variation in the near future due to its technological maturity.

Uncertainty

Furthermore, compressed air energy storage (CAES), sodium-sulfur batteries, flywheel (low speed), molten salt, and lithium-ion batteries are in the stage of deployment technology, but its capital requirements and technology risk are high.

The most uncertainties for molten salt will not have a variation due to its limited technology penetration. The energy storage by molten salt is a deployment technology and its capital requirements and technology risk are high. The uncertainty for energy losses during storage is the same to as in (Epp, 2018; Trabelsi, Chargui, Qoaider, Liqreina, & Guizani, 2016).

The uncertainty for specific investment, energy and capacity component was obtained from consultation with analyst of the GRISOL project through the Danish Energy Agency.

Data sheet

Technology	Molten Salt								
	2020	2030	2050	Uncertainty (2020)		Uncertainty (2030)		Note	Ref
Energy/technical data				Lower	Upper	Lower	Upper		
Form of energy stored	Thermal								
Application	CSP Plant / Energy intensive/ 9 h								
Energy storage capacity for one unit (MWht)	1362	1362	1362	1362	1362	1362	1362		[1]
Output capacity for one unit (MWth)	150	150	150	150	150	150	150	A	[1]
Input capacity for one unit (MWth)	256	256	256	256	256	256	256		[1]
Round trip efficiency (%)	95	95	95	95	95	95	95	Average	[1], [3], [2]
- *Charge efficiency (%)*	97	97	97	97	97	97	97		
- *Discharge efficiency (%)*	97	97	97	97	97	97	97		
Energy losses during storage (%/day)	3	3	3	1	5	1	5		[2], [4]
Forced outage (%)	n.a.								
Planned outage (weeks per year)	n.a.								
Technical lifetime (years)	30	30	30	30	30	30	30		[1]
Construction time (years)	n.a.								
Lifetime in total number of cycles	10000	10000	10000	10000	10000	10000	10000		[2]
Regulation ability									
Response time from idle to full-rated discharge (sec)	700	700	700	700	700	700	700	I	[5]
Response time from full-rated charge to full-rated discharge (sec)	-								
Financial data									
Specific investment (MUSD per MWht)	0.221	0.215	0.211	0.218	0.228	0.212	0.220	B, E	[3]
- energy component (MUSD$/MWht)	0.022	0.016	0.013	0.02	0.03	0.014	0.022	D, H	[3]
- capacity component (MUSD$/MW)	1.056	1.056	1.056	1.056	1.056	1.056	1.056	C	[3]
- other project costs (M$/MWh)	n.a.								
Fixed O&M (kUSD$/MW)	18.1	18.1	18.1	18.1	18.1	18.1	18.1	C1	[1]
Variable O&M (USD$2018/MWh)	0.78	0.78	0.78	0.78	0.78	0.78	0.78	C2	[1]
Technology specific data									
Alternative Investment cost (M$USD/MW)	1.175	1.141	1.124	1.162	1.216	1.130	1.173	F	[1]
Specific power (W/kg)	14	14	14	8	21	8	21	G	[2]
Power density (W/m3)	26	26	26	14	38	14	38	G	[2]
Specific energy (Wh/kg)	75	75	75	40.0	110.0	40.0	110.0		[2]
Energy density (Wh/m3)	138	138	138	75.0	200.0	75.0	200.0		[2]

Notes:

A. The value is inferred from reference [2], from the base capacity and storage values proposed for the analysis
B. This is comprised by both reference [2] and [6]. It is inferred through the previous data of energy component, capacity component and nominal capacity
C. Units adapted from the reference

C1. With fixed O&M cost of the steam turbine at 10.1kUSD/MW, and fixed O&M costs of the thermal energy storage at 8.0kUSD/MW

C2. With variable O&M cost of the steam turbine at 0.4 USD/MW, and variable O&M costs of the thermal energy storage at 0.3kUSD/MW

D. In the information obtained by the analysts of the Gridsol project, it is mentioned an indication of the range for 2020 was between 18,000 (large plant) and 30,000 (small plant) €/MWh-th. This data was considered at the reference uncertainty 2020
E. The costs per kilowatt-hour also depend on the storage temperature, as this temperature has an influence over how much energy is stored, given the same initial capital expenditures. For example, storing heat at 550 °C could double the storage capacity compared to heat at 400 °C, which means that the costs per kilowatt-hour will be cut in half
F. Thermal energy storage expressed per capacity in reference [2]

G. Dependent on the power conversion/heat exchanger and derived from the residual characteristics mentioned in the sheet
H. An indication of the uncertainty for 2030 was obtained by a similar range of uncertainty of 2020.
I. Qualitative assessment by the authors is based on that consideration of Molten Salt storage shares characteristics with CAES to an extent in that a heat exchanger and turbine (driven by either hot air or steam) are applied. Therefore, expect similar response times

The references in data sheet can be found in the quantitative data sheet file that supplements the qualitative technology description ("Molten_Salt.xlsx" file) as well as in "Appendix B references of datasheets"

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2.7 Compressed air energy storage

Brief technology description

A Compressed Air Energy Storage (CAES) system stores kinetic energy in the form of compressed air in a reservoir by increasing the pressure with a gas compressor. Large-volume air reservoirs are usually caverns, which are essential for large-scale CAES plants. In order to find suitable storage caverns for the compressed air, old natural salt deposits or depleted gas fields can be conditioned for use. Costs are significantly lower where an existing and suitable cavern is available. Constructing a purpose-built cavern to hold the compressed air increases the energy storage costs dramatically (IRENA, 2017).

Heat generated during compression can be stored in order to increase the round-trip efficiency. During discharging the air from the cavern or pressure vessel is released and drives the expander of a turbo, piston or radial expander. Before expansion the compressed air must be preheated to avoid freezing of the expander. In case that the heat from compression is used to preheat the air before expansion the process is adiabatic (A-CAES). If external heat input is used to preheat the air by combustion the process is diabatic (D-CAES) (EASE-EERA, 2017).

In order to compensate for the temperature drop, CAES technology is used in combination with gas turbine combustion. Therefore, CO2 is released in traditional CAES (Danish Energy Agency-ENERGINET, 2019).

Adiabatic compressed energy storage (AA-CAES, sometimes also called advanced adiabatic compressed air energy storage, AA-CAES) systems are a more recently developed concept that addresses this issue. In the A-CAES concept, the heat that normally would be released to the atmosphere during the compression phase is stored in a thermal energy storage (TES) system. This heat is added back through heat exchangers to the expanding air that is being released from the reservoir during expansion-mode operation.

This enables A-CAES systems to convert the energy in the compressed air to electricity without involving a combustion process and avoiding related emissions (IRENA, 2017). In contrast to this, conventional CAES systems are diabatic because of the exchange of heat between the storage system and the environment. Figure 2.47 schematically compares these two systems.

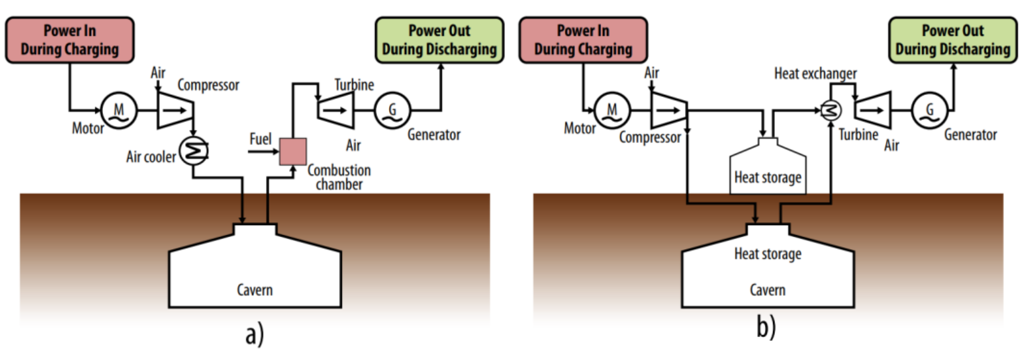

Figure 2.47. Schematic diagram of diabatic (a) and adiabatic (b) CAES systems. Source: (IRENA, 2017)

The CAES system is often used for large scale storage with frequent cycling capabilities because it is a cost-effective, mature, and reliable technology (Koohi-Fayegh & Rosen, 2020).

Mechanical principle

CAES stores mechanic energy and the input is electricity to drive an air compressor. Compressed air can subsequently be stored in pressure tanks or in huge amounts in underground cavities, where such suitable formations are available. When release of the stored energy is required, the compressed air is used to drive a turbine able to generate electricity. The expansion of air is associated with a temperature drop, which causes a loss of energy (DTU Energy, 2019).

Components in CAES system

The main components in adiabatic CAES system are (Komarnicki, Lombardi, & Styczynski, 2017):

- Low pressure compressor
- Intercooler
- High pressure compressor
- Motor generator
- Thermal energy storage
- Cavern, or potentially other alternative artificial pressure containers.
- Heat exchanger
- Turbine

Input/output

The input of CAES system is electric energy, which is converted to mechanical energy in the process. For diabatic CAES systems, additional fuel is needed to power the gas turbine.

The output of CAES system is electric energy. Diabatic CAES releases heat into the environment, while A-CAES contains the arising heat from the conversion process in the TES.

Energy efficiency and losses

The daily self-discharge is around 0 % (Nadeem, Hussain, Tiwari, Goswami, & Ustun, 2019). The energy efficiency for CAES system based on operating plants is 42 to 55 % (Koohi-Fayegh & Rosen, 2020). As there are only two commercial plants worldwide, there is little experience in terms of operation despite its technological maturity. Therefore, there is ongoing research on how the efficiency can be improved further. There is little information about energy efficiency, energy, and operational losses because of there are now only two CAES plants.

Typical characteristics and capacities

The typical characteristics and capacities are shown in Table 2.39.

Table 2.32. Typical characteristics of CAES system. Source: (Koohi-Fayegh & Rosen, 2020; Nadeem et al., 2019)

Characteristics	Value
Power density (kW/m^3)	0.04 – 10
Energy density (kWh/m^3)	0.4 – 20
Energy density (Wh/kg)	3 – 60
Cycle efficiency (%)	41 – 90
Lifetime (cycle)	> 104
Installed commercial capacity (MW)	35 – 300
Lifetime (years)	20 – 40

Typical storage period

The typical storage period for CAES is of approximately 8 hours (Kaldemeyer, Boysen, & Tuschy, 2016).

Regulation ability

CAES usually is used for grid management but it is expected to use for integrating renewable energy sources (Koohi-Fayegh & Rosen, 2020). The applications in the grid are:

Table 2.33. Type of services can be provided by CAES. Source: (Schmidt, Melchior, Hawkes, & Staffell, 2019)

Service	Can be provided
Energy arbitrage	√
Secondary response	√
Tertiary response	√
Peaker replacement	√
Black start	√
Seasonal storage	√
T&D investment deferral	√
Congestion management	√

Examples of market standard technologies

There is not a living market for CAES plants. Although the concept of CAES has been considered favorable for energy storage for many years for storing variable, renewable energy, only two plants have been realized until now, the first in Huntorf, Germany, in 1978 and the second in McIntosh, Alabama, USA, in 1991.

The Huntorf plant uses 0.8 kWh of electricity and 1.6 kWh of gas to produce 1 kWh of electricity and was the world's first CAES plant when it was commissioned in 1978. The newer McIntosh plant includes a recuperator, which recycles waste heat from the exhaust stream and uses 0.69 kWh of electricity and 1.17 kWh of gas to produce 1 kWh of electricity.

Table 2.34. Comparation Comparison of different example CAES system. Source: (Danish Energy Agency-ENERGINET, 2019)

Characteristics / CAES System	Hunfort, Germany (1978)	McIntosh, USA (1991)
Turbine power / Discharge time	Old 290 MW / 2 hrs 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	2.7	1.6
Efficiency Heat rate	42 % 6700 BTU / kWh (without heat recuperator)	54 % 4100 BTU / kWh (with heat recuperator)
Availability Reliability Star-up reliability	90 % 97 % 95 %	90 % 97 % 95 %
Cavern	2 x 150,000 m^3 (salt cavern)	538,000 m^3 (salt cavern)

Advantage/disadvantage

There are currently only two CAES system, called the Huntorf (Germany, 1978) and McIntosh plant (USA, 1991). Consequently, the advantages and disadvantages are about these plants. Advantages (Danish Energy Agency, 2019; Koohi-Fayegh & Rosen, 2020):

- The CAES plant can provide significant energy storage (typically around a few GWh per plant) at relatively low costs (approximately (in 2003 USD) $1/kWh to $40/kWh. The plant has practically unlimited flexibility for providing significant load management at the utility or regional levels.

- Expanders have a large size range and can easily be used modularly. 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. (EPRI-DOE, 2003)
- 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.
- CAES can potentially have a very high energy storage capacity if a cavern with large gas volume is available.
- CAES is a technically mature technology. Mainly, it uses a compressor and turbine technology.

Disadvantages (Danish Energy Agency-ENERGINET, 2019):

- For traditional CAES the use of natural gas implies CO2 emissions.
- 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 to where CAES can be placed.
- In the basic form (without intermediate heat storage) CAES shows a relatively low electricity to electricity efficiency around 45 % without recuperation.
- Air leakage on caverns walls
- In Mexico, the caves are typically in areas that are difficult to access and far from demand centres
- Some safety precautions are needed for use of systems with very high gas pressure.
- The efficiency is variable in every CAES because of depends of location, size of cave, and terrain

Environment

The main environmental impacts from operating a CAES plant - except from surface footprint – relate to the use of fossil energy in the expansion phase. The preparation of new salt caverns is associated with environmental concerns, as heavy metals are dissolved together with the salt as the cavern is solution-mined. (Danish Energy Agency-ENERGINET, 2019). Some minor impacts to the landscape are also considered.

Research and development

For the time being CAES achieves a relatively low round-trip efficiency; plants in operation achieve between 40 to 54% AC-AC roundtrip efficiency rate (in particular due to the heat losses during the compressing stage and the fact that compressor and expander cannot be attached to one shaft) (EASE/EERA, 2017).

Research and development efforts for CAES are directed towards improving the relatively low round cycle efficiency by intermediately storing the heat generated in the compression phase and reuse it during the expansion phase (A-CAES). (Danish Energy Agency-ENERGINET, 2019)

Today, all compressed air reservoirs are of constant volume type and their power output is not constant once the reservoir pressure falls below the maximum expander inlet pressure. The constant pressure storage approach would be more advantageous from compression and expansion efficiency point of view. (EASE/EERA, 2017).

Over ground small-scale CAES has recently undergone rapid development. It can be used as an alternative to the battery for industrial applications, such as Uninterruptible Power Supplies (UPS) and back-up power systems. Compressed air battery systems developed by the UK based Flowbattery (previously named Pnu Power) were recently successfully commercialized. It uses pre-prepared compressed air from air cylinders to drive a combination of a scroll expander and a generator to produce electricity. (Luo, Wang, Dooner, & Clarke, 2015).

Prediction of performance and costs

The most data presented for CAES were obtained from (IRENA, 2017) and (Danish Energy Agency, 2019) because the design is based on the same operational capacities of the energy storage system. The energy losses during storage and technical lifetime were obtained for the average the several authors. The CAES will not have a variation in this period due to its technological maturity.

The capital costs for adiabatic CAES are high. The capital cost are 400 – 1500 USD/kW (Koohi-Fayegh & Rosen, 2020).

Uncertainty

The most uncertainties of CAES will not have a variation in this period due to its technological maturity. The uncertainty of charge efficiency, forced and planned outage, construction time, response time from idle to discharge, fixed and variable O&M are the same as (Danish Energy Agency, 2019) to keep the consistency between data.

The capital costs of CAES system depend on the geologic formations. For example, for salt cavern is 1 USD/kW, and for hard rock is 30 USD/kW. For this reason, the account is to be taken of geologic formations, if not the degree of uncertainty will be high (Koohi-Fayegh & Rosen, 2020).

Data sheet

	Compressed Air Energy Storage								
	2020	2030	2050	Uncertainty (2020)		Uncertainty (2030)		Note	Ref
Energy/technical data				Lower	Upper	Lower	Upper		
Form of energy stored	Mechanical and chemical								
Application	Energy Shifting								
Energy storage capacity for one unit (MWh)	8500	8500	8500	8500	8500	8500	8500		[1]
Output capacity for one unit (MW)	1060	1060	1060	1060	1060	1060	1060		[1]
Input capacity for one unit (MW)	1060	1060	1060	1060	1060	1060	1060		[1]
Round trip efficiency (%)	64	71	72	55	64	64	71		[3]
- Charge efficiency (%)	80	84	85	80	80	80	84		[3]
- Discharge efficiency (%)	80	84	85	69	80	80	84		[3]
Energy losses during storage (%/day)	0.5	0.5	0.5	0	0.5	0	0.5		[2], [3], [9]
Auxiliary electricity consumption (% of output)									
Forced outage (%)	5	4	4	5	5	5	4		[3]
Planned outage (weeks per year)	5	4	3	5	5	5	4		[3]
Technical lifetime (years)	40	40	40	35	45	35	45	Average	[3], [8], [9]
Construction time (years)	3	3	3	2	3	2	3		[3]
Lifetime (total number of cycles)	50000	50000	50000	10000	100000	10000	100000		[1]
Regulation ability									
Idle to full discharge (sec)	700	1000	1000	500	1000	740	1350	F, G	[3]
Full charge to full discharge (sec)									
Financial data									
Specific investment (MUSD2020 per MWh)	0.238	0.224	0.206	0.136	0.278	0.132	0.260		[1]
-Energy component (MUSD2020/MWh)	0.048	0.044	0.034	0.002	0.077	0.002	0.071	B	[1]
-Capacity component (MUSD2020/MW)	0.781	0.693	0.630	0.331	0.869	0.294	0.771	C	[1]
-Other project costs (MUSD/MWh)	0.093	0.093	0.093	0.093	0.093	0.093	0.093		[9]
Fixed O&M (kUSD2020/MW/year)	2.73	2.73	2.73	2.2	4.4	2.2	4.4		[3]
Variable O&M (USD2020/MWh/year)	2.73	2.73	2.73	2.2	3.3	2.2	3.3	E	[3]
Technology specific data									
Specific investment ((MUSD2020/MW)	1.912	1.794	1.651	1.093	2.232	1.056	2.086		[1]

Notes:

A. This data is interpreted within the IRENA tool as: "Total Invest per usable kWh storage" and is verifiable as a result of: Energy Storage + Power Conversion/Usable Storage Capacity
B. This data is interpreted within the IRENA tool as: "Energy Installation cost"
C. This data is interpreted within the IRENA tool as: "Power Installation cost"
D. This data is interpreted within the IRENA tool as a result of: Maintenance/Installed conversion power
E. Variable O&M cost can vary depending on the gas price in case of a CAES plant supported by a gas turbine
F. 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 [3]
G. The obtainable ramping rate is likely to decrease after application of thermal energy storage. This is because the heat must be delivered to the storage material, which is a process that cannot be controlled independently.

The references in data sheet can be found in the quantitative data sheet file that supplements the qualitative technology description ("CAES.xlsx" file) as well as in "Appendix B references of datasheets"

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2.8 Supercapacitor

Brief technology description

Supercapacitors are a kind of energy storage device that has high charging and discharging speed, high power density, and long cycling life. The supercapacitors use high surface area electrode materials and thin dielectrics. They are considered as an energy storage device and are called electrochemical capacitors and ultracapacitors (Afif et al., 2019). The elements of a supercapacitor are a positive electrode, dielectric material, negative electrode, voltage and load resistance (Figure 2.48). The energy storage occurs when voltage is applied in the system, consequently, the opposite charges accumulate on the surface of each electrode. The dielectric material that separates these charges causes an electric field that allows the supercapacitors to store energy (Afif et al., 2019).

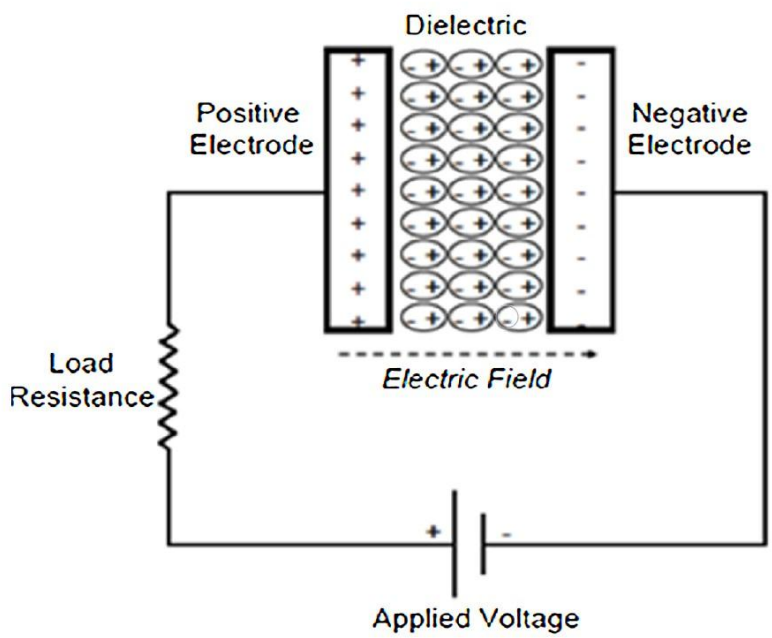

Figure 2.48. Schematic of conventional capacitor. Source: (Afif et al., 2019)

When a supercapacitor is charged, energy is stored in the dielectric material in an electrostatic field. Its maximum operating voltage is dependent on the breakdown characteristics of the dielectric material. This mechanism is highly reversible, therefore conventional capacitors and Electrochemical capacitors (EC), also referred to as "supercapacitors" or "ultracapacitors" that store electrical charge in an electric double layer at the interface between a high-surface-area carbon electrode and a liquid electrolyte, can be charged and discharged thousands of times. Electrode surface area in capacitors determines the capacitance and thus, the energy storage capability of the device. The amount of energy stored by a supercapacitor is very large compared to a standard capacitor because of the enormous surface area created by the porous carbon electrodes and the very small charge separation created in the double layer. (EASE/EERA, 2017).

Capacitors are appropriate for storing small quantities of electrical energy and conducting a varying voltage; they have a higher power density and shorter charging time compared to conventional batteries. However, they have limited energy capacity, relatively low energy density and high energy dissipation due to the high self-discharge losses. According to these characteristics, capacitors can be used for some power quality applications, such as high voltage power correction, smoothing the output of power supplies, bridging and energy recovery in mass transit systems. (Luo, Wang, Dooner, & Clarke, 2015)

The supercapacitors can be classified as asymmetric, symmetric, or hybrid (Berrueta, Ursua, Martin, Eftekhari, & Sanchis, 2019). Supercapacitor manufacturer Maxwell Technologies mentions that its main applications are in an area frequency control, spinning reserve, transmission line stability, wind turbine pitch control system, and industrial uninterruptible power supply (UPS) (Maxwell Technologies, 2019).

Supercapacitor chemistries

The supercapacitor can store energy by surface adsorption reactions of charged species on an electrode material. Consequently, they can deliver up to thousands of times the power of a battery of the same mass, however only for much shorter time spans (Koohi-Fayegh & Rosen, 2020).

Components in supercapacitor energy storage system

The components in supercapacitor energy storage system are current collectors, electrodes, electrolyte, and membrane (Figure 2.49).

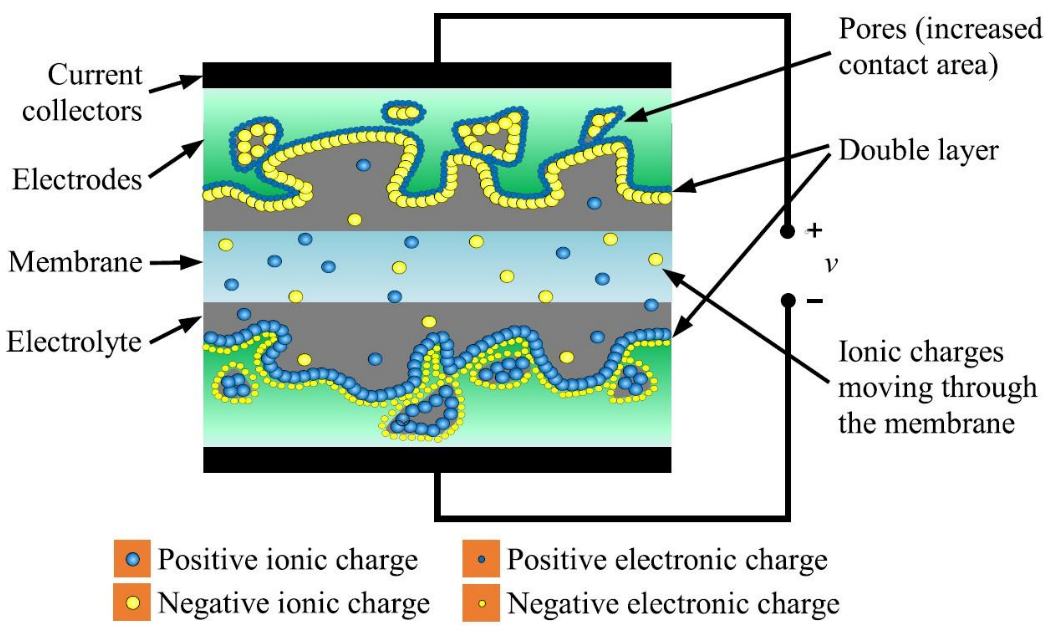

Figure 2.49. Principal component of supercapacitors. Source: (Berrueta et al., 2019)

Input/output

The input and output of supercapacitor is electricity.

Energy efficiency and losses

The variable capacitance is not critical to the supercapacitor performance and it does not represent a significant feature loss. The ohmic phenomena can to decrease energy efficiency because of caused a voltage drop in the supercapacitor (Berrueta et al., 2019).

When the energy is stored in a supercapacitor for two hours, the standby losses are 36 % (Berrueta et al., 2019). Supercapacitors have a wide range of energy efficiency between 60 to 100 % depending on materials and operation mode (Koohi-Fayegh & Rosen, 2020).

Typical characteristics and capacities

Table 2.42 shows typical characteristics and capacities of supercapacitors (Koohi-Fayegh & Rosen, 2020).

Table 2.35. Typical characteristics and capacities of supercapacitors. Source: (Afif et al., 2019; Koohi-Fayegh & Rosen, 2020)

Characteristics	Value
Cycle efficiency (%)	60 – 100
Energy density (Wh/kg)	1 – 15
Energy density (kWh/m^3)	1 - 30
Lifetime (cycles)	104 – 106
Power density (kW/m^3)	15 – 120,000
Voltage (V)	1.2 – 3.8

The table 2.43 shows the key features in accordance with the classification of supercapacitors.

Table 2.36. Key features of supercapacitors. Source: (Berrueta et al., 2019)

Characteristics	Asymmetric	Symmetric	Hybrid
Main storage	Double layer + Pseudocapacitance	Double layer	Double layer + Faradic
Energy density (Wh/kg)	30	5	100
Power density (kW/kg)	5	9	4

Characteristics	Asymmetric	Symmetric	Hybrid
Operating temperature (° C)	-25 – 60	-40 – 80	-40 – 60
Typical electrodes	Carbon, conducting polymers, and metal oxides	Carbon materials	Carbon and intercalation materials
Typical electrolyte	Aqueous	Organic	Organic
Applicability	Material research and early commercial	Commercial	Manufacturing research and commercial

The symmetric supercapacitor is considered when it uses the same double-layer material for both electrodes. On the other hand, when the electrodes are different the supercapacitor are called asymmetric. Finally, a hybrid supercapacitor uses a capacitor-like electrode and a faradaic electrode.

Figure 2.50 shows a comparison between energy and power density of electrolytic capacitors, film caps, Li-ion batteries, and supercapacitors, as well as response time.

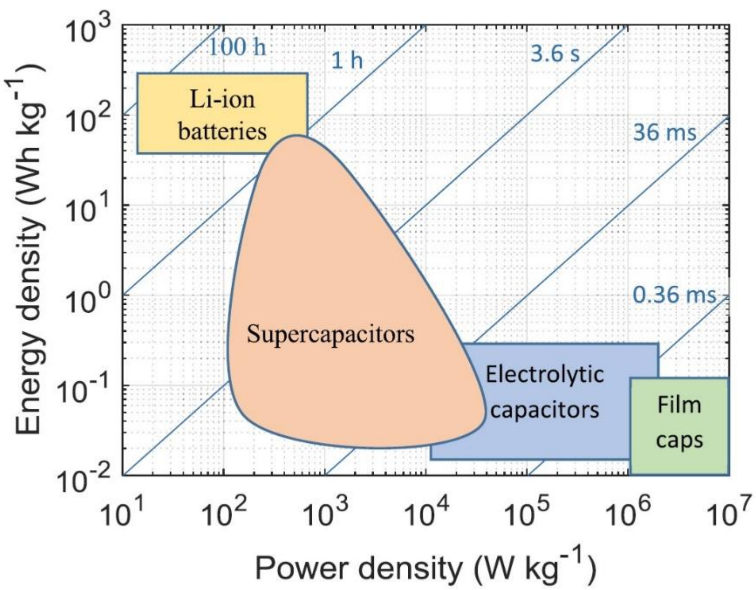

Figure 2.50. Plot of energy and power density for electrical energy storage systems. Source: (Berrueta et al., 2019)

Typical storage period

The typical storage period is from milliseconds to hours (Das et al., 2018).

Regulation ability

Supercapacitor has a response time extremely fast (e.g. 8 ms) (Das, Bass, Kothapalli, Mahmoud, & Habibi, 2018). Consequently, it can offer the following system services such as:

Table 2.37. Type of services can be provided by supercapacitors. Source: (Schmidt, Melchior, Hawkes, & Staffell, 2019)

Service	Can be provided
Primary response	√
Secondary response	√
Black start	√
Power Quality	√

Examples of market standard technologies

Until now, for grid applications the most common use of supercapacitors in UPS (Uninterruptible Power Systems) has been complemented by a very few demonstration projects, such as the use for load levelling in industrial services (by improving the efficiency of cranes), a pilot project of ENEA in Italy, or a 450 kW project in Palmdale, in California (USA), for wind generation and power reserve of a 1.25 MW micro-grid, used for a water treatment plant (EASE-EERA, 2017).

In Spain, there is a project called "stoRE – La Palma". This project is co-funded by the European Regional Development Fund (European Union), Centre of Industrial Technological Development (Government of Spain), ENESA Company (private sector), and various industrial partners and research centers (Mahmoudi, Ghaffour, Goosen, & Bundschuh, 2017). The stoRE – La Palma has an energy storage system by supercapacitors of 4 MW/5 s for frequency regulation (Figure 2.51). The supercapacitors were supplied by Ingeteam (Egido et al., 2015).

Figure 2.51. La Palma supercapacitor. Source: (Mahmoudi, Ghaffour, Goosen, & Bundschuh, 2017)

La Palma Supercapacitor is connected to the medium voltage (MV) grid through a power electronic converter and a MV/LV transformer (Figure 2.52). It has 55.55 F and 1080 Vdc of capacitance and voltage of the supercapacitor bank respectively.

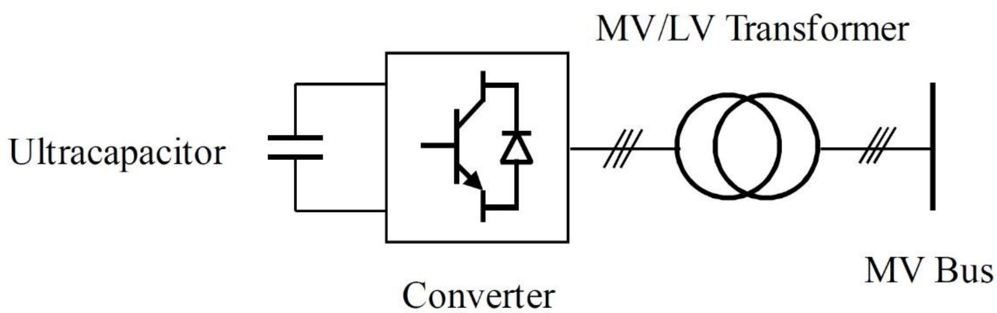

Figure 2.52. Block diagram representation of La Palma Supercapacitor. Source: (Egido et al., 2015)

Advantage/disadvantage

Advantage (EASE/EERA, 2013; Koohi-Fayegh & Rosen, 2020):

- Supercapacitors are appealing for a variety of applications in electricity grids: fast response time in milliseconds, high round-trip efficiency (more than 95%), high power density and long calendar and cycle life.
- Supercapacitors are interesting for their capacity to store very high power in a small volume and weight with high stability for a long time.
- High power density

Disadvantage (EASE/EERA, 2013; Koohi-Fayegh & Rosen, 2020):

- The low energy density and high capital costs (estimated in the range of 1,100-2,000 €/kW, including installation costs) limit the use of supercapacitors in electricity grids to high-power applications (up to 10 MW) with growing interest from electric utilities, which are looking to these devices for performance improvement and reliability in a variety of areas, with much higher power levels and with distribution voltages up to 600 V.

- Environmental implications such as soil pollution from synthesis process
- Interdependence of cells
- Lifecycle dependent on voltage imbalances between cells and maximum voltage thresholds
- Safety issues by chemicals and voltage

Environment

As with batteries, supercapacitors present potentially dangerous voltage levels, which, for grid applications, represent very little incremental risk. Aqueous electrolytes may contain hazardous materials including potassium hydroxide and methyl cyanide. Furthermore, certain electrolytes are flammable, such as acetonitrile, which releases hydrogen cyanide when burned.

This may provide limited risk in grid applications, where there is lower risk of release, and the expectation is that installation and maintenance would be performed by trained personnel only. As with batteries, supercapacitors must be properly disposed or recycled at end-of life. Most materials in current supercapacitors include common materials such as carbon, nickel, steel, aluminum, and a variety of plastics. Advanced asymmetric supercapacitors would use several materials used in advanced batteries, such as lithium and vanadium. It is difficult to estimate the total material requirements, but they would unlikely be greater than those for batteries, and this requirement must be placed in the context that the target applications for capacitors are those with limited actual energy capacity. (EASE-EERA, 2017).

Research and development

New, transformational or complementary power devices beyond current designs supercapacitors could play a role in advancing grid-scale storage. Such devices could be asymmetric or hybrid capacitors with increased specific energy, which could be combined with an electric double layer (EDL) capacitor electrode with a battery-type electrode, and large-scale dielectric capacitors, which could be enabled by the development of new materials and production processes. This design of new devices and modules will influence both the performances and manufacturing costs, which could be achieved by new electrodes mass production, improvement in cell performances and devices optimizations (EASE-EERA, 2017):

- The synthesis and development of new low cost and high performances materials for electrodes such as metal oxides/nitrides, carbon nanotubes (CNT), nanofibers (CNFs), graphene, graphite-based hard carbons, carbide-derived carbons, carbon gels and other nanomaterials (nanoparticles in 1D/2D/3D nanostructures). Optimization of the electrode fabrication and scaling up the process and related technology;
- The development of low cost and environmentally friendly electrolyte materials with wider voltage window such as neutral aqueous and polymer electrolytes, new formulation of mixtures of organic electrolytes, innovative Ionic liquids (IL). Hence, Ionic Liquids and other aqueous systems could allow higher voltage ranges with wide operational temperatures and high conductivity. Moreover, ionic Liquids-solvent mixtures with high voltage solvents as developed in Li-ion batteries (additives/new solvents);

Testing and demonstrating supercapacitors can help to validate technology lifetime, ramp rates, and other performance characteristics that need to be. Diagnostics and modelling could help to provide an understanding of the limitations of current electrochemical capacitor designs and could help to drive the development of high-energy electrodes, process optimization with the new electrodes, and scale-up of fabrication with new electrodes as well as new cell design. (EASE-EERA, 2017).

The performance depends on the choice of materials for cathodes and anodes such as additives, graphene, and graphene-based hybrid anodes (Koohi-Fayegh & Rosen, 2020). On the other hand, the research of supercapacitors focuses on design, materials science and engineering, application and fabrications of hybrid supercapacitors in 2019 (Berrueta et al., 2019).

Prediction of performance and costs

Table 2.45 shows exemplary energy and power capital cost for supercapacitors of 2014.

Table 2.38. Capital cost for supercapacitors. Source: (Koohi-Fayegh & Rosen, 2020)

Capital cost	Value
Energy ($/kWh)	10,000
Power ($/kW)	130 – 515

Uncertainty

The uncertainties were not made due to there is no available information about the storage system from supercapacitors directly connected to on the grid.

Data sheet

Nowadays, the supercapacitors are at the demonstration technology stage and therefore there is not data of energy storage at the electricity grid level. Consequently, this section was not performed.

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2.9 Flywheels

Brief technology description

Flywheels is considered as a technology with the main characteristics of high power and high energy density (Koohi-Fayegh & Rosen, 2020) and the possibility to decouple power and energy in the design stage. Moreover, it can be installed in any location and high power, but usually low energy compared with some other energy storage devices, are other important characteristics (EASE-EERA, 2017).

Flywheels store energy as rotational kinetic energy by accelerating and decelerating a rotating mass. Flywheel energy storage systems (FESS) consist of a rotating mass around a fixed axis (i.e. the flywheel rotor) which is connected to a reversible electrical machine that acts as a motor during charge that draws electricity from the grid to spin the flywheel up to operating speed, and as a generator during discharge when the already spinning flywheel delivers torque to the generator to provide power to the external grid or load (IRENA, 2017).

Mechanical principle

The mechanical principle of flywheel is the rotation of a mass to energy storage in the form of kinetic energy (see equations). The mass can be disc of Laval, solid disk, thick ring and thin ring.

$$E = \frac{1}{2} I w^2$$

$$\frac{E}{m} = K \frac{\sigma_{max}}{\rho}$$

Where E is the energy storage, I is the moment of inertia, w is the rotational speed, m is the mass, σ_{max} is the maximum stress, and ρ is the density of the flywheel (Mahmoud, Ramadan, Olabi, Pullen, & Naher, 2020).

Components in flywheel energy storage systems

A modern FESS is composed of five primary components:

- flywheel,
- group of bearings,
- reversible electrical motor/generator,
- power electronic unit and
- a vacuum chamber

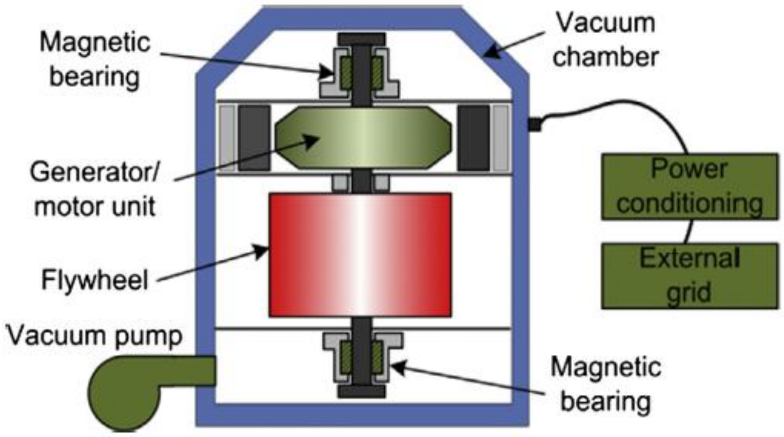

Figure 2.53. System description of a flywheel energy storage facility. Source: (Luo, Wang, Dooner, & Clarke, 2015)

FESS use electricity to accelerate or decelerate the flywheel, that is, the stored energy is transferred to or from the flywheel through an integrated motor/generator. For reducing wind shear and energy loss from air resistance, the FES system can be placed in a high vacuum environment. The amount of energy stored is dependent on the rotating speed of the flywheel and its inertia (Luo, Wang, Dooner, & Clarke, 2015).

Based on these properties, two key broad categories of flywheels have been developed: low-speed FES (not exceeding 10,000 revolutions per minute) and a high-speed FES (up to 100,000 revolutions a per minute). (IRENA, 2017)

Due to the fast response time flywheels can provide ultrafast ancillary services to the grid, with reaction times down to 3 ms. Primary reserves – and even synthetic inertia - for maintaining grid frequency can easily be provided and managed by use of flywheels. The reason for flywheels sometimes outshining batteries for certain applications is their high ramping rate. The fast up and down ramping rates and the power storage capacity makes flywheels suitable for (Danish Energy Agency-ENERGINET, 2019):

- Ramping (how fast an application can increase or decrease load)
- Peak Shaving
- Time Shifting (storing energy from one time to another)
- Frequency regulation
- Power quality (voltage) – Power distribution grids strive to have a power factor as close to 1 as possible. Using flywheels, power utilities may vary active and re-active power to reach a perfect power factor.

Input/output

The input and output are electricity.

Energy efficiency and losses

Today, the flywheels are operated with permanent magnet machines due to their high efficiencies. Furthermore, the rotating mass is mounted by magnetic bearings inside a vacuum chamber to eliminate frictional losses. Therefore, it has no lubrication requirements (Koohi-Fayegh & Rosen, 2020). Due to all the above, the efficiency of FESS is in between 85 to 90 % (Nadeem, Hussain, Tiwari, Goswami, & Ustun, 2019).

The flywheels have a high standby loss and 20 % of self-discharge per hour because of an unexpected dynamic load or external shock (Nadeem et al., 2019), but the technology has zero degradation in energy storage capacity over time. When the flywheel is operated, the losses can be caused by charging, discharging, and power electronics (Danish Energy Agency, 2019).

The requirement surface will depend on surface availability and energy needs. The power density for flywheels is between 40 to 2000 kW/m3 (Koohi-Fayegh & Rosen, 2020).

Typical characteristics and capacities

The energy storage for flywheel is 15 Wh/kg. Its specific power is between 400 to 1500 W/kg (Luo et al., 2015). Flywheels like energy storage is very flexible, it can deploy in numerous sizes and, capacities from kW to MW.

Typical storage period

The storage period from flywheels is shorter than days. It has a daily self-discharge > 3 % per hour (Luo et al., 2015). Therefore, they can be designed for each specific application, for example uninterruptable power supply for hospitals, airports, and server centers.

Regulation ability

Flywheel has a response time between below 3 milliseconds and to seconds (Das, Bass, Kothapalli, Mahmoud, & Habibi, 2018). Consequently, it can offer electricity storage applications such as:

Table 2.39. Type of services can be provided by FESS. Source: (Schmidt, Melchior, Hawkes, & Staffell, 2019)

Service	Can be provided
Primary response	√
Secondary response	√
Black start	√
Power Quality	√

Examples of market standard technologies

PJM, Hazle, Pennsylvania

The plant includes 200 flywheel modules lowered into the ground (5 on each side of a container). The plant currently provides 20 MW of frequency regulation service to PJM and reached full commercial operation in July 2014.

Figure 2.54. Hazle Township, Pennsylvania. Source: (DTU Energy, 2019)

Toluca and Mexico City, Mexico

Two other storage projects are the flywheel systems in the Mexico City and Toluca airports, which installed a 1,800 kVA and one 600 kVa kinetic energy storage flywheel systems, respectively, from Active Power to use as back up for runway lightning and other critical navigation systems (Active Power, 2018).

Advantage/disadvantage

The advantages are:

- Fast charge capabilities
- High energy storage density
- Long life cycle and no capacity degradation (lifetime largely unaffected by number of charge/discharge cycles)
- High power density, largely independent of stored energy level
- Low maintenance required
- State of charge is easy to determine (through rotational speed)
- Wide operational experience (due to use in motors and other industrial applications)
- No pollution
- Small area requirement

The disadvantages are:

- Low energy density compared with battery systems
- Very high idle losses (self-discharge rates)
- Need for bearing maintenance or power for energy magnetic bearings

- Unexpected dynamic loads or external shocks can lead to failure
- Noise issues when operate the flywheel
- Safety issues
- High cost per unit of energy stored

Environment

This technology has very low environmental impact because of the materials used and the mechanical principles (Das et al., 2018).

Research and development

Although there are some commercial products available in the market, some needs are still being demanded by the users. In general terms, an increase of the power and energy densities is required in order to be more competitive against the alternative technologies, and the reduction of the high investment cost.

The energy density of the flywheel can improve by the increase of rotational speed. Therefore, research is also needed to better materials for the flywheel, high-performance electrical machines, low losses electromagnetics and power electronics, and very fast and robust control platforms (EASE/EERA, 2013).

Prediction of performance and costs

The most data presented for flywheel were obtained from (IRENA, 2017). The data of forced and planned outage, construction time, specific energy and density were obtained from (Danish Energy Agency, 2019). For both cases, they were selected due to the design is based on the same operational capacities of the energy storage system. The fixed and variable O&M were obtained from (Zakeri & Syri, 2015).

The flywheels will not have a variation in this period due to its technological maturity. The other data will have a variation due to new materials or new electronics components. Consequently, the costs will be reduced.

Uncertainty

The most uncertainties of flywheels will not have a variation in the 2020-2030 period due to it is a deployment technology and there is not enough information about future projections. The most uncertainty is the same as (IRENA, 2017) to keep the consistency between data. The uncertainty for fixed and variable O&M is the same as (Zakeri & Syri, 2015). Finally, the uncertainty for specific energy and density were obtained from (Luo et al., 2015).

Data sheet

Technology	Flywheels								
	2020	2030	2050	Uncertainty (2020)		Uncertainty (2030)		Note	Ref
Energy/technical data				Lower	Upper	Lower	Upper		
Form of energy stored									
Application	Frequency Containment Reserve								
Energy storage capacity for one unit (MWh)	6.7	6.7	6.7	6.7	6.7	6.7	6.7	A	[1]
Output capacity for one unit (MW)*	5.0	5.0	5.0	5.0	5.0	5.0	5.0	A	[1]
Input capacity for one unit (MW)*	5.0	5.0	5.0	5.0	5.0	5.0	5.0	A	[1]
Round trip efficiency (%)	85	87	91	71	99	73	99	A	[1]
- Charge efficiency (%)	92	93	96	84	99	85	99	B	
- Discharge efficiency (%)	92	93	96	84	99	85	99	B	
Energy losses during storage (%/day)	53	39	21	16	78	9	43		[4]
Forced outage (%)	0								[2]
Planned outage (weeks per year)	0								[2]
Technical lifetime (years)	22	30	55	17	28	23	38		[1]
Construction time (years)	0.25	0.25	0.25	0.25	0.25	0.25	0.25		[2]
Regulation ability									
Response time from idle to full-rated discharge (sec)	0.001	0.001	0.001	0.001	0.001	0.001	0.001		[4]
Response time from full-rated charge to full-rated discharge (sec)	0.001	0.001	0.001	0.001	0.001	0.001	0.001		
Financial data									
Specific investment (MUSD2020 per MWh)	2.86	2.11	1.14	1.54	6.01	1.13	4.43	A, C	[1]
energy component (MUSD2020 per MWh)	2.66	1.96	1.06	1.33	5.31	0.98	3.92	A, D	[1]
capacity component (MUSD2020 per MW)	0.27	0.20	0.11	0.28	0.93	0.21	0.69	A, E	[1]
Fixed O&M (kUSD2020/MW/year)	5.8	5.8	5.8	4.8	6.7	4.8	6.7		[6]
Variable O&M (USD2020/MWh/year)	2.20	2.20	2.20	0.22	4.18	0.22	4.18		[6]
Technology specific data									
Specific investment (MUSD2020/MW)	3.80	2.80	1.52	2.05	7.99	1.51	5.90		[1]
Lifetime in total number of cycles	225,000	300,000	550,000	112,500	1,125,500	151,000	1,512,500		[1]
Specific power(W/kg)	950	950	950	814	1086	860	1083	F	[3],[2]
Power density (kW/m3)	1500	1500	1500	1300	2000	1300	2000	F	[3],[2]
Specific energy (Wh/kg)	15	15	15	13	17	14	17	F	[3],[2]
Specific density (kWh/m3)	50	50	50	43	67	43	67	F	[3],[2]

Notes:

A. IRENA has developed a tool to estimate costs for certain types of storage application
B. Inferred as the square root of the round-trip efficiency (supposing as charge and discharge efficiency should be equal)
C. This data is interpreted within the IRENA tool as: "Total Invest per usable kWh storage" and is verifiable as a result of: Energy Storage + Power Conversion/Usable Storage Capacity. Since the data for energy and capacity component are available is possible deducted the specific investment therefore some adjust is take by IRENA for showing the value for "Invest per usable kWh (ENERGY) storage"
D. This data is interpreted within the IRENA tool as: "Energy Installation cost"
E. This data is interpreted within the IRENA tool as: "Power Installation cost"
F. Ranges of uncertainty follow assumptions of market trends specified in [2], based on average values of [3]

The references in data sheet can be found in the quantitative data sheet file that supplements the qualitative technology description ("Flywheels.xlsx" file) as well as in "Appendix B references of datasheets"

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