A supplementary report for the techno-economic database for different storage technologies

Kabitri Chattopadhyay, Chris Graves, and Allan S. Pedersen

Department of Energy Conversion and Storage, DTU

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This report is created as part of an internal assessment of the project CORE to present a brief overview of some potential storage technologies discussed in the light of technical and economic characteristics. This project aims to determine if it is appropriate to establish targets for the procurement of viable and cost-effective energy storage systems for a flexible and sustainable Danish electricity grid. The idea is to explain why these technical terms can have a wide range of values depending on the formulation and to illuminate some underlying assumptions associated with their definitions and implementations. In the following sections a few details will be discussed for both surface- and sub-surface thermal energy storage and power-to-gas systems. Although investigating battery technologies is not part of the author's original agenda of this project, a comprehensive overview of battery technologies is included in this report to help readers make a comparative analysis with the investigated technologies. It is to be noted that this article is the result of a thorough literature review along with the collection of data from multiple published materials. The authors bear no responsibility towards the 'goodness' of the data quality. In case of any query about the data derivation and the underlying assumptions, the reader is referred to the Bibliography section and the supplementary materials provided with this article.

1 Batteries

Batteries are one of the most promising of all storage technologies available today. There are a number of battery technologies that are currently commercially available and several other under development. Depending on the application, batteries can be used in a variety of devices, ranging from small-scale cell phone batteries to those in large utility-scale appliances. This means that the purpose and the operation of a battery not only determine its size and power capacity, but also influence other technical characteristics such as lifetime, charging and discharging rate, cycling efficiency etc. In the next section, certain techno-economic aspects of batteries will be discussed, with a focus on the rechargeable Lithium-ion batteries.

1.1 Technical details

Batteries are usually configured either in the power configuration to inject a large amount of power into the grid in a relatively short period of time or in the energy configuration for a steady supply of power into the grid for an extended period of time. In either way, certain specifications should be used when evaluating battery storage options. In Table. 1, a list of selected specifications is included for Lithium-ion batteries. Other important specifications, such as specific power, nominal voltage, operating temperature etc, will be included in the next version of this draft. It is to be noted that most of the specifications included in Table. 1 not only span over a range of possible values, but also differ significantly between different sources. This is because these values are strongly influenced by their intended

Characteristics	Units	Values
Specific energy	(Wh/kg)	100-265 [1], 236-265 [2], 118-127 [3], 80-200 [4]
Volumetric energy density	(Wh/L)	620-800 [2], 200-400 [5], 143-215 [3]
Cell capacity	(mAh)	2900-4000 [2], 530-3350 [6], 68000-94000 [3]
Round-trip efficiency	(%)	85-95 [5], 83 [7]
Number of cycles	-	3150-3500 [3], 1000-10000 [5], 200-5000 [4], 3000-6000 [4]
Lifetime	(years)	10 [8], 20 [7]

Table 1: *Technical specifications for Lithium-ion batteries collected from different sources. The specific energy and volumetric energy density values from [3] are computed for Samsung Lithium-ion modules of M2994, M2963/M2968. All values from [2] are given for Panasonic 18650 Lithium-ion cells.*

usage and scalability. Additionally, data from different sources are not always very coherent and often gives rise to ambiguity from the lack of clarity in information. While using these numbers from Table. 1, the readers are recommended to carefully navigate through the associated references. It is very important to clearly understand if the values stand for single battery cells or indicate their certain combinations to form a module (or a tray or a rack!). The reader should also be very careful to distinguish between the commercially viable data and those which are presented as a plausible projection by the authors. Furthermore, it is absolutely essential to understand the operational mode of the batteries. This includes information like how long the battery is operated, their usual depth of discharge, how frequently they are charged, effectiveness of the chemical components constituting the battery etc. A clear understanding of these factors and their influences on battery's lifetime and efficiency is essential prior to using this data for any evaluation study or model development.

1.2 Economic details

Over the past few decades, batteries have continued to flourish in the power markets primarily due to the increasing penetration of fluctuating renewable sources to the operational power grid. This has led to an increased need for tools and analysis that evaluates financial benefits under various plausible scenarios. Although a detail economic analysis of storage technologies is beyond the scope of this article, a general overview of the levelized cost of electricity storage will be provided here, focusing mainly on Lithium-ion batteries.

Market survey of Lithium-ion batteries indicate that their prices are dropping steadily over the past few years. In an internal analysis, McKinsey announced a drop from $500 - $600/kWh in 2012 to about $200/kWh in 2020 and to about $160/kWh in 2025 [9]. In a 2017 survey, Bloomberg New Energy Finance has reported a 73% drop in the price from almost $1000/kWh in 2010 to around $273/kWh in 2016 [10]. This huge drop in battery prices will enable the broader adoption of electric vehicles , and may bring along wide ranging effects across different sectors, such as industries and transportation. In a 2014 study to determine appropriate energy storage procurement targets for load serving entities [7], the author made a detailed scenario analysis with a capital cost of $1800/kW ($900/kWh) and thereafter a replacement cost of $244/kWh for Lithium-ion batteries. This analysis also includes the operation and the maintenance cost with a fixed ($10/kW-yr) and a variable ($0.3/MWh) component. There has been many such studies in the past years, each with their respective advantages and disadvantages. For the present article, a levelized cost of storage analysis by Lazard has been chosen [8]. In Table. 2, the findings of Lazard's estimations are presented for Lithium-ion batteries. They have considered a few selected use cases for energy storage systems and included illustrative applications derived from industry survey data.

Table. 3 gives a comprehensive overview of techno-economic characteristics of selected well-established battery technologies relevant for this project.

2 Thermal Energy Storage (TES) systems

As part of the project CORE, four thermal energy systems will be reviewed. These are the Aquifer Thermal Energy Storage (ATES), Borehole Thermal Energy Storage (BTES), Pit Thermal Energy Storage (PTES), and Tank Thermal Energy Storage (TTES). It is to be noted that these systems are very different in design and operation than storage systems like the batteries. Therefore, a direct comparison using specific technological parameters is not recommended. In the following section this is illustrated with the example of ATES systems. A comparative overview of different TES systems are summarized in Table. 4. For a more detailed description with numerous case studies, the reader is kindly referred to the supplementary materials supplied with this report (`TES_datasheet` and `TES_P2G_datasheet`).[1]

[1] It is important to emphasize here that the numbers presented in these materials should be handled with cautions as they may not always refer to the thermal storage unit alone, but may also include additional components such as the solar collectors, heat pumps,

	LCOS	Capital cost	O&M	Charging	Taxes	Other
Peaker replacement	282-347	109-139	78-99	38	19-24	39-49
Distribution	272-338	105-134	74-95	39	18-23	37-47
Microgrid	363-386	110-121	65-72	132	19-21	36-40
Commercial	891-985	423-474	190-217	134	45-51	98-109
Residential	1028-1274	546-681	144-215	159	65-76	115-143

Table 2: *Lazard's estimate of levelized cost of storage (LCOS) and the consequent sub-categorizations over the five use cases given for Lithium-ion batteries [8]. All values are expressed in $/MWh.*

	Power rating (MW)	Self discharge (%)	Energy density (Wh/L)	Power density (W/L)	Efficiency (%)	Cell price ($/kWh)
Lithium-ion	0.05-100	0.1 - 0.3	200-400	1300-10000	85-95	550
Lead-acid	0.001-100	0.1 - 0.3	50-80	90-700	80-90	600*
Sodium-sulphur	10-100	0.05-20	150-300	120-160	70-90	535
Flow batteries	0.1-100	0.2	20-70	0.5-2	60-85	680

Table 3: *A comparative overview of different battery technologies. It excludes technologies with limited experience to date. The last column shows battery cell prices in 2014 [4] while the rest of the columns represent technical details [5]. [Note: The * value corresponds to the advanced lead-acid batteries.]*

2.1 Storage size and maximum capacity

The underground thermal energy storage systems operate under the principle that at depths larger than ∼10-15m, groundwater remains at a constant temperature all year long. Hence, warm/cold water from buildings or district heating systems can be injected in such depths where most of the thermal energy is retained and can be retrieved back when needed. The heat transport in a porous media of the aquifer [12] can be expressed as the following partial differential equation

$$(\rho_w c_w \theta + \rho_s c_s (1-\theta)) \frac{\partial T}{\partial t} = \nabla[(\rho_w c_w \alpha q + \lambda_b)\nabla T] - \rho_w c_w \nabla q T - \rho_w c_w q_s T_s \tag{1}$$

where, q_s is the source or sink term of water with density ρ_w and specific heat capacity c_w, q is the specific discharge, the subscript s denotes the same for the aquifer material, T is the temperature, T_s is the source temperature, θ is the effective porosity, α is the thermal dispersivity, λ_b is the bulk thermal conductivity. In case of an ATES system, there are at least two wells into a permeable underground geological layer containing ground water. The one well is called the warm well as it is charged by injecting hot water into it and discharged by extracting the stored hot water. The other well is similarly referred to as the cold well for the obvious reason. The heat storage capacity of ATES systems primarily depend on the thermal interference between these warm and cold wells in the aquifer. Kim *et al.* have identified that this thermal interference is mainly affected by the distance between the wells, the hydraulic conductivity, and the pumping/injection rate [13]. Their results on system performance indicate that if the ratio of the length of the thermal front to the distance between two wells equals (or exceeds) unity, the system performance fall $\sim 22\%$. Hence, it is extremely important to maintain a minimum distance between the wells to avoid thermal interference via overlapping thermal fronts. However, the thermal properties of the two wells are determined by the physical properties of the surrounding materials (such as soil texture, its chemical composition, orientation and distribution of its different constituents, vertical and horizontal temperature gradients, heat capacity, soil porosity, hydraulic conductivity etc) and are therefore extremely site-specific. The numerical values available in literature are usually derived for a particular site and shouldn't be applied for other studies without thorough investigation on the region of interest.

Unlike storage systems like the batteries, determining a general storage capacity for TES systems is extremely challenging. In principle, the physical area of the storage can be as large as possible, as long as the underground soil structure supports proper hydraulic and thermal conductivities. In reality, this requires a thorough site investigation coupled with a cost optimization analysis. Specific numbers can be included from literature to use as a reference value, but must be handled with caution as these represent only particular cases, and may not cover the plausible scenarios to be investigated in this project.

Another important aspect to be discussed is the max-

boilers etc as well.

	ATES	BTES	PTES	TTES
Capacity [MWh]	11,000	34,000	600-80,000	60-400
Efficiency (%)	60-95	60-95	80-95	95
Investment cost [DKK/MWh]	1,600	3,300	3,300-6,000	6,500-30,000

Table 4: *Summary of the key parameters regarding the four TES technologies assessed here [11].*

imum amount of energy that can be extracted to (or from) the storage at any given time, which, in case of the TES systems, depends on the injection/extraction rates. Most of the studies performing numerical simulations on the ATES systems compute the amount of heat injected/extracted depending on a set of predetermined warm and cold well temperatures, the circulated volume of water and usually assuming a constant mass flow rate [14, 15]. The exact procedure to be implemented as part of project CORE is still open for discussion.

$T_{in,warm}$ / $T_{out,cold}$ $^{\circ}C$	Capacity (MWh/a)	HRF
50 / 15	5000	0.9
50 / 15	1000	0.8
90 / 35	1000	0.5
50 / 35	1000	0.4
90 / 20	1000	0.6
50 / 20	1000	0.7

Table 5: *Changes in heat recovery factor (HRF) as a function of hot and cold well temperature and the overall storage capacity (taken from [14]).*

2.2 Efficiency

As mentioned earlier, the performance of the TES systems depend on multiple factors. Thereby, it is impossible to present a single number representing the general efficiency of such systems. To the best of our abilities, a range of values can be presented from literature which may cover a wide range of scenarios, not only with multiple structural configurations with different thermo-hydraulic properties, but also with additional features like use in combination with heat pumps or applying as part of a combined heat and power plant (CHP) which may largely change the system efficiency values. The evaluation of the thermal energy storage efficiency in literature is often based on the heat recovery factor (HRF), which accounts for the energy balance around the heat storage including the warm and the cold wells. It is defined as the ratio of output to input thermal energy stored over a period of time. HRF strongly depends on the overall storage capacity, rate of heat loss from the wells, and the combinations of warm and cold well temperatures. Kranz *et al.* have investigated the changes in HRF for a number of combinations of warm and cold well temperatures and with two different numerical models [14]. Their results are summarized in Table 5. In a Dutch case study, the authors have thoroughly analyzed the tendency of efficiency changes over time and reported ATES efficiency in the range of 68-87% and quantified the influence of thermal interference in determining ATES efficiencies [12].

2.3 Discharge time

Another interesting feature is the discharge time of the storages. For ATES systems, the system can be operated either in a continuous or in a cyclic mode. For this project, it is planned to implement a cost effective storage system running on a cyclic operational mode. This means, the system will be operational on the seasonal scale, storing excess (and waste) heat in summer and providing heat in winter period. That will indicate a discharge time of roughly 4-6 months.

3 Power-to-gas (P2G)

Power-to-gas refers to the storage of electrical energy in the form of chemical energy by electrolysis of H_2O to H_2 and O_2. The H_2 product can be used as a transportation fuel, stored in low concentration in the natural gas grid, or reacted with CO_2 to produce methane, which can be stored directly in the natural gas grid. Other hydrocarbons such as methanol, diesel or other liquids can also be produced and utilized directly in the existing infrastructure. Catalytic reactors for producing hydrocarbons from synthesis gas (H_2 and CO mixtures) or H_2-CO_2 mixtures are well-known, mature technologies used in the fossil fuel and chemical industries.

The heart of this energy conversion is the electrolyser and there are 3 main types of electrochemical cell for carrying out the electrolysis reaction: alkaline electrolysis cell (AEC), polymer electrolyte membrane electrolysis cell (PEMEC), and solid oxide electrolysis cell (SOEC). AEC is a mature technology and makes up the majority of commercial electrolyser installations today. PEMEC offers higher power density and reactant rates (throughput per unit area), but requires expensive membranes and platinum catalysts. SOEC operates at elevated temperatures, 600-800°C, which enables both high efficiency and reaction rates without the use of expensive materials like platinum, but requires a more complex balance-of-plant for heat management and device lifetime needs to be improved. SOECs can also electrolyse CO_2 to CO and O_2 due to the oxygen ion conducting ceramic electrolyte, which can be advantageous for producing hydrocarbons. R & D on advanced AEC and PEMEC aims to improve cost and efficiency compared with the conventional versions of those type of cells. The estimated costs for each technology, based on the 2030 technology roadmap from "Technology Data for Hydrogen Technologies" (2016) [16] are tabulated in the supplementary material (`TES_P2G_datasheet`). In these 2030 scenarios, PEMEC and SOEC are assumed to have the greatest production volume scale-up compared with today, implying that the more mature AEC offers the most certain costs.

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