Technology Data for Energy storage

October 2018

Danish Energy Agency

Amaliegade 44
DK-1256 Copenhagen K

P: +45 3392 6700
E: ens@ens.dk

www.ens.dk

AMENDMENT SHEET

Publication date

Publication date for this catalogue "Technology Data for Energy Storage" is October 2018. This amendment sheet has been added and also the possibility to add descriptions of amendments in the individual chapters if required. Hereby the catalogue can be updated continuously as technologies evolve, if the data changes significantly or if errors are found.

The newest version of the catalogue will always be available from the Danish Energy Agency's web site.

Amendments after publication date

All updates made after the publication date will be listed in the amendment sheet below.

Date	Ref.	Description
October 2018	142 Small-scale Hot water tanks, 150 Underground storage of gas, 151 Hydrogen storage, 160 PHS, 161 CAES and 180 Batteries	Chapters transferred from previous Technology Data Catalogue for Electricity and district heating production from May 2012.

PREFACE

The *Danish Energy Agency* and *Energinet*, the Danish transmission system operator, publish catalogues containing data on technologies for Energy Storage. This is the first edition of the catalogue. This catalogue includes updates of a number of technologies which replace the corresponding chapters in the catalogue for Energy Plants published in May 2012. The catalogue will continuously be updated as technologies evolve, if data change significantly or if errors are found. All updates will be listed in the amendment sheet on the previous page and in connection with the relevant chapters, and it will always be possible to find the most recently updated version on the Danish Energy Agency's website.

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

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

Finally, the catalogue is meant for international as well as Danish audiences in an attempt to support and contribute to similar initiatives aimed at forming a public and concerted knowledge base for international analyses and negotiations.

DANISH PREFACE

Energistyrelsen og Energinet udarbejder teknologibeskrivelser for en række energilagringsteknologier. Dette er den første udgave. Kataloget indeholder opdateringer af teknologier, som erstatter de tilsvarende kapitler i kataloget for el og fjernvarme, som blev udgivet i 2012. Kataloget vil løbende opdateres i takt med at teknologierne udvikler sig, hvis data ændrer sig væsentligt eller hvis der findes fejl. Alle opdateringer vil registreres i rettelsesbladet først i kataloget, og det vil altid være muligt at finde den seneste opdaterede version på Energistyrelsens hjemmeside.

Hovedformålet med teknologikataloget er at sikre et ensartet, alment accepteret og aktuelt grundlag for planlægningsarbejde og vurderinger af forsyningssikkerhed, beredskab, miljø og markedsudvikling hos bl.a. de systemansvarlige selskaber, universiteterne, rådgivere og Energistyrelsen. Dette omfatter for eksempel fremskrivninger, scenarieanalyser og teknisk-økonomiske analyser.

Desuden er teknologikataloget et nyttigt redskab til at vurdere udviklingsmulighederne for energisektorens mange teknologier til brug for tilrettelæggelsen af støtteprogrammer for energiforskning og -udvikling. Tilsvarende afspejler kataloget resultaterne af den energirelaterede forskning og udvikling. Også behovet for planlægning og vurdering af klima-projekter har aktualiseret nødvendigheden af et opdateret databeredskab.

Endeligt kan teknologikataloget anvendes i såvel nordisk som internationalt perspektiv. Det kan derudover bruges som et led i en systematisk international vidensopbygning og -udveksling, ligesom kataloget kan benyttes som dansk udspil til teknologiske forudsætninger for internationale analyser og forhandlinger. Af disse grunde er kataloget udarbejdet på engelsk.

TABLE OF CONTENTS

INTRODUCTION

This catalogue addresses technologies for energy storage. The focus is on the specific storage technology. Therefore, its interaction with the system and the combination with other technologies is not always considered. For example, hydrogen storage will be described as a gas storage system and not as a potential mean to store electricity. Each storage unit is defined by its energy carrier such that the boundary to the energy system is the input and output of this same energy carrier. For example, while a flywheel stores kinetic energy, it is in this catalogue for all intend and purposes defined as an electricity storage. Therefore, the conversion from electricity to kinetic energy and back again is included in the storage technology. Likewise, when defining the boundaries of an ATES a heat pump is not included in the storage since ATES is defined as a heat storage while the heat pump requires an external energy source - usually in the form of electricity or steam.

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

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

These guidelines serve as an introduction to the presentations of the different technologies in the catalogue, and as instructions for the authors of the technology chapters. The 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.

General classification

Since there are different forms of energy stored and different possible applications of certain technologies, these are categorized as shown in the following table.

The possible forms of energy stored are electricity, heat or gas. The applications are divided into system or local level. While the former includes large scale technologies to provide system services, the latter refers to household level or other smaller size applications.

The table only lists the technologies included in the catalogue.

		Application	
		System level	Local level
Form of energy stored	Electricity	Flywheel (FES) Large Batteries (NaS, VRB, SoNick)	Lead-acid batteries Flywheel (FES) Stationary lithium-ion batteries Electric car batteries
	Heat	Seasonal Heat storage – Water pits Aquifer thermal energy storage (ATES) Large Scale Hot Water tank	Small scale hot water tank
	Gas	Underground natural gas storage (caverns and aquifer) Hydrogen Storage above ground Hydrogen Storage in caverns	Compressed hydrogen storage

Technologies for electricity storage are further divided into power-intensive storage services and energy-intensive storage services. See section 1.4 for definitions.

The table below shows a categorization of electricity storage technologies.

	Service provided	
Technology	Power-intensive	Energy-intensive
Flywheel (FES)	✓	✓
Large Batteries (NaS, VRB, SoNick)	✓	✓
Lead-acid batteries		✓
Stationary lithium-ion batteries		✓
Electric car batteries		✓

1.2. Qualitative description

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

Contact information

Containing the following information:

- Contact information: Contact details in case the reader has clarifying questions to the technology chapters. This could be the Danish Energy Agency, Energinet.dk or the author of the technology chapters.
- Author: Entity/person responsible for preparing the technology chapters
- Reviewer: Entity/person responsible for reviewing the technology chapters.

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, as mentioned in the table in the introduction. Moreover, the type of services that the storage technology can provide is expressed (e.g. storage for production plants, primary frequency regulation, load shifting, etc.)

The system boundaries are identified in this section. In cases where the conversion units are not parts of the system, examples of typical conversion technologies used with the storage unit are mentioned such as heat pumps for ATES systems etc.

An illustration of the technology is included, showing the main components and working principles.

Input/output

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

Energy efficiency and losses

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

Regulation ability and other system services

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

- Inertia
- Short circuit power

- Black start
- Voltage control
- Damping of system oscillations (PSS)

Typical characteristics and capacities

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

The typical characteristics expressed are:

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

Beside electricity, the units MW and MWh are used for heat and gas as well. While this is not in accordance with thermodynamic formalism, it makes comparisons easier and provides a more intuitive link between capacities, production and full load hours.

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

For example, in electrical batteries there could be a lower bound for the state of charge (SOC) and for gas storage in caverns a certain amount of cushion gas is normally required. In such cases, only the “active storage capacity” is specified, meaning the amount of energy between maximum and minimum level. Information regarding the minimum required amount of energy stored is also explained here.

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

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.

Space requirement

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

Advantages/disadvantages

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

Environment

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

For water reservoirs, as well as for cavern gas storage, the methane leakage is specified.

For batteries the use of critical, toxic or regulated materials is specified.

Research and development perspectives

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

Examples of market standard technology

Recent full-scale commercial projects, which can be considered market standard, are mentioned, preferably with links. A description of what is meant by "market standard" is given in the introduction to the quantitative description section (Section 1.3). For technologies where no market standard has yet been established, reference is made to best available technology in R&D projects.

Prediction of performance and costs

Cost reductions and improvements of performance can be expected for most technologies in the future. This section accounts for the assumptions underlying the cost and performance in 2015 as well as the improvements assumed for the years 2020, 2030 and 2050.

The specific technology is identified and classified in one of four categories of technological maturity, indicating the commercial and technological progress, and the assumptions for the projections are described in detail.

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

Data for 2015

In case of technologies where market standards have been established, performance and cost data of recent installed versions of the technology in Denmark or the most similar countries in relation to the specific technology in Northern Europe are used for the 2015 estimates.

If consistent data are not available, or if no suitable market standard has yet emerged for new technologies, the 2015 costs may be estimated using an engineering based approach applying a decomposition of manufacturing and installation costs into raw materials, labor costs, financial costs, etc. International references such as the IEA, NREL etc. are preferred for such estimates.

Assumptions for the period 2020 to 2050

According to the IEA:

"*Innovation theory describes technological innovation through two approaches: the technology-push model, in which new technologies evolve and push themselves into the marketplace; and the market-pull model, in which a market opportunity leads to investment in R&D and, eventually, to an innovation*" [6].

The level of "market-pull" is to a high degree dependent on the global climate and energy policies. Hence, in a future with strong climate policies, demand for e.g. renewable energy technologies will be higher, whereby innovation is expected to take place faster than in a situation with less ambitious policies. This is expected to lead to both more efficient technologies, as well as cost reductions due to economy of scale effects. Therefore, for technologies where large cost reductions are expected, it is important to account for assumptions about global future demand.

The IEA's New Policies Scenario provides the framework for the Danish Energy Agency's projection of international fuel prices and CO_2-prices, and is also used in the preparation of this catalogue. Thus, the projections of the demand for technologies are defined in accordance with the thinking in the New Policies Scenario, described as follows:

"New Policies Scenario: A scenario in the World Energy Outlook that takes account of broad policy commitments and plans that have been announced by countries, including national pledges to reduce greenhouse gas emissions and plans to phase out fossil energy subsidies, even if the measures to implement these commitments have yet to be identified or announced. This broadly serves as the IEA baseline scenario." [7].

Alternative projections may be presented as well relying for example on the IEA's 450 Scenario (strong climate policies) or the IEA's Current Policies Scenario (weaker climate policies).

Learning curves and technological maturity

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

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

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

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

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

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

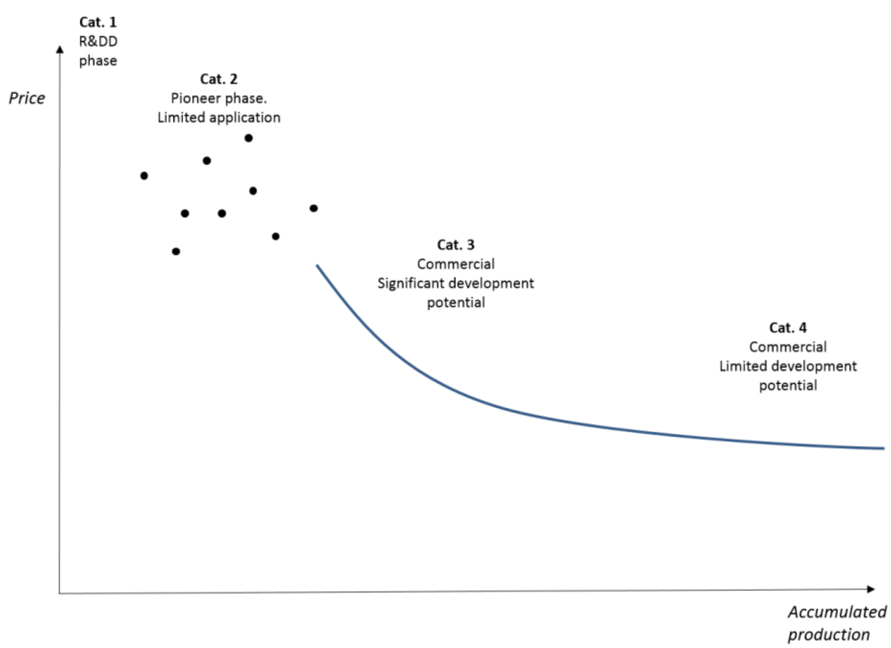


Figure 1: Technological development phases. Correlation between accumulated production volume (MW) and price.

Uncertainty

The catalogue covers both mature technologies and technologies under development. This implies that the price and performance of some technologies may be estimated with a relatively high level of certainty whereas in the case of others, both cost and performance today as well as in the future are associated with high levels of uncertainty.

This section of the technology chapters explains the main challenges to precision of the data and identifies the areas on which the uncertainty ranges in the quantitative description are based. This includes technological or market related issues of the specific technology as well as the level of experience and knowledge in the sector and possible limitations on raw materials. The issues should also relate to the technological development maturity as discussed above.

The level of uncertainty is illustrated by providing a lower and higher bound beside the central estimate, which shall be interpreted as representing probabilities corresponding to a 90% confidence interval. It should be noted, that projecting costs of technologies far into the future is a task associated with very large uncertainties. Thus, depending on the technological maturity expressed and the period considered, the confidence interval may be very large. It is the case, for example, of less developed technologies (category 1 and 2) and long time horizons (2050).

Additional remarks

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

References

References are numbered in the text in squared brackets and bibliographical details are listed in this section.

Quantitative description

To enable comparative analyses between different technologies it is imperative that data are actually comparable: All cost data are stated in fixed 2015 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 (2015, 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 or the group of technologies (power, gas, heat storage). The generic part is made to allow for an easy comparison.

Each cell in the table contains only one number, which is the central estimate for the market standard technology, i.e. no range indications. Uncertainties related to the figures are stated in the columns named *uncertainty*. To keep the table simple, the level of uncertainty is only specified for years 2020 and 2050.

The level of uncertainty is illustrated by providing a lower and higher bound. These are chosen to reflect the uncertainties of the best projections by the authors. The section on uncertainty in the qualitative description for each technology indicates the main issues influencing the uncertainty related to the specific technology. For technologies in the early stages of technological development or technologies especially prone to variations 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; in other words, the uncertainty interval does not represent the product range (for example a product with lower efficiency at a lower price or vice versa).

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. The following separators are used:

; (semicolon)	separation between the four time horizons (2015, 2020, 2030, and 2050)
/ (forward slash)	separation between sources with different data
+ (plus)	agreement between sources on same data

Notes include additional information on how the data are 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:

Technology	name/ decription									
	2015	2020	2030	2050	Uncertainty (2020)		Uncertainty (2050)		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 (%)										
- 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)										
Regulation ability (only for electricity storage)										
Response time from idle to full-rated discharge (sec)										
Response time from full-rated charge to full-rated discharge (sec)										
Financial data										
Total investment cost (M€2015 per MWh)										
- energy component (M€/MWh)										
- capacity component (M€/MW)										
- other project costs (M€)										
Fixed O&M (% total investment)										

Variable O&M (€2015/MWh)										
Technology specific data										
Alternative Total investment cost (M€2015 per MW)										

Energy/technical data

Energy storage capacity for one unit

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

In the case of a modular technology such 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 is found in the notes.

The unit MWh is used for electricity, heat and gas 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.

Charge and discharge efficiencies (round trip efficiency)

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 and expresses the fraction of the input energy, which can be recovered at the output, assuming no losses during the storage period. It represents the ratio between the energy provided to the user and the energy needed to charge the storage system.

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

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

Energy losses during storage

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

Technologies with different storage periods will show very different behaviour 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 for heat and gas usually need auxiliary systems to operate, such as pumps and/or compressor. 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, while planned outage (for example due to renovations) is given in days per year.

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 experience. The expected technical lifetime takes into account a typical number of start-ups and shut-downs.

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

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

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

Construction time

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

Regulation ability

The regulation ability parameters are expressed for electricity storage application, while for heat and gas storage these parameters are not relevant.

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. It is assumed to be equal for the charging process.

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. It is assumed to be equal in the other direction.

Financial data

Financial data are all in Euro (€), fixed prices, at the 2015-level and exclude value added taxes (VAT) and other taxes.

Several data originate in Danish references. For those data a fixed exchange ratio of 7.45 DKK per € has been used.

The previous catalogue was in 2011 prices. Some data have been updated by applying the general inflation rate in Denmark (2011 prices have been multiplied by 1.0585 to reach the 2015 price level).

European data, with a particular focus on Danish sources have been emphasized in developing this catalogue. This is done as generalizations of costs of energy technologies have been found to be impossible above the regional or local levels, as per IEA reporting from 2015 [8]. For renewable energy technologies this effect is even stronger as the costs are widely determined by local conditions.

Investment cost

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

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

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

The total investment cost is reported on a normalized basis, i.e. cost per MWh of 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 cost of energy component includes all the cost related to the equipment to store the energy, which you would incur in case you want to expand the MWh rating of the system, for example battery modules, reservoirs in a pumped-hydro plant or heat tank. The cost of capacity component refers to the part of equipment which condition or convert the energy carrier and make it available to the user or the grid, for example converter and grid connection for a battery system, turbine/pump and grid connection for pumped-hydro plant and heat exchanger and piping for a heat storage. This is the cost you would incur if you would increase the MW capability of the system. Finally, another cost component reflects the fixed costs related to the project, such as data management and control system, project engineering, other civil works, commissioning.

Summarizing, the components considered are the following:

- *Cost of Energy component* (C_E) [M€/MWh]: cost related to the equipment to store the energy (incl. their installation);
- *Cost of Capacity component* (C_P) [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);
- *Other project costs* (C_{other}) [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 for one unit* in MWh.

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

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

where:

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

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

$h = \frac{E_{sc}}{P_{out}}$ = unload 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 taken into account in the presented data (deep costs).

Business cycles

The cost of energy equipment shows fluctuations that can be related to business cycles. This was the case of the period 2007-2008 for example, where costs of many energy generation technologies surged dramatically. The trend was general and global. An example is combined cycle gas turbines (CCGT), where 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 data-sheet. 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 is expressed in terms of percentage (%) of the *Total investment cost*, as defined in the previous paragraph 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. Reinvestments are discounted at 4 % annual discount rate in real terms. 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).

Auxiliary electricity consumption is included for heat and gas storage technologies. The electricity price applied is specified in the notes for each technology, together with the share of O&M costs due to electricity consumption. This enables corrections from the users with own electricity price figures. The electricity price does not include taxes and PSO.

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

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.

Technology specific data

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

In heat and gas storage systems the volume (m^3) and pressure (bar) is specified. For heat applications, the storage temperature sets are indicated as well (°C).

For heat storage units, energy density (Wh/m^3) at relevant temperatures is expressed, for example 80/40°C, 60/35°C and 20/5°C (ATES).

Energy density for gas storage systems is indicated in Wh/Nm^3.

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

Moreover, for technologies where it is relevant, such as pumped hydro and cavern gas storage, the leakage of methane is shown in m^3 per year.

The following table summarizes the technology specific data for each of the categories:

Technology specific data		
Electricity	**Heat**	**Gas**
Alternative Total investment cost (M€/MW) for power-intensive applications	-	-
-	Volume (m^3)	Volume (m^3)
-	Pressure (bar)	Pressure (bar)
	Temperature sets (°C)	
Lifetime in total number of cycles		
Specific power (W/kg)	-	-
Power density (W/m^3)	-	-
Specific energy (Wh/kg)	-	-
Energy density (Wh/m^3)	Energy density (Wh/m^3)	Energy density (Wh/Nm^3)
Methane leakage (m^3/year) for pumped hydro	-	Methane leakage (m^3/year) for gas storage in cavern.

Definitions

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.

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

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

References

Numerous reference documents are mentioned in each of the technology sheets. The references mentioned below are for Chapter 1 only.

[1] Danish Energy Agency: ”Forudsætninger for samfundsøkonomiske analyser på energiområdet” (Generic data to be used for socio-economic analyses in the energy sector), May 2009.

[2] “Technology Data for Hydrogen Technologies”, EUDP Project, 2015.

[3] “Strategy for Storage and Distribution of Energy”, The Danish Partnership for Hydrogen and Fuel Cells, June 2015.

[4] “Thermal Energy Storage. Technology Brief”, IEA-ETSAP and IRENA, January 2013.

[5] “Electricity Storage. Technology Brief”, IEA-ETSAP and IRENA, April 2012.

[6] “Energy Technology Perspectives”, International Energy Agency, 2012.

[7] International Energy Agency. Available at: http://www.iea.org/. Accessed: 11/03/2016.

[8] “Projected Costs of Generating Electricity”, International Energy Agency, 2015.

[9] “Konvergensprogram Danmark 2015”. Social- og Indenrigsministeriet. March 2015.

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. The technologies presented in this chapter will help to cope with the integration challenges arising from intermittent generation sources: the needs to both ensure the balance of production and consumption in real time maintaining the quality of supply and to store excess electricity over different time horizons (minutes, days, weeks).

In 2017, it is estimated that 4.67 TWh of electricity storage exists, 96% of which in form of pumped-hydro storage. 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 [1].

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

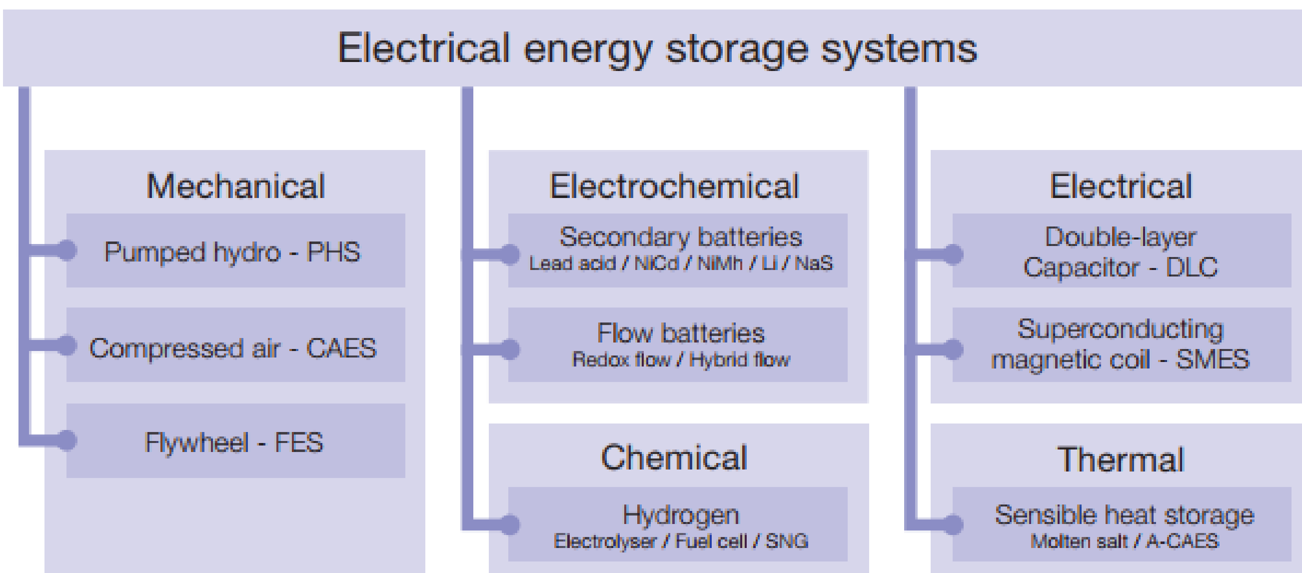


Figure 1 Classification of electrical energy storage systems according to energy form. Source [2]

Electricity storage characteristics and services

The services electricity storage can provide are various and are inherently related to the physical characteristics of the storage media and the storage system. 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. Figure shows how different types of storage classify with respect to these two variables.

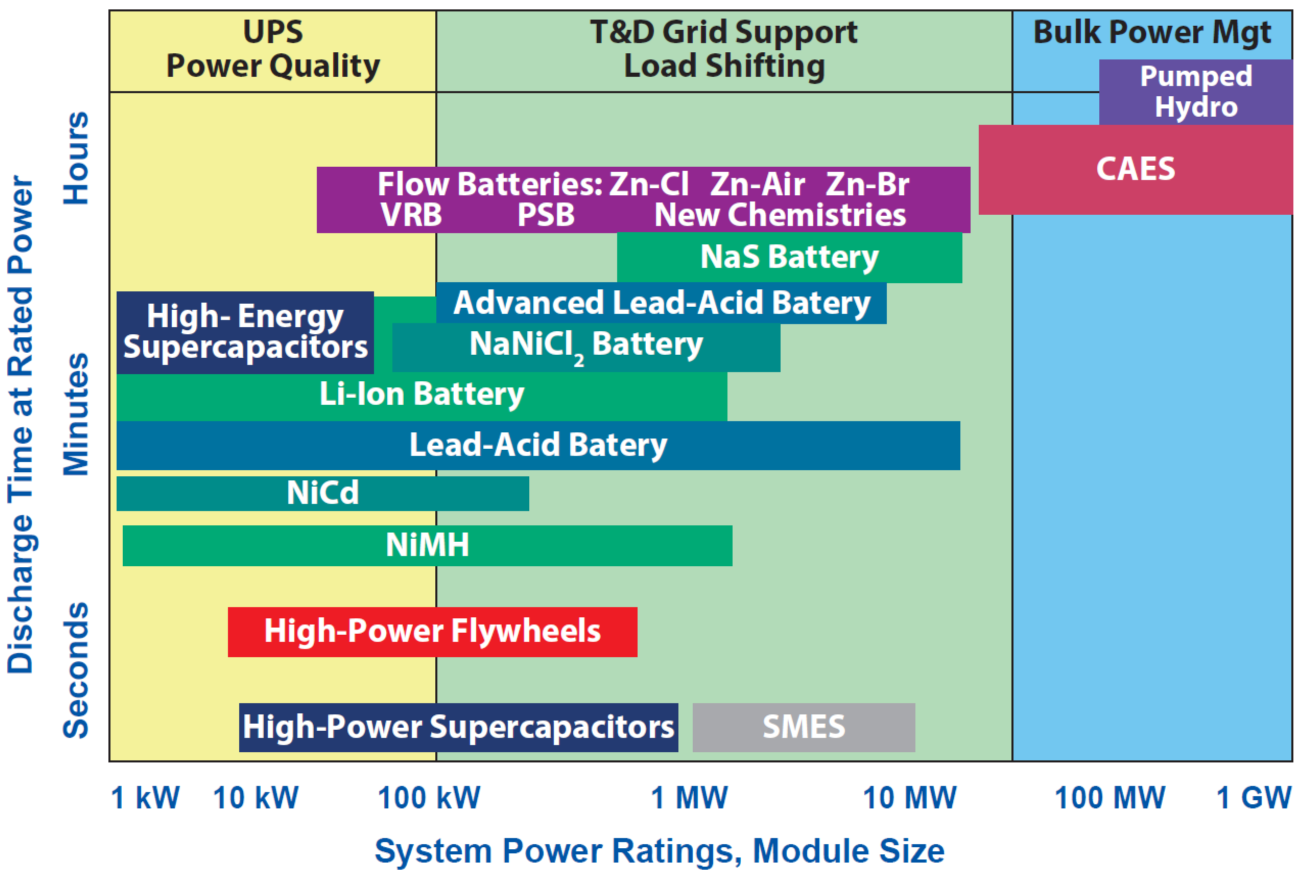


Figure 2. System power rating versus discharge time at rated power for different storage technologies [1].

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

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

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

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

- **Time-shift:** purchase of electricity when the price is lower to use it or sell it when the price is higher (also referred to as *arbitrage*). The effect is an increased demand in hours with lower load, with advantages related to the generation pattern of conventional plants, and a reduction of the peak demand, 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].
- **Time-of-use management and self-consumption:** residential and small commercial application to maximize the self-consumption of solar photovoltaics or to shift the consumption in hours with lower tariffs. The application principle is similar to time-shift, but more small-scale/local.
- **RE capacity firming and production smoothing:** compensation of the fluctuations of the production from variable renewables (e.g. solar and wind) to obtain a more predictable and regular generation profile. Reduction of the balancing cost for the plant operator and, from a system perspective, reduced need for reserve and modulation/ramping of conventional plants.
- **Network support and investment deferral:** postponement of costly expansion of the power network thanks to the reduction of situations of overload and 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.

---

[1] The list of descriptions and applications are based on elaborations from [1], [11] and [12].

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

- **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 a number of services related to the improvement of the quality of the power supplied. For example, improved voltage quality (compensation of voltage dips and distortion of voltage), reduction of the impact of distorting loads (e.g. harmonics, flicker) and shaving of localized power peaks (timescale of seconds).

The suitability of different storage technologies for the specific applications described are shown in **Error! eference source not found.**[3].

Application	Hydro	CAES	NaS	NaNiCl	Li-Ion	Redox	Fly-wheel
Time-shift	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Time-of-use management	🔴	🔴	🟡	🟢	🟢	🟡	🟢
RE firming and smoothing	🟢	🟡	🟢	🟢	🟢	🟢	🟢
Network support and deferral	🟢	🟡	🟢	🟢	🟢	🟢	🟢
Primary regulation	🟡	🟡	🟢	🟢	🟢	🟢	🟢
Secondary regulation	🟢	🟡	🟢	🟢	🟢	🟢	🟢
Tertiary regulation	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Black start	🟢	🟢	🟢	🟢	🟢	🟡	🟢
Voltage support	🟡	🟡	🟢	🟢	🟢	🟡	🟢
Power quality	🔴	🔴	🟡	🔴	🟡	🟡	🟢

Legend: 🟢 Suitable 🟡 Less suitable 🔴 Not suitable

Table 1 Suitability of different electricity storage technologies for different applications [3].

[3] The suitability for the different services is primarily based on [1], [3] and [11]. Additional and more 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: [13], [14] and other Li-ion projects with more than 4h of storage duration in [4].

Based on data from the U.S. DOE Database of Storage project [4], today the main uses of electricity storage by technology group are those displayed in Figure. The vast majority of pumped-hydro storage is used for Time-shift applications, followed by capacity firming and black start capabilities. Differently, electro-chemical storage is used for frequency regulation and provision of reserve, with a lower share dedicated to more energy-intensive services like time-of-use management and time shift. Electro-mechanical storages, like flywheel systems, see the largest deployment in on-site power quality services and black start.

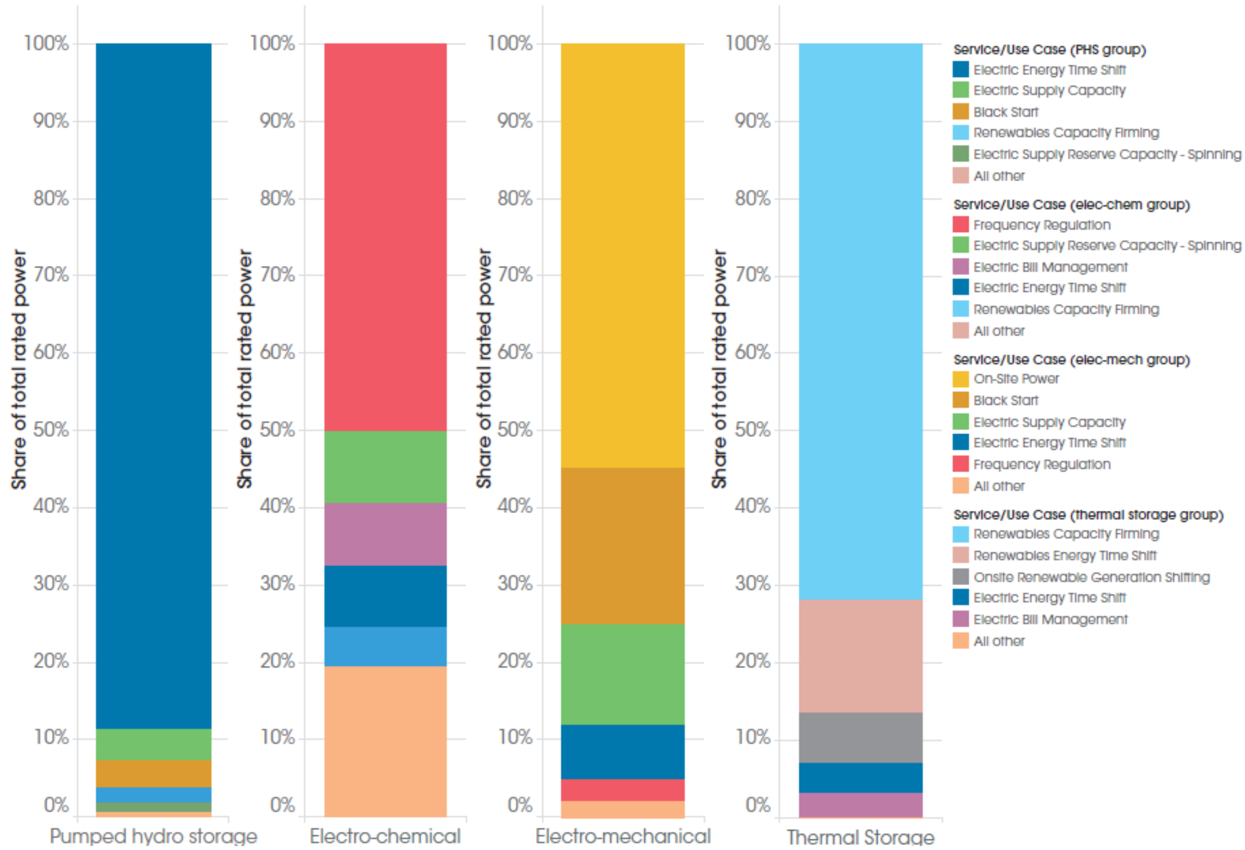


Figure 3 Global Energy Storage power capacity share by main use and technology group. Source [1].

In the future, electro-chemical storage is expected to experience an evolution towards more energy-intensive applications, following the reduction of battery cost. IRENA [1] 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

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. The system boundaries and the subdivision of the equipment in the three cost components, as defined in the *Investment cost* paragraph of the main guideline, are shown below for different electricity storage technologies.

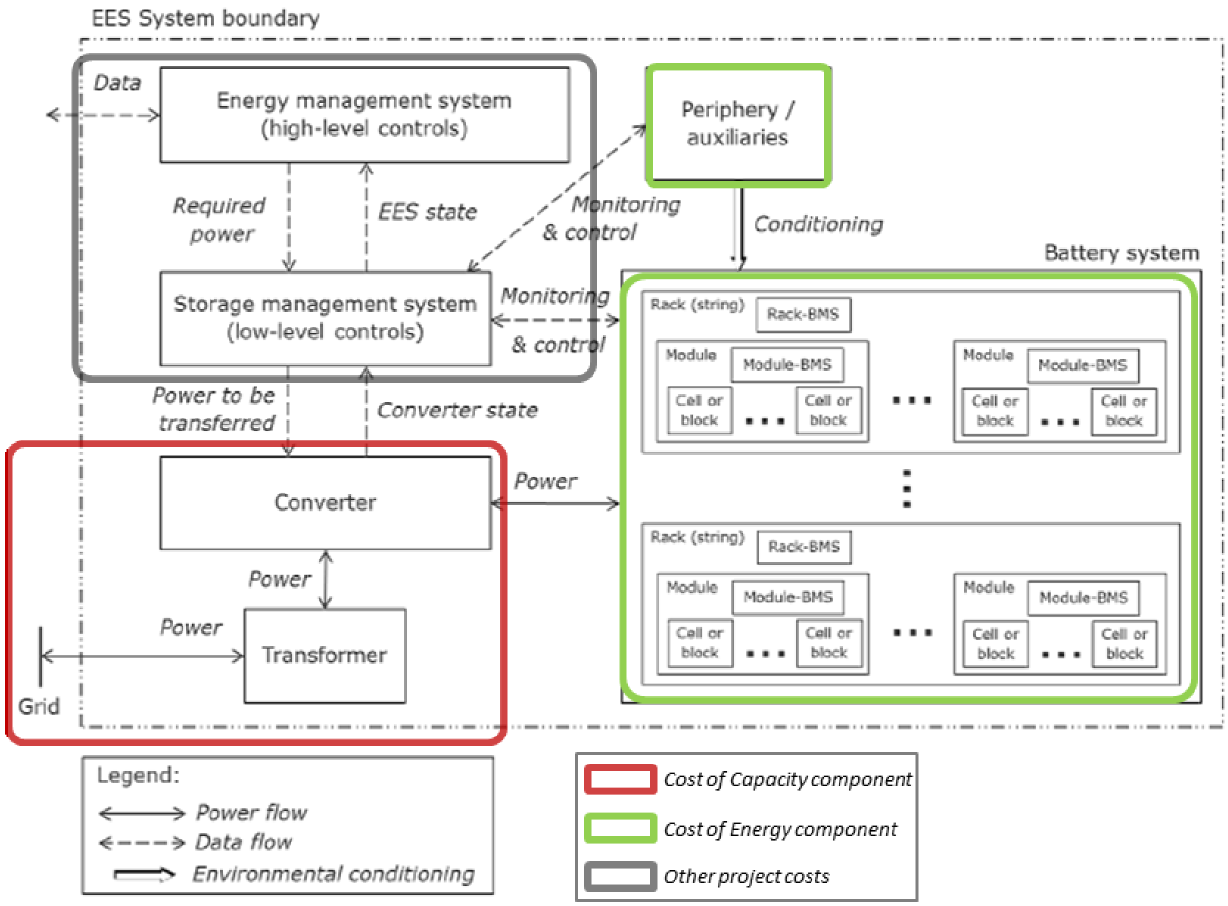


Figure 4 Components and their categorization for cell-based batteries, such as Li-ion, NaS and NaNiCl. Source: elaboration of [5].

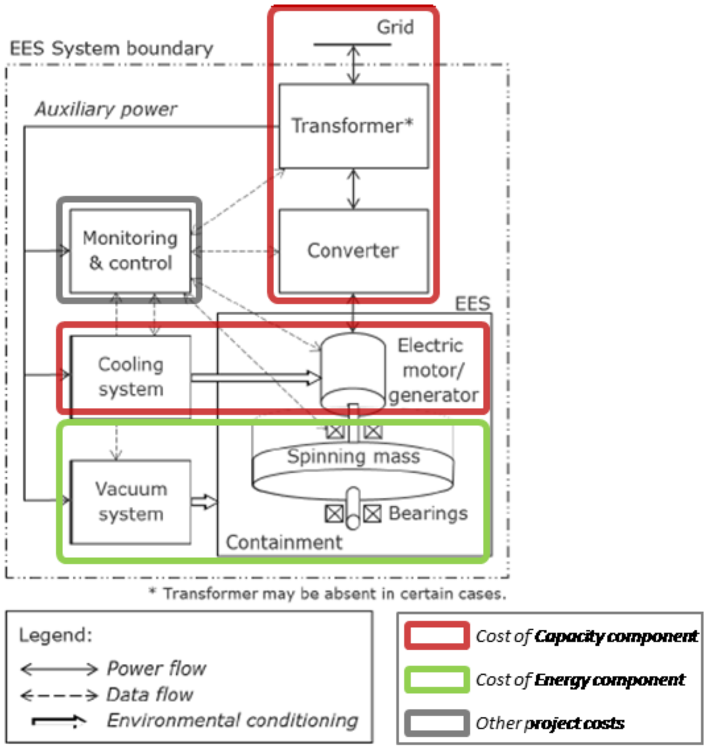


Figure 5 Components and their categorization for Flywheel. Source: elaboration of [5].

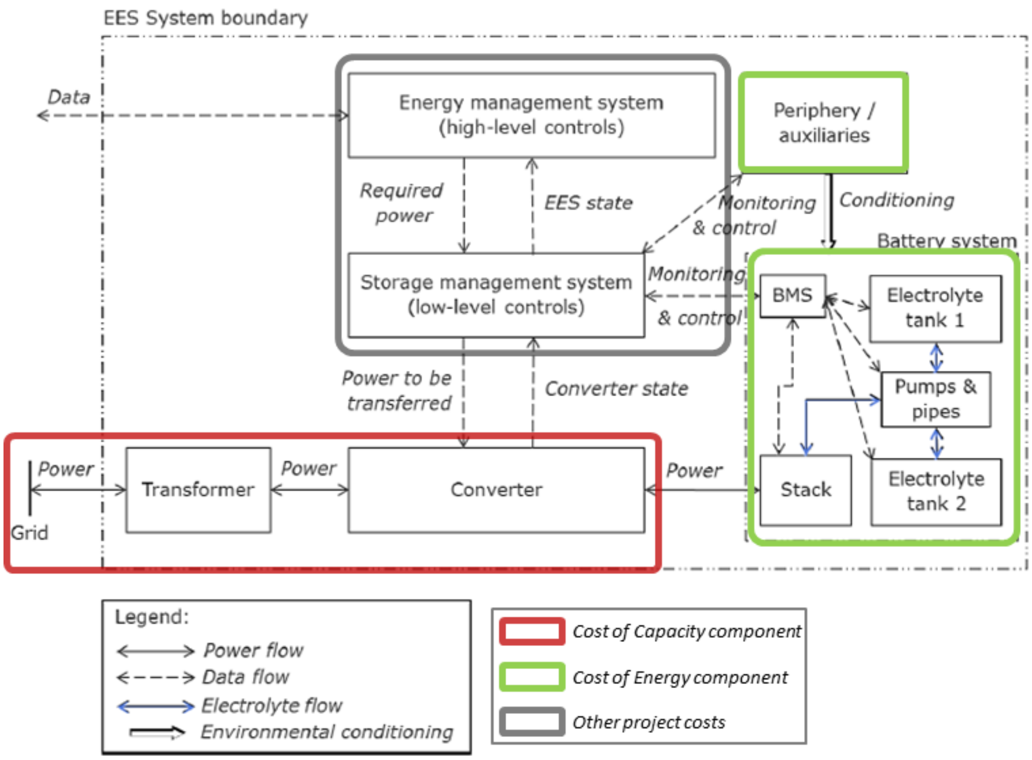


Figure 6 Components and their categorization for Vanadium-redox flow battery. Source: elaboration of [5].

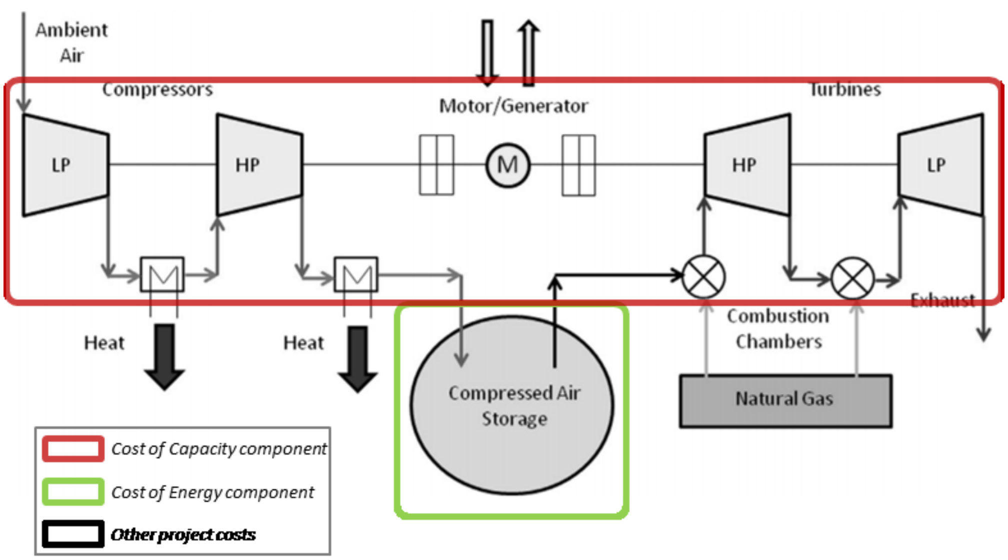


Figure 7 Components and their categorization for CAES. Source: elaboration of [5].

Energy component

The energy component includes the following equipment and its installation:

- Cell-based batteries: battery modules, battery management system (BMS), local protection, racking frame/cabinet;
- Vanadium-redox: electrolytes, pumps and pipes, stack, battery management system (BMS);
- Flywheel: spinning mass, bearings, containment and vacuum system;
- Compressed Air Energy Storage: pressure tank or underground cavern, cavity or aquifer. Includes the air shaft.

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

Capacity component

The capacity component includes the following equipment and its installation:

- Cell-based batteries and vanadium-redox: power conversion system (PCS), grid connection and protection;
- Flywheel: power conversion system (PCS), grid connection and protection, as well as electric motor/generator and cooling system;
- Compressed Air Energy Storage: all the components excluding tank/cavern (energy component) and those that falls under *other costs*. Includes the grid connection.

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 taken into account.

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

Power conversion system (PCS)

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

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

The cost of power conversion for battery storage systems, based on a number of references [8] [9] [10], is the range 0.2-0.3 M€/MW (0.4-0.5 M€/MW if including the connection to the grid). This 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 [7].

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

References

The following list includes the references used in Chapter 2.

[1] IRENA, “Electricity storage and renewables: Costs and markets to 2030,” 2017.

[2] International Electrotechnical Commission (IEC), “Electrical Energy Storage - White Paper,” 2011.

[3] A. Schrøder Pedersen, “European Energy Storage Technology Development Roadmap towards 2030,” 2014.

[4] U.S. Department of Energy, “Global Energy Storage Database.” [Online]. Available: https://www.energystorageexchange.org/. [Last viewed 01.12.17].

[5] DNV GL, “Safety, operation and performance of grid-connected energy storage systems,” 2017.

[6] M. Andriollo, R. Benato, M. Bressan, S. D. Sessa, F. Palone, and R. M. Polito, “Review of power conversion and conditioning systems for stationary electrochemical storage,” *Energies*, vol. 8, no. 2, pp. 960–975, 2015.

[7] “Interview with the manufacturer NIDEC.” 2018.

[8] R. Benato, G. Bruno, F. Palone, R. M. Polito, and M. Rebolini, “Large-scale electrochemical energy storage in high voltage grids: Overview of the Italian experience,” *Energies*, vol. 10, no. 1, 2017.

[9] B. Zakeri and S. Syri, “Electrical energy storage systems: A comparative life cycle cost analysis,” *Renew. Sustain. Energy Rev.*, vol. 42, pp. 569–596, 2015.

[10] G. Huff *et al.*, “DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA,” 2013.

[11] Ricerca sul Sistema Energetico - RSE, “RSEview: L’accumulo di energia elettrica,” 2011.

[12] Energinet.dk, “Ancillary Services To Be Delivered in Denmark,” 2017.

[13] Enel, “Enel signs 85 mw of capacity storage agreements in us with pacific gas and electric,” 2017. [Online]. Available: https://www.enel.com/media/press/d/2017/12/enel-signs-85-mw-of-capacity-storage-agreements-in-us-with-pacific-gas-and-electric. [Last viewed 01.02.18].

[14] Lyon Energy, “LYON’s Energy Storage Projects,” 2017. [Online]. Available: http://lyonbatterystorage.com.au/. [Last viewed 01.02.18].

140 SEASONAL HEAT STORAGE

New descriptions and data will be published by the end of week 45. Datasheet from previous publication is included below.

Quantitative description

Technology	**Seasonal heat storage in water pits**					
	2015	**2020**	**2030**	**2050**	**Note**	**Ref**
Energy/technical data						
Store volume (m3)	60000					
Storage capacity, kWh/m3	60-80					2
Efficiency, %	80-95				A	3
Construction time (years)	0.5	0.5	0.5	0.5		3
Technical lifetime (years)	20	20	20	20	B	3
Financial data						
Specific investment costs (€ per m3)	35	35	34	30	C	1;3;3;3
Electricity consumption (MWh/year)	40				D	3
O&M (% of investment per year)	0.7					3

References:

1 "Seasonal heat storages in district heating networks", Ellehauge & Kildemoes and Cowi, July 2007. A project (Preheat) funded by Intelligent Energy – Europe and the Danish systems operator Energinet.dk.

2 Dirk Mangold: "Seasonal Heat Storage. Pilot projects and experiences in Germany". Presentation at the PREHEAT Symposium at Intersolar 2007, Freiburg, Germany, June 2007.

3 Planenergi (Danish company; www.planenergi.dk), which in 2010 is installing a 60,000 m3 pit store in Northern Jutland.

Notes:

A The storage loss depends on several parameters, such as store volume, insulation, whether a heat pump is part of the system etc. The stated interval covers a large store, storage temperature 85-90 C, without (80%) and with (95%) a heatpump to discharge the store.

B The most critical part is the cover. The technical lifetime depends much on the water temperature. The lifetime of the store may be extended by reinvesting in a new cover.

C 2010: Budget cost for a 60,000 m3 pit. The cost development assumes a 10-20% reduction from 2020 to 2050, caused by replication of pits, pipes, pumps, heat exchangers and control system. For other store volumes, please refer to paragraph 'Additional remarks' above.

D Electricity for internal pumps etc. only. If a heat pump is used, the drive electricity shall be added.

E Cost data are the same as in the 2010 catalogue, however inflated from price level 2008 to 2011 by multiplying with a general inflation factor 1.053

141 LARGE-SCALE HOT WATER TANKS

New descriptions and data will be published by the end of week 45. Datasheet from previous publication is included below.

Quantitative description

Technology	Large steel tanks for heat storage					
	2010	**2020**	**2030**	**2050**	**Note**	**Ref**
Energy/technical data						
Storage capacity, kWh/m3	60-80					1
Efficiency, %	95				A	
Environment						
Financial data						
Specific investment costs (€ per m3)	160-260				B	2
O&M						

References:

1 Dirk Mangold: "Seasonal Heat Storage. Pilot projects and experiences in Germany". Presentation at the PREHEAT Symposium at Intersolar 2007, Freiburg, Germany, June 2007.

2 "Heat storage technologies". Report, June 2007, from the PREHEAT project, funded by the Intelligent Energy – Europe programme (www.preheat.org).

Notes:

A This is an example: A 10,000 m3 store operating between 90 and 50 C, an outdoor temperature of 5 C, and a storage cycle of one week. Cf. description above under 'Additional remarks'.

B Store volume 10,000 m3.

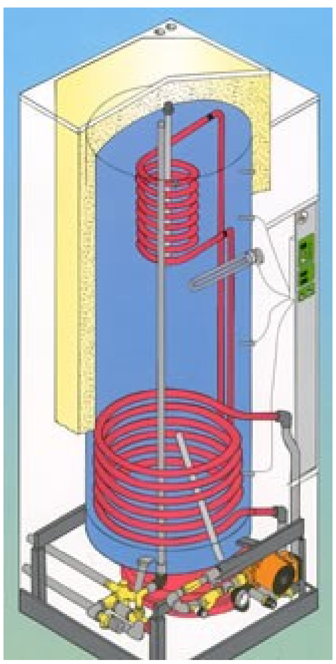
142 SMALL-SCALE HOT WATER TANKS

This chapter has been moved from the previous Technology Data Catalogue for Electricity and district heating production from May 2012. Therefore, the text and data sheets do not follow the same guidelines as the remainder of the catalogue.

Brief technology description

Hot water storage vessels in private homes are used for different purposes:

- Domestic hot water; to ensure sufficient flow for high demands such as showers and filling bath tubs. Basically a drum filled with water and equipped with a heating mechanism on the bottom or inside.
- Space heating; to function as 'peak shavers' for district heating or solar heating.
- Shift load storage to capture the cheaper, off-peak electricity and using it at other times, effectively shifting portions of peak load to off-peak hours. Reshaping the load curve improves the utility's capacity factor and, by extension, its financial health.



For solar domestic hot water, the heat exchanger from the solar collectors is usually placed in the bottom of the store, cf. the lower coil in figure 1. Often, an extra coil is placed in the top of the store to raise the temperature by an additional heat source, when needed.

For shift load storage there is no need to have heat exchanger coils, if for example the store is a component in a closed circuit with a heat pump.

In Denmark, hot water vessels are typically made in steel, corrosion protected by enamel and anode. Other countries also use stainless steel, which is generally found too costly in Denmark [1].

Figure 1: Typical domestic hot water store used for solar heating [1].

Input

Heat

Output

Hot water

Typical capacities

To store domestic hot water, the volume is often 100 - 150 litres for a single-family dwelling.

For solar water heaters, with no seasonal storage, the store volume needs be around 50-65 litres per m^2 solar collector [1].

If a large volume is needed, the limit is often determined by the available space, e.g. in the laundry room of the dwelling. A cupboard solution, 60 by 60 cm horizontal and 2+ metres high, has a water volume of approx. 400 litres [5].

The energy content of heated water (in kJ per litre) is 4.187 times the temperature difference, so with a temperature difference of 40 ^{o}C, the storage capacity is 167 kJ/litre. For illustration, to deliver a heat output of 1 kJ/s for a full week, you need a tank of about 3000 litres.

Regulation ability

The Danish electricity transmission and systems operator Energinet.dk has funded a demonstration project (‘From Wind Power to Heat Pumps’, 2010-12) involving 300 homes with heat pumps to test how these can be used to create dynamic demand, responding to electricity prices or serving the electricity distribution companies in providing regulation power to the overall system. As part of the project, Energinet.dk has analysed the potential for operating heat pumps with increased flexibility by means of hot water stores [4].

Under Danish conditions, the potential benefit from full utilization of flexible electricity demand is 1.35 – 2.90 €cents/kWh. If an owner of a heat pump, with an annual electricity demand of 6000 kWh/year, received the entire benefit, this gives an annual saving of 80 – 140 €/year. However, a heat pump has very little flexibility during the coldest months, when it is operated next to full load. Therefore, moving electricity demand within 24 hours at anytime during the year will realistically yield a benefit of less than 40 €/year [4].

A hot water store of 400 litres enables disconnecting a heat pump 1 – 2 hours during cold days, in average up to 4 hours, without significantly compromising the indoor temperature. A cheap store, with no heat exchanger, costs 540 – 670 € [5]. Thus, the solution is not very attractive for home owners, unless more of the societal benefits are transferred to the home owners through price mechanisms or other incentives.

Advantages/disadvantages

Tanks are ideally suited for water storage since they are cheap and easy to produce (for example, 50-1000 liter tanks are built by millions each year for the domestic and international market).

The major challenges with water stores are that they are difficult to insulate sufficiently, and that they take much space. Therefore, developers are searching for feasible stores using chemical processes.

Environment

Electricity is produced and delivered more efficiently during off-peak hours than during on-peak periods. The reduction in source fuel normally results in a reduction of greenhouse-gas emissions produced by the power plant

Additional remarks

The heat loss coefficient for a 200 liters store insulated by 10 cm mineral wool is about 1.1 J/s per ^oC, and about 2.0 J/s per ^oC, if the volume is 600 liters. The coefficients are twice as big, if the insulation is only 5 cm. Thus, a 600 liters store, insulated by 10 cm mineral wool, and storing water at 40 ^oC above an average room temperature of 20 ^oC loses 2.5 GJ/year.

The cost of a hot water store is almost a linear function of the volume [2]. The figure below shows the nominal prices of some hot water stores in Denmark, including heat exchanger coil and excluding installation:

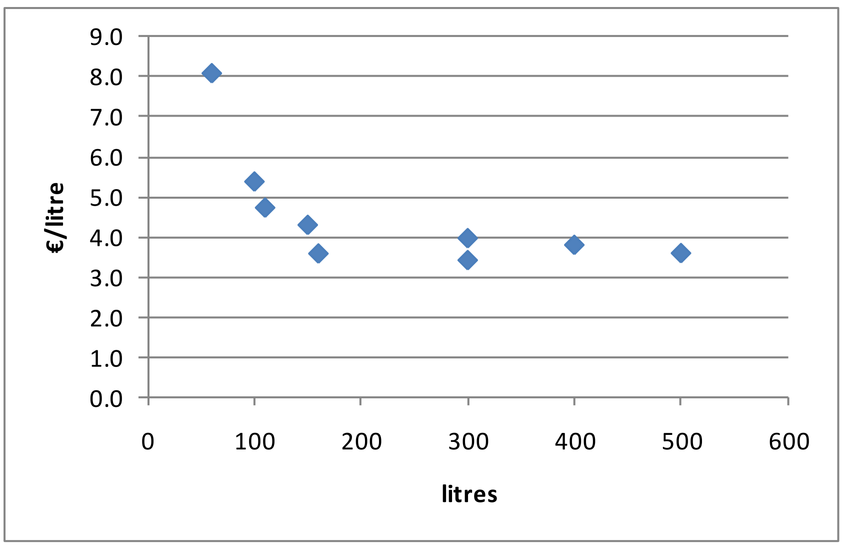


Figure 2: Prices of hot water stores in Denmark, 2011 [3].

References

[1] ”Solvarme – status og strategi” (Solar heat – status and strategy). Danish Energy Agency and Energinet.dk, May 2007.

[2] ”Forsyningskataloget” (Supply catalogue). Danish Energy Agency, 1988.

[3] www.hedestoker.dk, September 2011.

[4] ”Potentiale og muligheder for fleksibelt elforbrug med særligt fokus på individuelle varmepumper”(Opportunities for flexible electricity demand using heat pumps in private homes), Energinet.dk, January 2011.

[5] Interview with mr. Mikael Byllemoes, Sydenergy, participant in Energinet.dk’s project ’From Wind Power to Heat Pumps’, September 2011.

150 UNDERGROUND STORAGE OF GAS

This chapter has been moved from the previous Technology Data Catalogue for Electricity and district heating production from May 2012. Therefore, the text and data sheets do not follow the same guidelines as the remainder of the catalogue.

Brief technology description

Large volumes of gas may be stored in underground reservoirs or as liquefied gas in tanks (e.g. LNG - liquefied natural gas). This technology element is about underground storage, of which there are three principal types:

Depleted gas reservoirs are the most prominent and common form of underground storage. They are the reservoir formations of natural gas fields that have produced all their economically recoverable gas. The depleted reservoir formation is readily capable of holding injected natural gas. Using such a facility is economically attractive because it allows the re-use, with suitable modification, of the extraction and distribution infrastructure remaining from the productive life of the gas field which reduces the start-up costs. Depleted reservoirs are also attractive because their geological and physical characteristics have already been studied by geologists and petroleum engineers and are usually well known. Consequently, depleted reservoirs are generally the cheapest and easiest to develop, operate, and maintain of the three types of underground storage.

However, off-shore depleted gas fields are generally quite expensive.

Aquifer reservoirs are underground, porous and permeable rock formations that act as natural water reservoirs. In some cases they can be used for natural gas storage. Usually these facilities are operated on a single annual cycle as with depleted reservoirs. The geological and physical characteristics of aquifer formation are not known ahead of time and a significant investment has to go into investigating these and evaluating the aquifer's suitability for natural gas storage.

Salt caverns allow no gas to escape from storage. The walls of a salt cavern are strong and impervious to gas over the lifespan of the storage facility. Once a suitable salt feature is discovered and found to be suitable for the development of a gas storage facility a cavern is created within the salt feature. This is done by the process of cavern leaching. Fresh water is pumped down a borehole into the salt. Some of the salt is dissolved leaving a void and the water, now saline, is pumped back to the surface.

The process continues until the cavern is the desired size. Once created, a salt cavern offers an underground natural gas storage vessel with very high deliverability. Cushion gas requirements are low, typically about 33 percent of total gas capacity.

Input

Underground storage is primarily used for natural gas (almost pure methane, CH_4), but other gasses may also be stored underground.

That may include hydrogen (H_2), but the surface facilities need be designed differently, as hydrogen is much more explosive and also aggressive towards steel structures. The costs of storing hydrogen would be larger, since the heating value per volume is about three times less (cf. Technology element 42).

If biogas (approx. 65 % CH_4 and 35 % CO_2) is to be stored underground, it would be instrumental to remove the CO_2 before storage. This is because stores are always wet, i.e. containing some water, and CO_2 in contact with water becomes acidic, posing potential problems for the surface facilities. Also, the energy density will be increased, when the CO_2 is removed.

Output

Same as input gas, but it will have to be cleaned before usage, e.g. water has to be removed.

Typical capacities

The characteristics of gas storage differ depending on the geological properties of the reservoir, which in turn define their use [2]:

	Depleted field	Aquifer	Salt cavern
Working gas volume[4]	High	High	Relatively low
Cushion gas	~50 %	~80 %	~30 %
Injection rate*	Low	Low	High
Withdrawal rate*	Low	Low	High

*as compared to working gas volume

Working gas is the volume of gas that can be extracted during an operation of a facility.

---

[4] A depleted field is often above 1 billion m^3, an aquifer store from around 0.3 – 0.4 to above 1 billion m^3, and salt caverns about 35 – 100 million m^3 per cavern. There are several caverns in one store.

Cushion gas (or base gas) is the share of residual gas that needs to be maintained to ensure appropriate reservoir pressurization.

Using highly sophisticated technology, depths of up to 3,000 m are made accessible and cavern diameters of 60 to 100 m, heights of several hundred meters, and geometrical volumes of 800,000 m^3 and more can be realized today [1].

Regulation ability

The short-term regulation characteristics of an underground gas store are not relevant for the overall gas system, as the gas transmission and distribution pipelines normally have substantial storage capacity (so-called line pack). If, for example, a power plant wishes to start up from zero to full load in a moment, the required gas volume is ready by the gate. The gas pressure in the pipeline will drop a little, much within the operational limits, and the pressure will soon rebuild by drawing gas from other parts of the system, incl. underground stores.

The primary regulation values of underground gas stores are as seasonal stores (gas production is fairly constant, while summer demand is much lower than winter demand) and as back-up supply-security in cases of emergency.

Examples of best available technology

The total gas storage capacity in Europe is around 67 billion m^3. Of 125 storage facilities analyzed by Gas Storage Europe, 64 % were depleted fields, 26 % salt caverns, 8 % aquifers and 2 % LNG peak shaving [3].

Example, aquifer reservoir: Stenlille, Denmark. Gas is stored in porous water-saturated sandstone approx. 1.5 km below surface. Total gas volume 1.5 billion m^3, working gas 0.6 billion m^3.

Example, salt caverns: Lille Torup, Denmark. Gas is stored in 7 caverns 1-1.7 km below ground. Each cavern is 200-300 metres high and 40-60 metres in diameter. Total gas volume 0.7 billion m^3, working gas 0.44 billion m^3. The store can extract 8 million m^3/day and inject about half this flow.

References

[1] Deep Underground Engineering (www.deep.de).

[2] "Underground Natural Gas Storage: ensuring a secure and flexible gas supply", presentation by Jean-Marc Leroy, President of Gas Storage Europe (a sub-division of Gas Infrastructure Europe; www.gie.eu.com), January 2011.

[3] Gas Storage Europe's "Investment Database", February 2010 (www.gie.eu/maps_data/GSE/database/index.asp).

Data sheet

Cavern leaching

Plant for cavern leaching	Mill. €
Total	9.9

Establishment of one cavern, 100 million Nm3 (approx. 1.1 TWh)

	Mill. €
Construction and equipment	22
Cushion gas for one cavern (40% of total)	14
Total cost, 100 mio Nm3 active volume	36

Process equipment; injection 200,000 Nm3/hour (approx. 2200 MW), withdrawal 600,000 nM3/hour (approx. 6600 MW)

	Mill. €
Construction work	2.8
Compressors, incl. auxiliaries	30
Udtrækstog	13
Withdrawal equipment	4.5
Connections, transformer, regulation, and instruments	13
Total investment cost	63

A new greenfield store, equivalent to Lille Torup in Denmark, would require one leaching plant, 5 caverns, and one process plant.
Total investment cost 254 mill. €

Operation and maintenace, salt cavern, 400-500 million m3 working gas

	Mill. € per year
Electricity	0.7 - 1.1
Gas consumption to reheat extracted gas	0.13
Total, incl. administration	6.5

151 HYDROGEN STORAGE

This chapter has been moved from the previous Technology Data Catalogue for Electricity and district heating production from May 2012. Therefore, the text and data sheets do not follow the same guidelines as the remainder of the catalogue.

Brief technology description

Hydrogen serves as a storage and transportation medium for energy. In general there are five different ways of storing hydrogen [1]:

- storage of pressurised gas
    - in caverns
    - in tanks e.g. for mobile applications up to 700 bar
    - in pipelines between producers and consumers (like natural gas)
- storage of liquid hydrogen
    - liquefied at -253°C, stored in cryo-tanks
- storage via absorption
    - Metal hydride storage used in submarines commercially today, heavy
- storage in chemical compounds, including SNG, ammonia and synthetic liquid hydrocarbons (DME, Methanol)
- storage via adsorption
    - Adsorption at low temperatures on high surface area carbon and similar compounds, under development.

Input

Hydrogen

Output

Hydrogen

The lower heating value of hydrogen is 10.79 MJ/Nm^3 (0 ^{o}C and 1.015 bar) or 3.00 kWh/Nm^3, while the higher heating value is 12.75 MJ/Nm^3. The density is 0.0899 kg/Nm^3.

Typical plant capacities

Hydrogen storages can differ greatly in sizes from caverns of 100-100.000 GJ down to pressurised tanks of 300 bar with capacities of 0.4-2.5 GJ [1][5].

Regulation ability

Production and storage of hydrogen is a tool to enhance regulation ability of the overall energy system, without having to convert the electricity into low value energy like heat. How fast the hydrogen can be converted into electricity and heat depends on the type and number of hydrogen converting fuel cells.

Environmental aspects

Hydrogen is, like electricity, an energy carrier, which is only as clean as the energy source from which it is produced.

Some emissions of hydrogen will take place during storage, distribution and utilisation of the hydrogen. Hydrogen emits to the stratosphere, where it connects with oxygen to form water. An increased amount of water in the stratosphere will lead to further destruction of the ozone layer. It is however calculated that the increase in water in the stratosphere due to hydrogen will be significantly less than the increases, which are expected already to have appeared in the stratosphere during the last 50 years. Therefore, it is uncertain whether future emissions of hydrogen may lead to further damages on the ozone layer [2+3].

Research and development

Most research in hydrogen storage is directed towards storage in tanks for mobile applications, where the challenge is to store hydrogen in tanks under high pressure or liquefied with low weight while ensuring safety and energy amounts for ranges comparable to cars run on fossil fuels today.

Examples of best available technology

When it is necessary to store large amounts of hydrogen in a future energy economy then hydrogen can be pumped into subterranean cavern storages. The method is already in use in UK (Tees Valley), France and the USA (ConocoPhillips Clemens Terminal built a 2500 tonnes cavern store in Texas in the 1980'es, while Praxair established a hydrogen cavern store, also in Texas, more recently). Caverns used for storage of natural gas could be used for the storage of hydrogen in the future.

[5] General Motors and QUANTUM Fuel System Systems Technology Worldwide has furthermore developed and tested a 700 bar hydrogen storage system which extends the range of a fuel cell vehicle by 60-70 percent compared to an equivalent-sized 350 bar system. (4)

References

1) http://www.hynet.info/hydrogen_e/index00.html

2) http://www.dmi.dk/dmi/brint_fra_brandselsceller_kan_maske_skade_ozonlaget

3) http://www.sciencemag.org/cgi/content/full/300/5626/1740

Data sheet

Technology	Hydrogen storage, cavern					
	2015	**2020**	**2030**	**2050**	**Note**	**Ref**
Energy/technical data						
Output capacity, MW	2					1
Storage volume, MWh	10					1
Overall cycle efficiency, AC-AC (%)	35				A	1
Technical lifetime (year)	30					1
Financial data						
Investment storage, € per kWh storage volume	11				A+B+C	1
Investment converter, € per kW output capacity	3000				A+B+C	1
Fixed O&M (€/MW/year)						
Variable O&M (€/MWh)						

References:

1 "Economical and technical evaluation of energy storage systems", presentation by J. Oberschmidt & M. Klobasa, Fraunhofer Institut, at the "Third International Renewable Energy Storage Conference (IRES 2008)", Berlin, November 2008

Notes:

A System: PEM electrolysis, storage of hydrogen at 30 bar, and a gas engine to convert back to AC.
B The two investment components shall be added, cf. paragraph 1.3 in the introductive chapter.
C Cost data are the same as in the 2010 catalogue, however inflated from price level 2008 to 2011 by multiplying with a general inflation factor 1.053

160 PUMPED HYDRO STORAGE

This chapter has been moved from the previous Technology Data Catalogue for Electricity and district heating production from May 2012. Therefore, the text and data sheets do not follow the same guidelines as the remainder of the catalogue.

Brief technology description

For bulk electricity storage in utility grids, pumped hydro power plants dominate, with approximately 100 GW in service around the globe [2].

A typical pumped hydro store (PHS) consists of two water reservoirs (lakes), tunnels that convey water from one reservoir to another, a reversible pump-turbine, a motor-generator, transformers, and transmission connection. The amount of stored electricity is proportional to the product of the volume of water and the height between the reservoirs. As an example, storing 1,000 MWh requires an elevation change of 300 m and a water volume of about 1.4 million m^3.

A new PHS, including dams, has high capital expenditures and a long construction time. If an existing hydro plant is extended to also be a PHS, the investment per installed MW is significantly lower and the construction time between 2 and 3 years.

With this technology electricity is basically stored as potential energy. Others ways of storing electricity as potential energy may have similar characteristics.

Input

Electricity

Output

Electricity

Typical capacities

PHS facilities are dependent on local geography and currently have capacities up to 1,000 MW. In addition to large variations in capacities PHS is also very divers regarding characteristics such as the discharge time, which is ranging from several hours to a few days. Efficiency typically is in the range of 70 % to 80 %, due to the losses in the process of pumping water up into the reservoirs.

Regulation ability

The primary intent of PHS is to provide peaking energy each day. However, their duty can be expanded to include ancillary service functions, such as frequency regulation in the generation mode. A variable-speed system design allows providing ancillary service capability in the pumping mode as well, which increases overall plant efficiency [2].

Advantages/disadvantages

The advantage of PHS is the large volumes compared to other storages e.g. various batteries. In addition PHS does not use fossil fuel such as e.g. CAES.

A disadvantage with PHS is the need for differences in height between the two reservoirs. When a new PHS is not built in connection with an existing hydropower plant there are also environmental concerns in flooding large areas.

Research and development

In the 1890's PHS was first used in Italy and Switzerland. After over 100 years of development PHS is considered to be a mature technology. New developments include seawater pumped hydro storage that was built in Japan in 1999 (Yanbaru, 30 MW). It is also technically possible to have a pumped underground storage by using flooded mine shafts or other cavities.

A new (2009) Danish concept is storing electricity as potential energy by elevating sand. The sand is lifted by pumping water into a balloon underneath the sand, and then lowered by taking the water out through the pump, now acting as a turbine.

Additional remarks

There are frequently several hydro power plants on the same river, and the operation of these plants is to some degree interlinked. The benefits of a new PHS therefore depend also on the existing hydropower infrastructure.

For new large hydropower plants in OECD countries, capital costs are about 2400 USD/kW and generating costs around 0.03-0.04 USD/kWh. The cost of pumped storage systems depends on their configuration and use. They may be up to twice as expensive as an equivalent unpumped hydropower system. Depending on cycling rates, their generating costs may be similar to those of unpumped systems [1].

References

[1] "Energy technology perspectives 2008", International Energy Agency, 2008.

[2] "Capturing Power Grid", IEEE Power & Energy Magazine, July/August 2009, http://www.electricitystorage.org/images/uploads/docs/captureGrid.pdf

Data sheet

Technology	Pumped hydro storage					
	2015	**2020**	**2030**	**2050**	**Note**	**Ref**
Energy/technical data						
Generating capacity for one unit (MW)	10-1000	10-1000	10-1000	10-1000	A	2
Total efficiency (%) net	70 - 80	70 - 80	70 - 80	70 - 80	A	1
Technical lifetime (years)	50	50	50	50	A	1
Construction time (years)	2-3	2-3	2-3	2-3	A	
Financial data						
Investment, pump part (M€/MW)	0.6	0.6	0.6	0.6	B;C;A	1&2
Investment, total, greenfield plant (M€/MW)	< 4	< 4	< 4	< 4	D;A	4
Fixed O&M (€/MW/year) - 1-2% of investment	6-12,000	6-12,000	6-12,000	6-12,000	B;A	3
Variable O&M (€/MWh)	Depends on power price					

References:

1 BKK, presentation on Nygard Pumpekraftverk
2 Tonstad Pumpekraftverk, Sira-Kvina kraftselskap, 2002
3 BKK and Sira-Kvina
4 “Energy technology perspectives 2008”, International Energy Agency, 2008.

Notes:

A No significant technology advance or cost decrease is expected, since hydropower and water pumping are established technologies.
B Based on the September 2004 exchange rate of 1NOK = 0,12€
C Cost data are the same as in the 2005 catalogue, however inflated from price level 2002 to 2011 by multiplying with a general inflation factor 1.2306
D Cf. paragraph 'Additional remarks' above.

161 COMPRESSED AIR ENERGY STORAGE

This chapter has been moved from the previous Technology Data Catalogue for Electricity and district heating production from May 2012. Therefore, the text and data sheets do not follow the same guidelines as the remainder of the catalogue.

Brief technology description

Compressed air energy storage (CAES) is a technology for large-scale electricity storage. Air is compressed, preferably at times with low electricity prices, and injected into an underground store for later use. The underground geological formation may be a mine, a salt cavern, or a depleted gas well. When needed, the stored air is used together with gas to produce electricity.

In a conventional industrial gas turbine the compressor and turbine are operating on the same axis. The compression typically accounts for up to 2/3 of the total energy input. The generator output is therefore fairly small compared to the power generated by the turbine.

The basic concept of a CAES power plant is to split the gas turbine into a compressor unit for compressing the combustion air and an expansion turbine to generate mechanical power to drive a generator. This enables the utilization of the full capacity of the turbine, while leaving the compressor idle in periods of high demand.

CAES is characterized by being built in modules in form of a) compressors for air injection capacity; b) turbines/generator for withdrawal capacity; and c) underground storage for storage capacity. The storage can therefore be formed to a specific need, by altering one of these variables. This means that the storage is very flexible e.g. the storage capacity (can be doubled by creating another cavern) and the relationship between the loading and consuming time can also be easily altered. The numbers mentioned in the data sheets are only example of how the storage configuration can be.

Since a CAES plant uses fuel to heat air during the discharge generation cycle, it is not truly a 'pure' energy storage plant such as pumped hydro and batteries. In general, a CAES plant provides approximately 25-60% more electricity to the grid during on-peak times than it uses for compression during off-peak times [5].

Theoretically, all heat generated during compression could be recovered and used later to reheat the stored air during the generation cycle to eliminate the fuel consumption. However, this is rather costly and presently being researched only, and the table below therefore assumes no heat recovery.

For illustration, to generate 1 MWh electricity, the electricity needed for compression is 0.6 MWh, while 1.2 MWh of fuel is required for air heating and the turbine. Thus, the storage efficiency is

$1 / (0.6 + 1.2) * 100 = 55\%$.

Input

Electricity, when the store is filled. Gas for air heating and turbine operation, when the store is emptied.

Output

Electricity and heat (optional, as is the case for SCGT or CCGT)

Typical capacities

There is no typical capacity. The two currently operating plants have generating capacities of 110 and 290 MW, but new plants can be both smaller and larger.

Regulation ability

A CAES plant will be able to generate at full capacity within 15 minutes from cold start.

Advantages/disadvantages

CAES is in addition to pumped hydro storage the only storage technology that currently is capable of operating over 100 MW for several hours. The potential production period is at any time limited by the actual filling level in storage.

CAES can be built in such a way that it also is possible to produce power by only using gas and no compressed air. In this situation the plant will be similar to a single cycle gas turbine.

The CAES positive environmental profile is the ability to store wind generated power from the time of generation to the time of consumption. On the negative side is that some energy is lost in this process and that fuel is used in the generation process.

Research and development

World wide there have only been built two CAES plants so far. The CAES technology has potential for being improved and optimized. A major EU research project is currently being carried out with the aim of significantly improving the efficiency of future CAES power plants by using compression heat.

Examples of best available technology

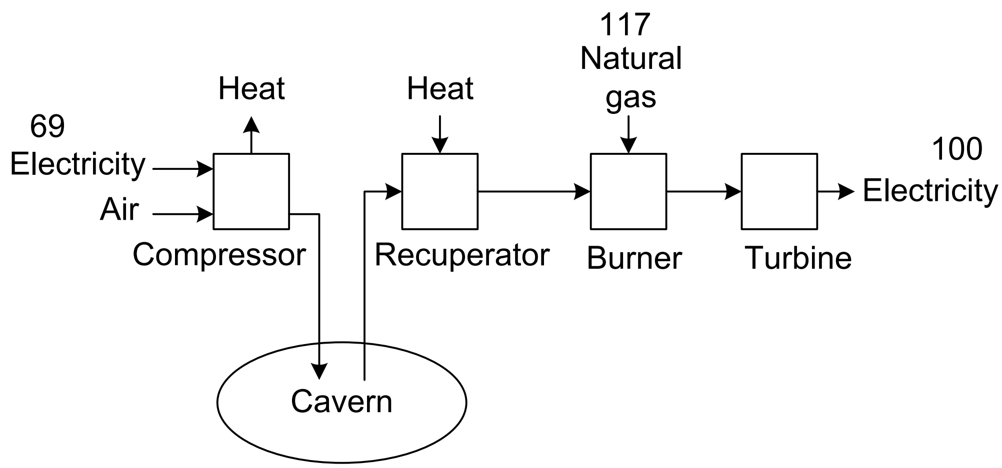
- The CAES plant in Huntorf near Bremen, Germany, is operated by E.ON Kraftwerke. It was built in 1978 and has two caverns, each 155.000 m^3, 72 bar storage pressure. Original power output 290 MW; revamped to 321 MW in 2007. Storage efficiency 42% [6].
- The CAES plant in McIntosh, Alabama, USA operated by AEC (Alabama Electricity Corporation). It was commissioned in 1991 and has a maximum power output of 110 MW. Storage efficiency 54% [6].

Additional remarks

Currently, the energy storage technology receiving the most attention for use in large-scale energy storage in U.S.A. is CAES, since the number of environmentally acceptable sites for future pumped hydroelectric facilities is very limited [8].

CAES needs to have an underground storage and salt caverns are most suitable, but natural aquifer structures and abandoned mines can also be used. This limits the location of CAES plants, there are however numerous salt deposits in Denmark, along the North Sea coast and some in the Baltic Sea coastal area.

The overall principle and energy balance of the newest plat in operation (McIntosh, USA) is shown below:



The air, which is compressed, gets warm and needs be cooled. Similarly, the high pressure air from the cavern is cooled, when the pressure is reduced, and therefore needs be heated before entering the burner. No external heat is needed, since heat from compression is re-used. The overall energy efficiency is 100 / (69 + 117) = 0.54.

Some of the generated electricity originates from natural gas. If this part is ignored, the storage efficiency, defined as the share of the electricity input, which is regained, is about 0.43 [7]. This means that the 100 units of output electricity consist of 30 units from input electricity plus 70 units from natural gas.

References

[1] Huntorf CAES: More than 20 Years of Successful Operation, by Fritz Crotogino KBB GmbH, Hannover, Germany and Klaus-Uwe Mohmeyer and Dr. Roland Scharf E.ON Kraftwerke Bremen, Germany.

[2] U.S. Department of Energy, Energy Efficiency and Renewable Energy: Renewable energy Technology Characterizations, December 1997

[3] ESA, Electricity Storage Association, www.electricitystorage.org

[4] CAES development company, www.caes.net

[5] EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, EPRI, 2003

[6] “30 years compressed air energy storage plant Huntorf – Experiences and outlook”, presentation by P. Radgen, E.ON Energie, at the “Third International Renewable Energy Storage Conference (IRES 2008)”, Berlin, November 2008.

[7] “CAES – Compressed air electricity storage”, presentation by B. Elmegaard, Technical University of Denmark, January 2009.

[8] “Bottling Electricity: Storage as a strategic tool for managing variability and capacity concerns in the modern grid”, Electricity Advisory Committee, December 2008, http://www.oe.energy.gov/DocumentsandMedia/final-energy-storage_12-16-08.pdf

Data sheet

Technology	Compressed Air Energy Storage (CAES)					
	2015	2020	2030	2050	Note	Ref
Energy/technical data						
Generating capacity for one unit (MW)	100 - 350					
Electricity efficiency (%) net	60	71	71	71	A	1
Time for warm start-up (hours)	0	0	0	0		2
Starting reliability (%)	99	99	99	99		3
Availability (%)	95	95	95	95		3
Technical lifetime (years)	30	30	30	30		2
Construction time (years)	3	3	3	3		2
Environment						
NO_X (kg per GJ fuel)	< 0,006	< 0,002	< 0,002	< 0,002	B	4
CH_4 (kg per GJ fuel)	0.0015	0.0015	0.0015	0.0015		4
N_2O (kg per GJ fuel)	0.0022					4
Financial data						
Investment storage, € per kWh storage volume	240	246	246	246	C+D	5
Investment converter, € per kW output capacity	2000	1970	1970	1970	C+D	5
Fixed O&M (€/MW/year)	< 14,000	< 14,000	< 14,000	< 14,000	C+E	3
Variable O&M (€/MW/year)	-	-			F	
Regulation ability						
Fast reserve (MW per 15 minutes)	100%	100%	100%	100%		1

References:

1 "30 years compressed air energy storage plant Huntorf – Experiences and outlook", presentation by P. Radgen, E.ON Energie, at the "Third International Renewable Energy Storage Conference (IRES 2008)",
2 KBB GmbH (a Schlumberger company),
3 EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, EPRI, 2003
4 It is estimated that emissions will be similar to Gasturbine single cycle so data is copied from technology sheet no. 04.
5 "Economical and technical evaluation of energy storage systems", presentation by J. Oberschmidt & M. Klobasa, Fraunhofer Institut, at the "Third International Renewable Energy Storage Conference (IRES 2008)", Berlin, November 2008.

Notes:

A The 2010 efficiency data is for the two plants in operation. Efficiency improvements are based on a concrete case study.
B NOx emission today 25 ppm, 2010-15 < 9 ppm and 2020-30 < 1 ppm.
C No significant cost decrease is expected, since all equipments are established technologies.
D The two investment components shall be added, cf. paragraph 1.3 in the introductive chapter.
E Cost data are the same as in the 2005 catalogue, however inflated from price level 2002 to 2011 by multiplying with a general inflation factor 1.2306
F Variable O&M costs depend mainly on power and gas consumption and the specific fuel costs.

180 BATTERIES

This chapter has been moved from the previous Technology Data Catalogue for Electricity and district heating production from May 2012. Therefore, the text and data sheets do not follow the same guidelines as the remainder of the catalogue.

Brief technology description

There are several technologies available or being developed for storing electricity. Below is a classification of a selection of these technologies regarding their capacities and discharge times.

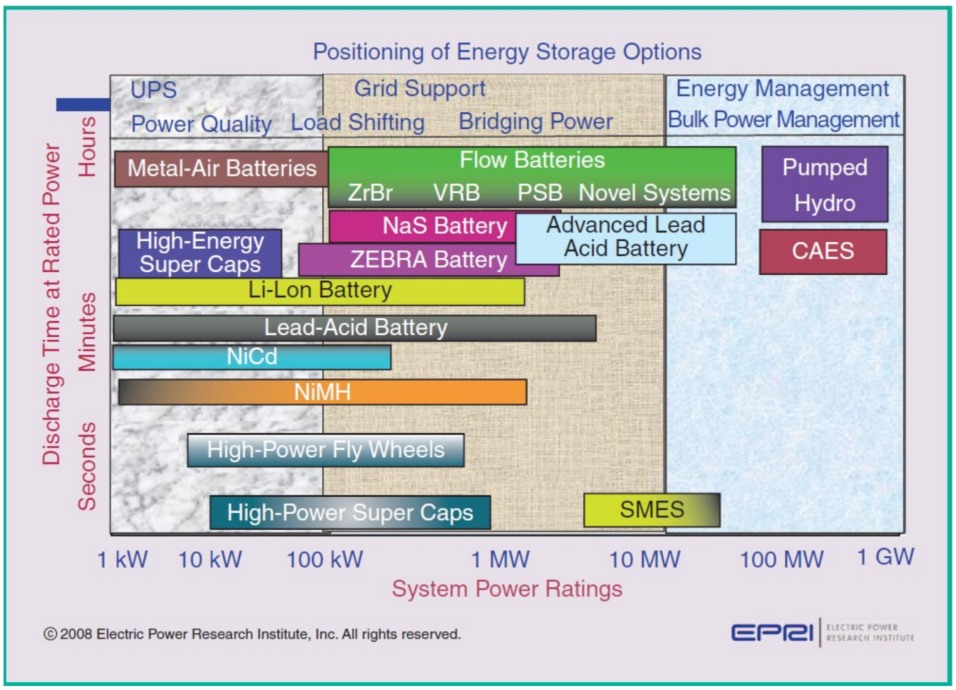


Figure: Storage technology comparison by application (power level) and storage time ([3]. UPS: Uninterruptible Power Supply (e.g. backup for data centres to support the Internet and communication centres).

The battery technology with the broadest base of applications today is the lithium-ion battery, used e.g. in laptop computers and electric vehicles. The ability of lithium-ion batteries to economically serve electric utility applications has not yet been demonstrated, except for some ancillary services provisions to independent system operators [4].

Three main battery types are most relevant for large-scale electricity storage:

- Advanced lead acid batteries
- NaS (Sodium Sulphur) batteries
- Flow batteries, in particular:
  - Vanadium Redox (VRB)
  - Zinc-bromine (ZnBr)

The lead-acid battery is one of the oldest and most developed battery technologies. A lead-acid battery is an electrical storage device that uses a combination of lead plates or grids and an electrolyte consisting of a diluted sulphuric acid to convert electrical energy into potential chemical energy and back again.

The sodium sulphur (NaS) battery is a high-temperature (about 300 °C) battery system that consists of a molten sulphur positive electrode and a molten sodium negative electrode separated by a solid ceramic electrolyte. During discharge, positive sodium ions flow through the electrolyte and electrons flow in the external circuit of the battery, producing about 2 V. This process is reversible [3].

Flow batteries utilize an active element in a liquid electrolyte that is pumped through a membrane similar to a fuel cell to produce an electrical current. The system's power rating is determined by the size and number of membranes, and the runtime (hours) is based on the volume of electrolyte pumped through the membranes. Pumping in one direction produces power from the battery, and reversing the flow charges the system.

The Vanadium redox battery (VRB) is based on vanadium as the only element, and is based on the reduction and oxidation of the different ionic forms of Vanadium. Energy can be stored indefinitely in a liquid – very low self-discharge.

The Zinc-bromine (ZnBr) battery is based on cells with two different electrolytes flowing past carbon-plastic composite electrodes in two compartments separated by a microporous polyolefin membrane.

For batteries to be practically applied in the utility grid, reliable power conversion systems (PCSs) that convert AC power to battery DC and back to AC are needed.

Typical capacities

See figure on previous page.

Input

Electricity

Output

Electricity.

Some of the electricity losses may be regained as useful heat. However, a heat pump may be necessary to produce valuable heat.

Regulation ability

The potential benefits for electricity systems are:

- Deferred or avoided substation upgrade
- Energy cost savings, e.g. reduce peak energy generation/purchases or shift off-peak wind generation to peak
- Transmission and/or generation capacity reduction credit
- Regulation control and black start

Advantages/disadvantages

Advantages of the Vanadium Redox (VRB) system is a high-energy efficiency of over 75% (AC to AC) and over 85% (DC to DC); a very low self discharge; storage capacity can be increased by increasing electrolyte volume (no change to battery cell-stacks); the lifetime charge-discharge cycle is over 13,000 cycles without need for membrane replacement. The battery has a charge/discharge window of 1 to 1.

The strengths of the NaS battery are also the high average DC energy efficiency (charging/ discharging) of 85%, its relative long-term durability of 15 years and assumed specification of 2,500 cycles, and a high energy density i.e. reduced space requirements.

Research and development

The basic principals behind the NaS battery were discovered in the 1960s by the Ford Motor Company. NGK of Japan began research in NAS batteries in 1987, began testing of prototypes for commercial use at the Tokyo Electric Power in 1992 and in Japan are currently 19 sites totalling 52 MW, mainly for demonstration purposes. The major stakeholders are NGK (producer) and Tokyo Electricity Power (alliance with NGK).

Early work on VRB was undertaken by NASA in the 1970s. Currently the major stakeholders and developers are VRB Power Systems (Canada), Sumitomo Electric Industries (Japan) and Squirrel Holdings (Thailand).

Examples of best available technology

<u>VRB</u>

- PacifiCorp installation of 250 kW, 8 hours (2 MWh) battery completed in February 2004, which also should be used for peak shaving.
- Hydro Tasmania has a 200 kW, 4 hours (0.8 MWh) battery completed in November 2003, in connection with wind turbines on Kings Island.
- Tottori SANYO Electric Co. has a 1500 kW and 1500 kWh battery for Peak shaving.

<u>NaS</u>

- The NaS battery technology for large-scale applications was perfected in Japan. There are 190 battery systems in service in Japan, totalling more than 270 MW of capacity with stored energy suitable for six hours of daily peak shaving. The largest single NaS battery installation is a 34 MW, 245 MWh system for wind power stabilization in northern Japan [3].

- American Electric Power is deploying a 5.0 MW NaS battery to solve a transmission issue in southern Texas [4].

ZnBr

The Zinc-bromine battery is currently in use in the United States [4].

Additional remarks

The figure below shows the investment costs of various technologies for electricity storage:

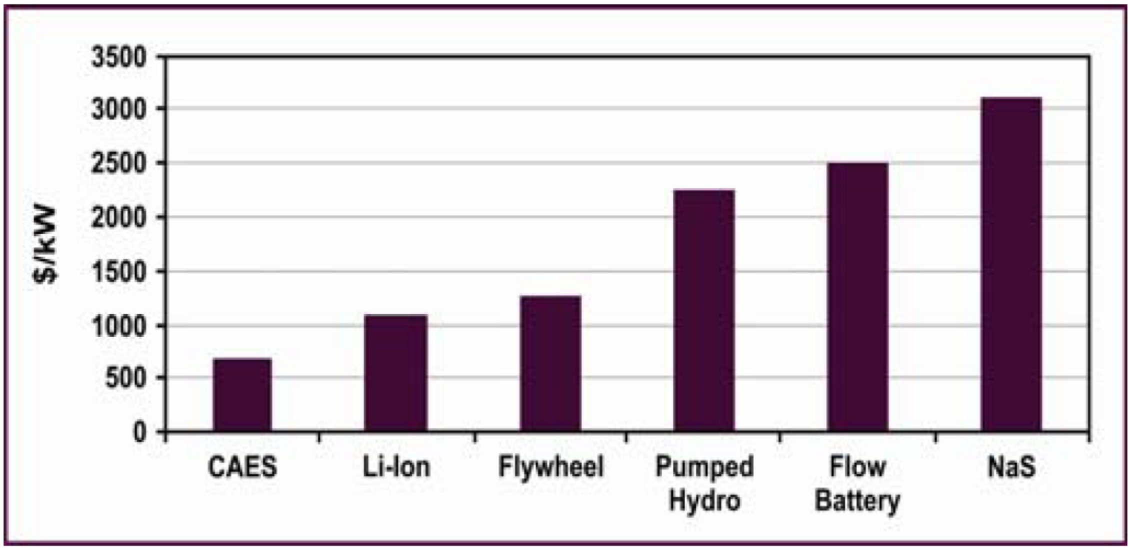


Figure: Energy storage technologies cost estimates. The CAES technology (cf. technology element 41) also requires fuel costs for discharging, which are not captured in the figure. If the system operated on compressed air alone, the costs per kilowatt (kW) would be approximately three times greater [4].

The RD&D in batteries has increased dramatically in recent years, primarily due to the huge political focus and demand for electric vehicles. This development may yield a positive spin-off for large stationary batteries, in terms of efficiencies, technical life and cost. Thus, the cost forecasts in the tables below may be somewhat to the conservative side.

References

[1] EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, EPRI, 2003

[2] Electricity Storage Association, http://www.electricitystorage.org/tech/technologies_comparisons_ratings.htm

[3] "Capturing Power Grid", IEEE Power & Energy Magazine, July/August 2009, http://www.electricitystorage.org/images/uploads/docs/captureGrid.pdf

[4] "Bottling Electricity: Storage as a strategic tool for managing variability and capacity concerns in the modern grid", Electricity Advisory Committee, December 2008, http://www.oe.energy.gov/DocumentsandMedia/final-energy-storage_12-16-08.pdf

Data sheets

The investment costs of the two selected batteries are stated in different terms:

- The total investment of the NAS battery has been converted to specific cost in two different ways, by dividing by the stored amount of energy (€/MWh) and by the generating capacity (€/MW). This is due to lack of data for the NAS battery. The two alternative ways shall not be added.
- The investment of the VRB battery is separated into two components, which shall be added (through the discharge time per cycle): 1) The equipment, which is primarily determined by the amount of energy stored (i.e. the battery itself); and 2) The equipment, which determines how much power the system can deliver (i.e. converter).

Cf. further explanation in paragraph 1.3.

Technology	**Sodium Sulphur (NaS)**					
	2015	**2020**	**2030**	**2050**	**Note**	**Ref**
Energy/technical data						
Storage capacity (MWh)	100	100	100			2
Generating capacity for one battery (MW)	10	10	10			2
Charge-discharge ratio	2:1				A	2
Cell efficiency (%)						
System efficiency (%), AC to AC, net	85%					3
Lifetime in full charge-discharge cycles	2500					2
Technical lifetime (years)	15	15	15			5
Construction time (months)	6-8					1
Financial data						
Specific investment, storage capacity (k€/MWh)	210-940	136	136		D	7;4;4
or specific investment, output capacity (M€/MW)	1.8-2.6	1.7	1.7		D	4+5+6;4,4
Fixed O&M (€/MW/year)	51000	51000	51000		D	4
- do -	7100				D	5
Variable O&M (€/MWh)	5.3	5.3	5.3		B+D	4
- do -	16				C+D	5

References:

1 Commercial Deployment of the NaS Battery in Japan, by Hyogo Takami, Tokyo Electric Power Company and Toyoo Takayama, NGK Insulators, Ltd.
2 Electric energy storage solution group, R&D center, engineering R&D division, Tokyo electric power company (e-mail)
3 NAS battery energy storage system for power quality support in Malaysia, Siam, Hyogo Takami, (TEPCO)
4 EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, EPRI, 2003.
5 "Economic valuation of energy storage for utility.scale applæications", Dan Mears, Technology Insigths (Canada) at Workshop on Electricity Storage, Toronto, June 18 2008.
6 Information from NGK Insulators Ltd. (www.ngk.co.jp/english), Japan, to Danish Energy Authority, September 2008
7 Electricity Storage Association, California, http://electricitystorage.org/tech/technologies_comparisons_capitalcost.htm

Notes:

A Number of hours it takes to charge the battery for having one hour to discharge the battery.
B Based on 2500 operating hours a year
C Assuming 1000 hours/year. If the battery is used for regulation control and black start, the variable O&M is only 3
D Cost data are the same as in the 2010 catalogue, however inflated from price level 2008 to 2011 by multiplying with a general inflation factor 1.053

The number of charge-discharge cycles and thus the O&M costs strongly depend on how a battery is applied, e.g. for deferring a substation upgrade, for energy cost savings (shift off-peak generation to peak), transmission and generation capacity reduction, or regulation control and black start service. The above table therefore gives two sets of O&M costs.

Technology	**Vanadium Redox (VRB)**					
	2015	**2020**	**2030**	**2050**	**Note**	**Ref**
Energy/technical data						
Storage capacity (MWh)						
Generating capacity for one unit (MW)	10	10	10			1
System efficiency (%), DC to DC, net	80					3
System efficiency (%), AC to AC, net	70					4
Lifetime in full charge-discharge cycles	13000					1
Construction time (months)	6-8					1
Financial data						
Investment storage, k€ per MWh storage volume	70	51	51	51	C	4
Investment converter, M€ per MW output capacity	1.5	1.1	1.1	1.1	C	4
Fixed O&M (€/MW/year)	54,000	54,000	54,000		A	2
Variable O&M (€/MWh)	2.8	2.8	2.8		A;B	2

References:

1 VRB Power Systems Incorporated, an electrochemical Energy Storage Company, Executive Summary
2 EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, EPRI, 2003.
3 “Vanadium redox flow battery”, presentation by M. Schreiber, Cellstrom, at the “Third International Renewable Energy Storage Conference (IRES 2008)”, Berlin, November 2008
4 “Economical and technical evaluation of energy storage systems”, presentation by J. Oberschmidt & M. Klobasa, Fraunhofer Institut, at the “Third International Renewable Energy Storage Conference (IRES 2008)”, Berlin, November 2008

Notes:

A Cost data are the same as in the 2005 catalogue, however inflated from price level 2002 to 2011 by multiplying with a general inflation factor 1.2306

B Based on 2500 operating hours a year

C A 27% cost decrease for the mature technology is expected (ref.2).