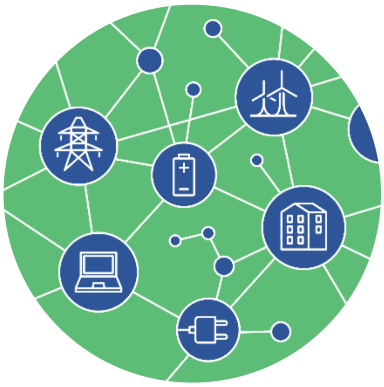
OSMOSE

OPTIMAL SYSTEM-MIX OF FLEXIBILITY SOLUTIONS FOR EUROPEAN ELECTRICITY

Flexibility cost and operational data outlook

D1.2



Contact: www.osmose-h2020.eu

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773406

Document properties

Project Information

Programme	**O**ptimal **S**ystem-**M**ix **O**f Flexibility **S**olutions For **E**uropean Electricity
Project acronym	OSMOSE
Grant agreement number	773406
Number of the Deliverable	D1.2
WP/Task related	WP1/Task 1.1.3

Document information

Document Name	Report: Current and Perspective Technology and Cost Data of Flexibility Options
Date of delivery	May 17, 2019
Status and Version	Final, v1.0
Number of pages	33

Responsible

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Dissemination Level

Type (distribution level)	☒ PU, Public ☐ CO – full consortium, Confidential, only for members of the consortium (including the Commission Services) ☐ CO – some partners, Confidential, only for some partners (list of partners to be defined)

Review History

Version	Date	Reviewer	Comment
V0.1	31.10.2018		Initial Version
V0.2	04.12.2018		Update after Review
V0.3	22.03.2019		Update after Review
V1.0	17.05.2019		Final version

Table of content

0 Executive summary 1
1 List of acronyms and abbreviations 2
2 Introduction 3
3 Storage systems 5
3.1 Electrochemical storage 5
3.1.1 Lithium-ion battery 5
3.1.2 Redox flow battery 9
3.1.3 Aging mechanism of batteries 11
3.2 Mechanical storage 16
3.2.1 Compressed air energy storage 16
3.2.2 Pumped storage 18
3.2.3 Flywheel storage system 18
3.3 Chemical storage 19
3.4 Comparison of storage technologies 21
4 Thermal power plants 24
5 Flexible demand 26
6 Interconnection 27
7 Conclusion 28
8 References 29
9 Annexes 33

List of figures

Figure 1: Typology of flexibility requirements 4
Figure 2: Projections of energy costs, lithium-ion battery (utility scale) 8
Figure 3: Projections of energy costs, redox flow battery (utility scale) 11
Figure 4: Aging mechanism, dependency from depth of discharge 13
Figure 5: Aging mechanism, dependency from temperature 13
Figure 6: Aging mechanism, dependency from current amplitude; variable charging/discharging (symmetric) 14
Figure 7: Aging mechanism, dependency from current amplitude; charging at fixed conditions; variable discharging 14
Figure 8: Aging mechanism, dependency from current amplitude; discharging at fixed conditions; variable charging 15
Figure 9: Derivative of discharging (blue) and charging (red) voltage with respect to SOC for a LFP cell 15
Figure 10: Projection of power costs, AA-CAES 17
Figure 11: Technical potential of pumped storage 18
Figure 12: Projection of power costs, electrolysis 20
Figure 13: Projection of power costs, methanation 21
Figure 14: Average cost projections of different storage systems, 2030 22
Figure 15: Price projections for battery systems, 2030 23
Figure 16: Comparison of LCOS for different power prices and utilizations, 2030 24
Figure 17: Flexibility parameters of thermal power plants 25
Figure 18: Start-up costs (excluding fuel costs) for thermal power plants 25
Figure 19: Average potential for load reduction [9] 27
Figure 20: Average potential for load increase [9] 27

0 Executive summary

This report describes technologies that can serve as sources of flexibility for the electricity system and includes electrochemical, mechanical, and chemical storage systems as well as flexible thermal power plants. In addition, it is discussed how the demand side and interconnections between regions can provide flexibility as well. Derived from an extensive literature study, current and future cost data has been derived. This report is accompanied by a comprehensive data set of technical parameters and cost data.

1 List of acronyms and abbreviations

You can find in the table below the list of the acronyms and abbreviations used in this document.

Acronym	Meaning
CAES	Compressed Air Energy Storage
CCGT	Closed Cycle Gas Turbine
DSM	Demand Side Management
FCR	Frequency Containment Reserve
FRR	Frequency Restoration Reserve
FSS	Flywheel storage systems
LCOS	Levelized Costs of Electricity Storage
OCGT	Open Cycle Gas Turbine
RR	Replacement Reserve

2 Introduction

Flexibility can generally be defined as a power system's ability to cope with variability and uncertainty in demand and generation. Flexibility is becoming more and more important for power system operation with a continuously increasing share of generation from non-dispatchable renewable sources (such as solar photovoltaics and wind) to comply with decarbonisation targets.

Power generation from variable renewables is only predictable to a certain extent and cannot be dispatched freely: operators can curtail generation, but not increase it. These characteristics create a need for different temporal kinds of flexibility within the energy system. The need for long-term flexibility is largely independent from forecasts and forecast errors. It is due to fundamental mismatches between demand and renewable supply patterns. Solar power generation during the summer and winter peak load is an example of such a mismatch. Over the medium term (from hours to weeks), dispatchable generators adjust to forecasts in advance to keep deviations small in the first place. In the short term finally, demand/supply deviations stemming from forecast errors have to be balanced out by ancillary services almost immediately to ensure grid stability.

Once renewables reach a certain penetration share, conventional power plants' inertia is no longer sufficient; large imbalances generate unauthorized frequency changes. If taken to the extreme in a system where there are no rotating machines whatsoever, there no longer is a frequency "conductor". These challenges may be addressed either by guaranteeing the presence of synchronous compensators running on no load, or through the use of inverter connected assets (renewables, batteries), which set the frequency and minimise frequency changes (grid forming).

These examples illustrate that "flexibility" is used as an umbrella term covering various needs in the power system. When trying to identify the most crucial ones, one may mention:

- adequacy - ensuring long term equilibrium between power supply and demand
- power transmission - allowing power to flow between supply and demand, while respecting physical and operational limits on flows between buses[1]
- reactive power control - keeping the bus voltages within predefined limits
- frequency stability - ensuring frequency stability in the event of a large unforeseen imbalance
- voltage stability – ensuring voltage stability in the event of insufficient reactive power infeed

Short-, medium- and long-term flexibility for adequacy and frequency stability all serve the same purpose: balancing supply with demand in energy systems with high shares of variable renewables. Yet, they differ in the time available for balancing and the energy required to achieve the balance as displayed in Figure 1. While short-term flexibility has to provide ancillary

[1] In particular, the n-1 reliability criterion, implying that no single contingency should result in a large disturbance.

services on very short notice, compared to long-term seasonal storage the amount of energy required is small. The opposite applies for long-term flexibility.

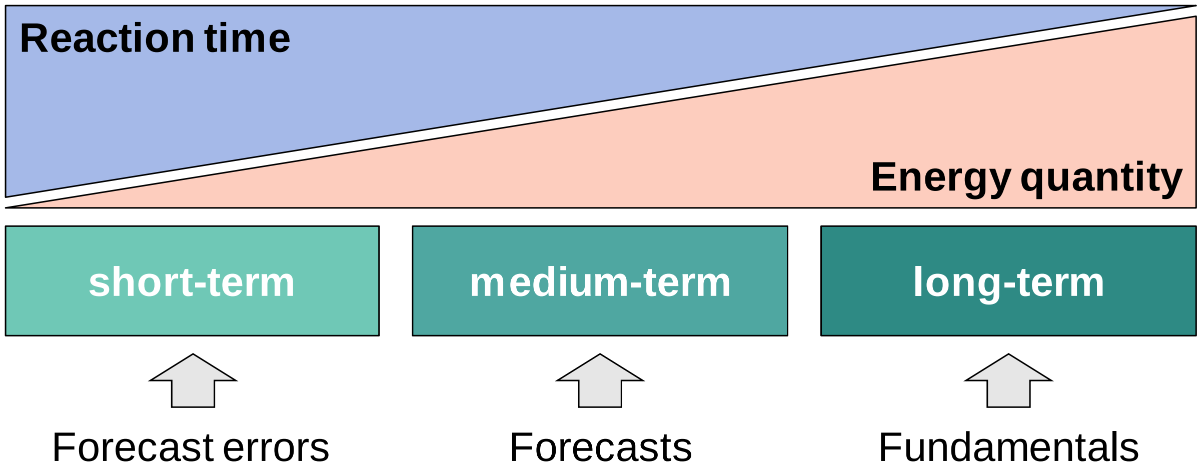

Figure 1: Typology of flexibility requirements

There are four main ways of providing flexibility: flexible generation, flexible demand, energy storage systems and network interconnection. While today's markets for short-term flexibility are dominated by thermal power plants and hydro storage systems, batteries and other novel storage technologies could be suitable for this purpose as well. In most countries, the need for medium- and especially long-term flexibility at current shares of variable renewables can still easily be covered by the remaining thermal power plants. However, these are expected to not be sufficient in the future, which is why further options need to be considered.

In the following, several flexibility options are discussed regarding their ability to satisfy the different needs for flexibility. Since many of these technologies' future costs are subject to great uncertainty, in addition, a comparative analysis of cost projections is carried out. In this way, this report can serve as a basis for follow-up studies investigating the cost-efficient mix of flexibility in future energy systems characterized by variable renewables.

Disclaimer: In line with the goals of task T1.1 and T1.2, the flexibility levers listed in the present document are mainly focused on adequacy and frequency stability:

- Flexibility levers regarding other aspects will be considered in separate documents.
- As far as adequacy and frequency stability are concerned, the list will evolve during the project to reflect improved understanding on levers functioning and modelling (costs, relevant constraints…).

3 Storage systems

For the purpose of this report, storage systems are subdivided into electrochemical, mechanical, and chemical storage systems. Storage is often viewed as a natural complement to solar and wind power, since it allows to store excess generation and feed it back to consumers at times of insufficient renewable generation. However, many promising storage technologies are still at the beginning of their technological development and thus their future role in the energy system is still subject to great uncertainty.

3.1 Electrochemical storage

Electrochemical storage systems, commonly referred to as batteries, showed unexpected technological progress in recent years. As a result, batteries, mostly combined with electric vehicles or photovoltaic systems, are already gaining importance for the energy system. While there are various competing electrochemical storage concepts, this report focuses on the two from a cost perspective most promising technologies lithium ion and redox flow batteries. Other technologies include lead acid, zinc bromine flow or sodium sulphur batteries.

3.1.1 Lithium-ion battery

Lithium is attractive as a storage material due its lightweight, high reduction potential and low resistance. The lithium-ion cell contains no metallic lithium and is therefore much safer on recharge than the earlier, primary lithium-metal design of cell. In terms of working principle, the lithium ions shuttle between one electrode and the other during charge and discharge. The most of commercial lithium-ion cells have positive electrodes composed of various metallic oxide (cobalt, nickel, manganese, aluminium, iron phosphate, …) that can also be combined together (blends). The negative electrode is carbon-based, in the form of either graphite or an amorphous material with a high surface-area. Carbon is an available and cheap material of low weight, and it is able to absorb a good quantity of lithium. When paired with a metal oxide as the positive electrode, it gives a cell with a relatively high nominal voltage. The electrolyte is usually composed from organic liquid (carbonates) and a lithium dissolved salt ($LiPF_6$). The positive and negative active mass is applied to both sides of thin metal foils (aluminium on positive and copper on negative). Microporous polymer sheet between the positive and negative electrode works as the separator.

The most important advantages of lithium-ion cell are high energy density up to 250 Wh/kg (and up to 600 Wh/L), high nominal voltage (3.6 V for lithium-ion batteries with LCO, NCA, NMC, and LMO positive electrodes), high allowed number of charging-discharging cycles, extremely low self-discharge, absence of memory effects, possibility of fast recharging. Main disadvantage is that the Li-ion technologies don't tolerate any over-charge or over-discharge. Each cell's voltage must be very accurately controlled during both charging and discharging processes. It is imperative that the voltage of each cell does not exceed the cut-off voltage during charge (e.g. 4.2 V for lithium-ion batteries with LCO, NCA, NMC, and LMO positive electrodes with graphite negative electrode, or 3.6 V for LFP/G batteries) and doesn't go below the cut-off voltage defined for the discharge (typically between 2.5 and 3.0 V). Overcharging or heating above approximately 80-100°C can trigger a series of highly exothermic reactions due to the decomposition of the different components of the battery (passivation layer, electrolyte, negative and positive electrode [1]).

Nowadays, Li-ion batteries are widely extended for mobile electronics applications due to their good performance and density, as well as their advances in system design and manufacturing. Moreover, this technology has not only advantages but also some challenges, as following:

- Li-Ion batteries have an inherit risk of fire, heat generation, and thermal runaway in the presence of flammable organic electrolyte solvents. To minimize this risk, lithium ion batteries are equipped with both passive and active safety elements. Passive elements such as Current Interrupt Device (CID), safety vents, and Positive Temperature Coefficient (PTC) thermistors are usually installed on each battery cell and are the last defences against safety issues. An active safety element is also mandatory to avoid over-charge and over-discharge, fast charging at low temperature, or operation at inadequate temperature.
- In order to monitor working conditions of the battery, normally a BMS (Battery Monitoring System) is being used. In its basic form, it just monitors voltage and temperature of each cell. In an advanced version (i.e. becoming a Battery Management System), it also includes some balance circuits, in order to prevent voltage deviations among individual cells.
- When high power is required, this technology must have a proper thermal management, in order to dissipate the heat generated during charging and discharging operations, to extend the cycle life of the battery.

Lithium-ion batteries are very interesting, thoroughly studied, and there are many types studied in laboratories and on the market. Today those on the market essentially belong to the following six families:

1. *NCA (Nickel-Cobalt-Aluminium)*. The positive electrode is composed of $Li(Ni_{0.85}Co_{0.1}Al_{0.05})O_2$. This allows for cost reductions due the reduction of cobalt.
2. *NMC (Nickel-Manganese-Cobalt)*. The positive electrode is formed by $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ and new formulations as $Li(Ni_{3/5}Co_{1/5}Mn_{1/5})O_2$ and $Li(Ni_{8/10}Co_{1/10}Mn_{1/10})O_2$ are proposed. This composition is able to guarantee better performance and reduced costs with respect to a monolithic matrix of Ni, Co or Mn.
3. *LMO (Lithium-Manganese Oxide)*. They have a positive electrode formed by lithium manganese oxide. They are characterised by high level of power and specific energy, but some degradation mechanisms lead to capacity fading and the cell resistance increasing, causing a low life cycling of LMO batteries.
4. *LFP (Lithium-Iron-Phosphate)*. They are characterised by a $LiFePO_4$ based positive electrode. Compared to the previous ones, they show a greater stability at high temperatures regarding safety and ageing issues. The voltage is typically lower (voltage window 2 to 3.6 V against 2.7 to 4.2 V), and it corresponds to a 25% reduction in energy and power per mass. Nevertheless, a similar cost and the highest security make them currently among the most attractive for stationary use. A particular subset of LFPs consists of the so-called nanostructured LFP cells. These are characterised by

very high specific power both in delivery and in absorption: it can reach values of 3 kW/kg, which makes them almost unique, and in direct competition with another type of electric energy storage system characterized by modest mass energy and high mass power: the so-called super capacitors.

5. *LTO (Lithium-Titanate)*. For all the above types of positive electrode, the associated negative electrode is most of the time made of a graphite carbon matrix. LTO cells, on the other hand, contain the Li-titanate ($Li_4Ti_5O_{12}$) at the negative electrode and a positive electrode among the previous ones, which, in addition to excellent safety features, have the ability to accept charging and discharging currents much higher than those of other types (short-term currents even 30 times the discharge value in a nominal hour against 2-8 times). These characteristics are particularly due to the LTO electrode potential being more distant from the lithium metal potential than for carbon-based negative electrode, but it implies lower nominal voltage (from 1.9 to 2.4 V depending on the positive electrode) and hence lower energy density. These batteries are in direct competition with the above-mentioned nanostructured LFP batteries, and therefore also with the super capacitors.

6. *LCO (Lithium-Cobalt Oxide).* The electrode is made of $LiCoO_2$. Due to its high specific energy, it is frequently used within electronic devices such as cell phones or laptops. Disadvantages of this technology are limits on the charging capacity and a rather short service life [2].

As for all storage systems, investment costs for lithium-ion storage systems (batteries, associated auxiliaries, and conversion) can be subdivided into energy costs relating to the storage size and power costs depending on the maximum charge or discharge capacity. In case of lithium-ion batteries, energy costs are dominating and offer the greatest potential for cost reductions. In Figure 2, a range of energy costs for high capacity (utility scale) lithium-ion storage systems is displayed based on an extensive literature research even if numerous parameters and uncertainties (market size, materials price, investments etc.) could impact these costs. On average, costs are expected to drop sharply by 2030 and continue to decrease moderately until 2050 archiving an overall reduction by a factor of 2.64 compared to 2015.

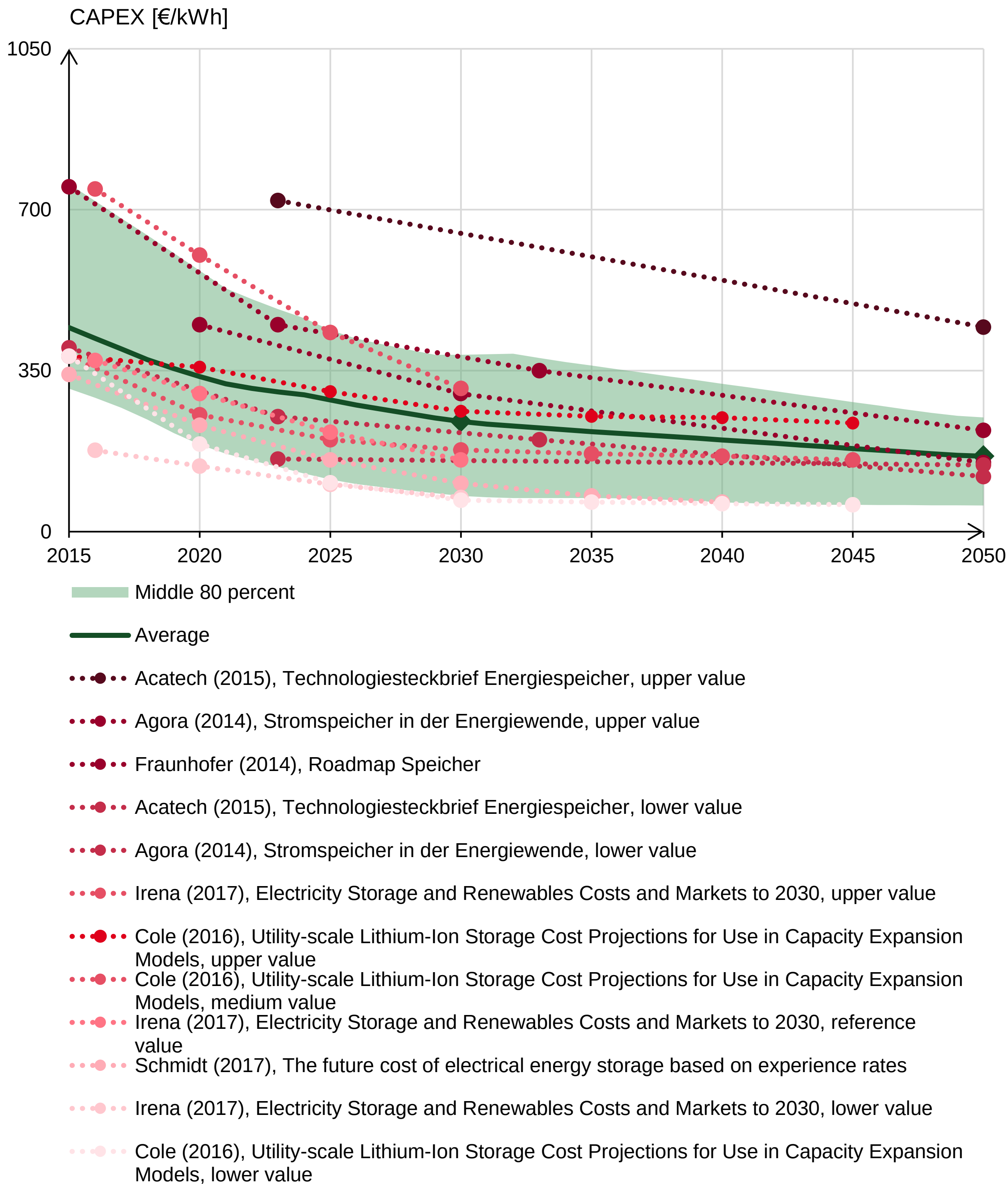

Figure 2: Projections of energy costs, lithium-ion battery (utility scale)

3.1.2 Redox flow battery

A flow battery is an electrochemical device that converts the chemical energy in the electro-active materials directly into electrical energy, similar to a conventional battery and fuel cells. The electro-active materials in a flow battery, however, are stored mostly externally in an electrolyte and are introduced into the device only during operation. True flow batteries have all the reactants and products of the electro-active chemicals stored external to the power conversion device. Systems in which all the electro-active materials are dissolved in a liquid electrolyte are called redox (for reduction/oxidation) flow batteries (RFBs).

Although much flow battery research dates back to the 1970's, some research has continued over the past several decades and the state-of-the-art has been reviewed in the recent literature. Most of redox flow batteries consist of two separate electrolytes, one storing the electro-active materials for the negative electrode reactions and the other for the positive electrode reactions. Both the fresh and spent electrolytes may be circulated and stored in a single storage tank or separately, in order to control the concentrations of the electro-active material. An ion-selective membrane is often used to prevent mixing or cross-over of the electroactive species which result in chemical short-circuit of electro-active materials. With the electrolyte and electroactive materials stored externally, true flow batteries have many advantages, one of which is the separation of the power and energy requirements.

The electrodes, not being part of the electrochemical fuel, can be designed to have optimal power acceptance and delivery properties (e.g. catalytic, electrical, and transport) without the need to also maximize energy storage density. Furthermore, the electrodes do not undergo physical and chemical changes during operation (because they do not contain active materials), thus leading to a more stable and durable performance. Therefore, engineered microstructures developed to optimize performance can be maintained over the lifetime of the device. With longer lifetimes, the capital costs of the battery system can be amortized over a longer period, and with a wider state-of-charge operating window, the quantity of active material required to deliver power over the entire required duration of discharge can be minimized. The energy capacity requirement of a flow battery is addressed by the size of the external storage components. Consequently, a redox flow battery could approach its theoretical energy density as the system is scaled up to a point where the weight or volume of the battery is small relative to that of the stored fuel and oxidant.

In a flow battery there is inherent safety of storing the active materials separately from the reactive point source. Other advantages are quick response times (common to all battery systems), high electricity-to-electricity conversion efficiency, no cell-to-cell equalization requirement, simple state-of-charge indication (based on electro-active concentrations), and, at least in theory, low maintenance and tolerance to over-charge and over-discharge, and perhaps most importantly, the ability for deep discharges without affecting cycle life. However, in practice, delivered systems so far required frequent maintenance caused by membrane pollution, damaged pumps, or fitting leakage due to corrosion. In addition, the state of charge and discharge is limited to 90% and 10% respectively by diffusion of species to the electrodes. Overall, the total efficiency at lower power levels is rather small.

The hybrid systems like those involving zinc plating do not offer all these advantages, but still have many of the desirable features of a true flow battery. The main disadvantage of flow batteries is their more complicated system requirements of pumps, sensors, flow and power management, and secondary containment vessels, thus making them more suitable for largescale storage applications.

Only a few flow battery systems have seen deployment. Consequently, the technologies are relatively new and unfamiliar with a lack of experience feedback.

Further development will require research activities in the following areas: low-cost for capital and operation, efficient and durable electrodes; chemically stable redox couples, having large potential differences, with high solubility of both oxidized and reduced species, and fast redox kinetics; highly perm selective and durable membranes; electrode structure and cell design that minimize transport losses; designs with minimal pumping and shunt current losses and large scale power and system management and grid integration. Overall, the primary barriers to commercialization for large-scale energy storage are round trip energy storage efficiency, cost for energy storage and cost for the power capacity.

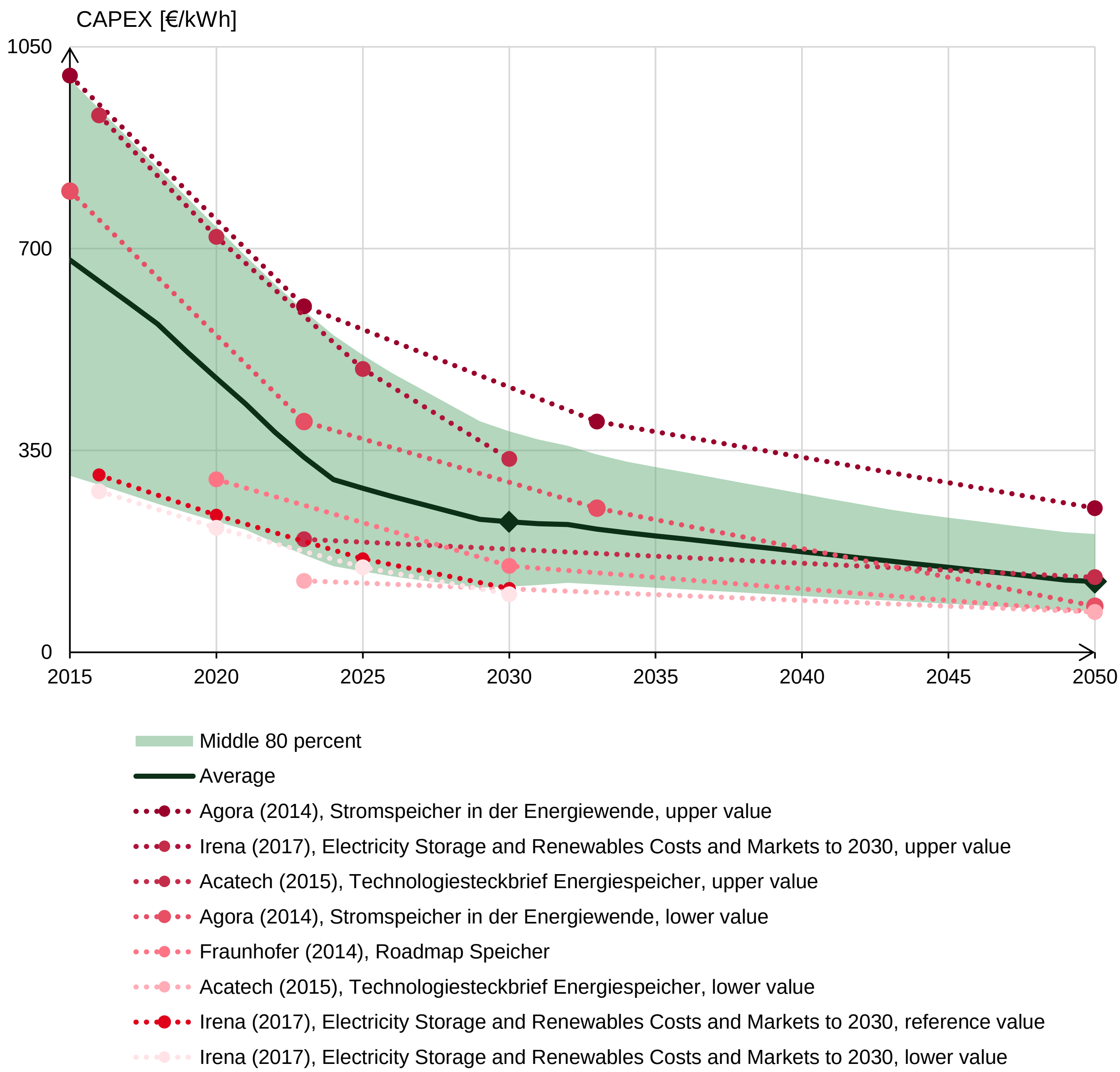

Figure 3: Projections of energy costs, redox flow battery (utility scale)

3.1.3 Aging mechanism of batteries

Among the different performance offered by electrochemical storage systems, the aging mechanism is one of the most significant aspects since it can significantly reduce performance and influence the storage behaviour. Indeed, the main causes capable to stimulate the cycling aging (i.e. the aging due the use of the battery), especially in terms of reduction in available capacity, have been deeply analysed, considering a multiplicity of factors. In this way, dependency from depth of discharge, temperature, current amplitude, and state-of-charge window have been considered and shown in the next paragraphs. In general, aging of batteries is not only triggered by charging and discharging, but occurs as well when the battery just stores electricity over time. All these effects will be analysed individually, that is, every aspect will be described under nominal conditions of others. In this way, fully discharging condition, ambient temperature fixed at 25°C and stress current limited at 1C will be taken as nominal reference.

The proposed approach has the main aim to illustrate causes of aging in reference to a generic battery typology. However, a lithium cell will be taken as reference. This choice has been made because of the great diffusion of this cell typology for all sectors, from stationary to mobile systems. However, the aging mechanisms would be different for other battery technology as for instance the different technologies of redox flow battery.

Depth of discharge

Battery manufacturers typically declare the number of allowed charging-discharging taking as reference fully or almost fully discharging conditions, that is, within the DOD interval 50÷100%. Significant lack of data occurs when cycles characterised by shallow discharges are considered. This is the typical situation for storage systems deployed for power-oriented applications, in which high currents are required for a very short time, thus corresponding to low energy content. Event tough few data is available, literature on this topic was deeply analysed, and the trends illustrated in Figure 4 have been obtained [1], [2], [3]. As visible, the characteristic is not linear and the number of allowed charging-discharging cycles with reduced depth of discharge (i.e. within 5%) tends towards about one million of charging-discharging cycles. However, if just experimental data is considered, several hundreds of thousands have been guaranteed.

Temperature

In the following, the influence of temperature will be considered. This was analysed by cycling under the nominal conditions already expressed before and by varying only the ambient temperature. As observable, high ambient temperature may significantly reduce up to one half the allowed charging-discharging cycles (see Figure 5). Further decreases occur due to ambient temperature about 60°C.

Current amplitude

The behaviour of the electrochemical cells subjected to symmetric charging-discharging conditions for different current amplitudes is shown in Figure 6. The values are expressed in p.u. by considering as reference the number of allowed cycles executed with 100% depth of discharge and 1C as nominal condition. Results are not clear as before, because of a significant difference for the two considered examples [4].

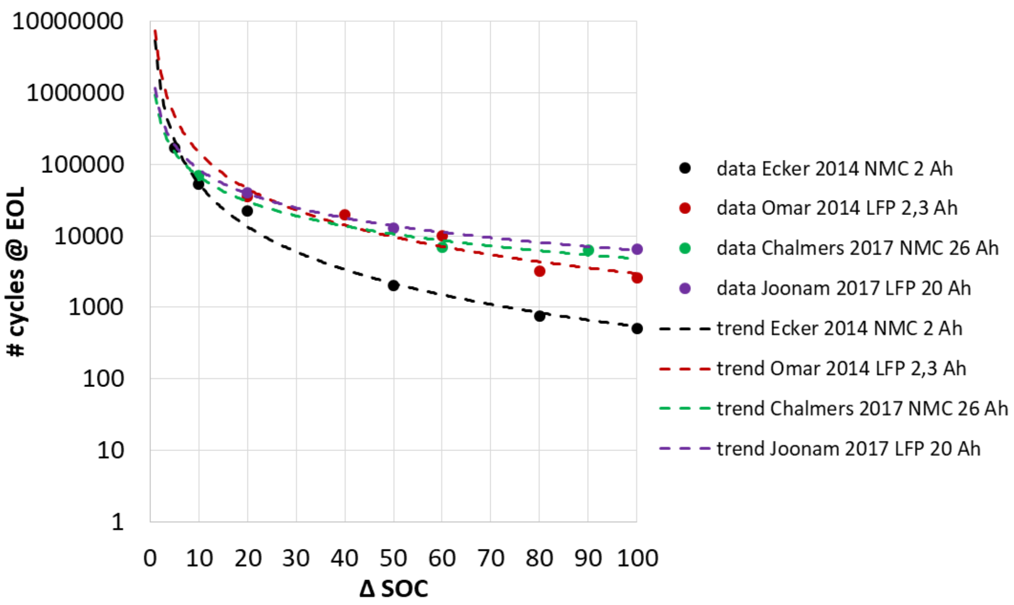

Figure 4: Aging mechanism, dependency from depth of discharge

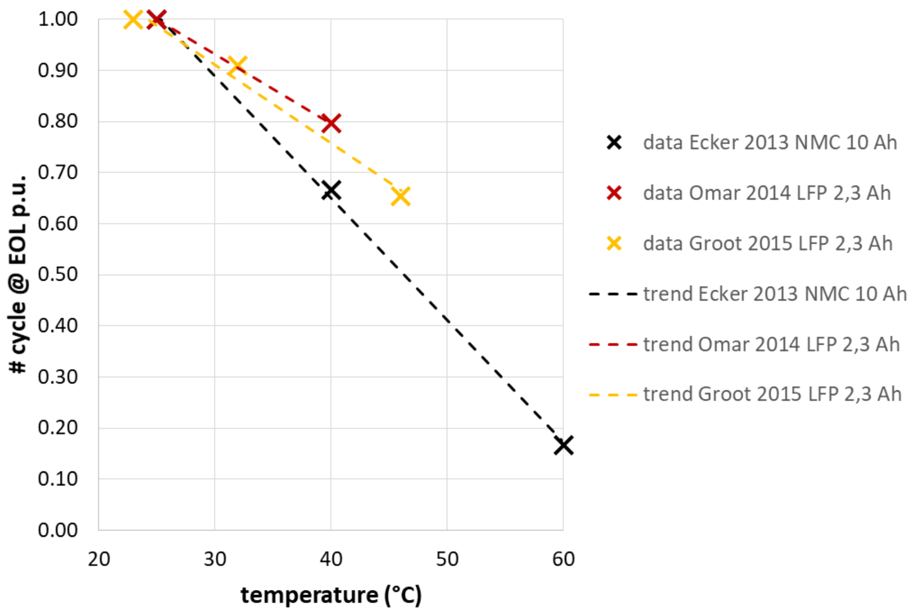

Figure 5: Aging mechanism, dependency from temperature

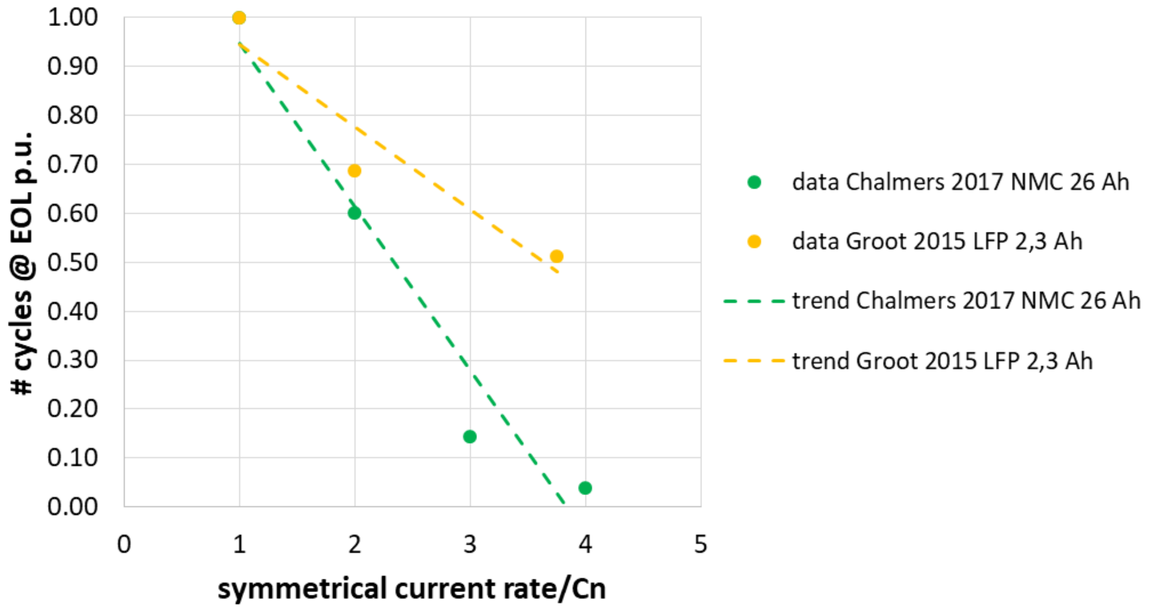

Figure 6: Aging mechanism, dependency from current amplitude; variable charging/discharging (symmetric)

When different conditions are considered, that is, having charging fixed at 1C and discharging at different conditions, results modify as follow in Figure 7. As in the previous case, it is not possible to reconstruct a clearly interpretable trend.

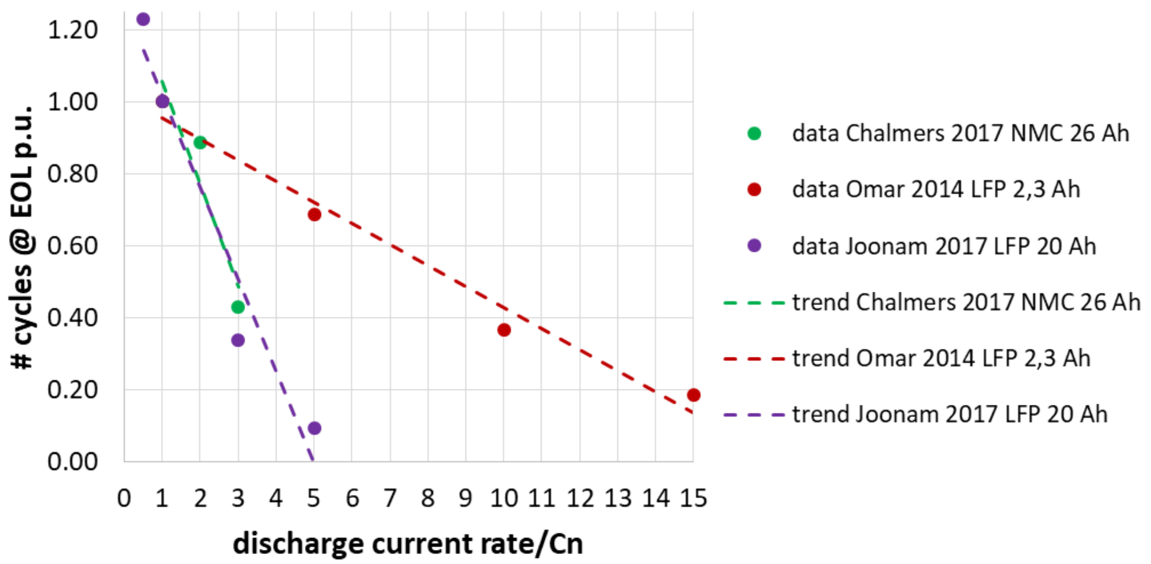

Figure 7: Aging mechanism, dependency from current amplitude; charging at fixed conditions; variable discharging

On the opposite, with discharging fixed at 1C and different charging currents, the trend as shown in Figure 8 was achieved from literature.

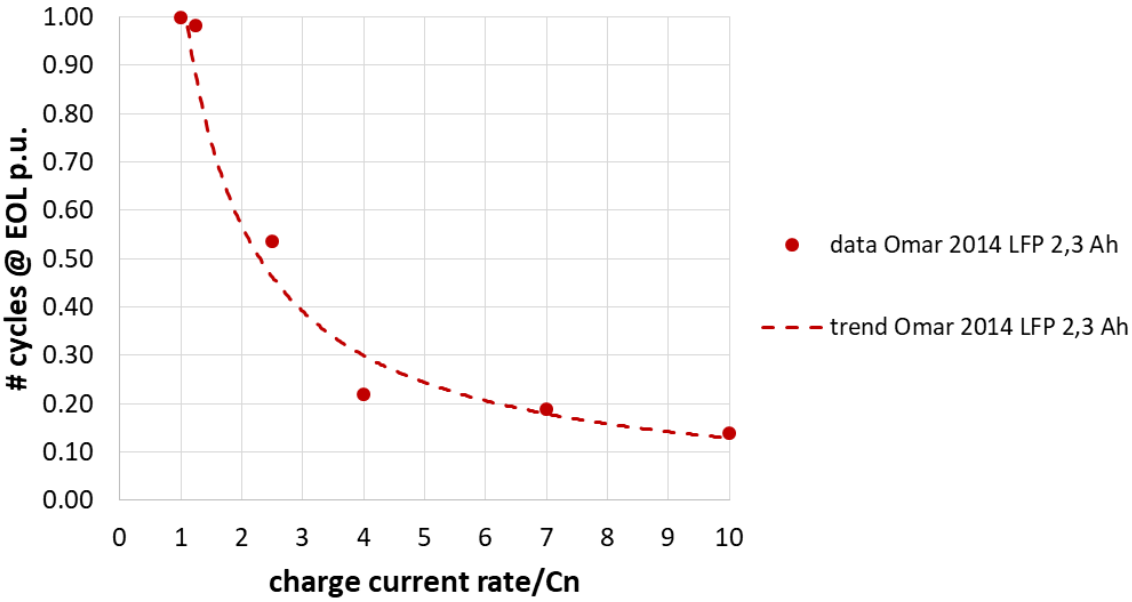

Figure 8: Aging mechanism, dependency from current amplitude; discharging at fixed conditions; variable charging

State-of-charge window

The last analysed dependence considers the state-of-charge window (SOC). As first assumption, it is possible to correlate the aging directly to the voltage variation: the bigger the variation, the greater the aging. In this way, it is of interest to derive the discharging curve, executed at fixed constant current, in order to obtain voltage variation vs SOC, as shown in Figure 9 [5].

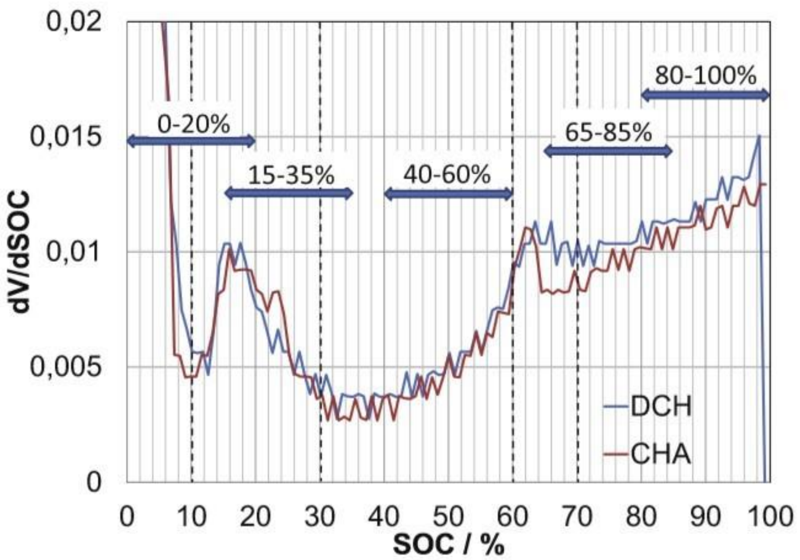

Figure 9: Derivative of discharging (blue) and charging (red) voltage with respect to SOC for a LFP cell

In this way, when the derivate value is low, the voltage variation is limited, thus aging is reduced. On the opposite, when the derivative tends to be higher, the voltage variation has a more pronounced effect on aging. If finally we fix depth of discharge at 20%, and take as reference results of Figure 9, it is possible to observe in Figure 9 how for SOC windows around 50% it is possible to achieve a maximum number of fully charging-discharging cycles 4-5 times higher than what obtained at extreme values (i.e. 20% or 80%).

In conclusion, the ageing process of electrochemical storage systems is very complicated compared to other technologies and can hardly be represented with every detail in energy system models. For this reason, it may be advisable to approximate the aging process with a simple lifetime assumptions and check the plausibility of this assumption based on final results.

3.2 Mechanical storage

Mechanical storage systems store energy by changing the potential energy of a fluid, usually air or water, by compressing a fluid (compressed air energy and liquefied air energy storage) or moving it to a higher level (pumped storage). To release the stored electricity again, the fluid is either decompressed or lowered down again. The only exception to this are flywheel storage systems.

3.2.1 Compressed air energy storage

Compressed air energy storage (CAES) systems compress ambient air, which is then transported into a natural underground reservoir like a salt cavern. To create power again, the compressed air is released through a turbine. CAESs can be equipped with a heat storage unit to conserve the heat dissipated energy during compressing. This thermal energy can later be used to preheat air before expanding to increase the yielded energy. Also, an integration in flexible district heating systems is conceivable.

The overall efficiency of CAESs amounts to 40-60%. According to forecasts, adiabatic systems suited for industrial use can reach up to 70%. Unfortunately, a high self-discharge rate of around 25% per month, depending on the storage characteristics, could render CAES unsuitable for seasonal storage. Unlike all storage systems introduced so far, CAESs cannot be freely installed anywhere but depend on appropriate geological conditions. Since it is not a widespread technology so far, the technical potential for CAES in Europe has not been excessed yet.

Although CAES is not a fully developed technology[2], the literature only shows a minor decrease in projected costs until 2050. Average cost projections only show a small decrease in costs until 2050 compared to other storage technologies as displayed in Figure 10. Energy costs are not really important for this technology of storage. The same applies to the development of overall efficiency.

[2] However, diabatic CAES systems are a mature technology and already being used in some places (Huntorf, McIntosh).

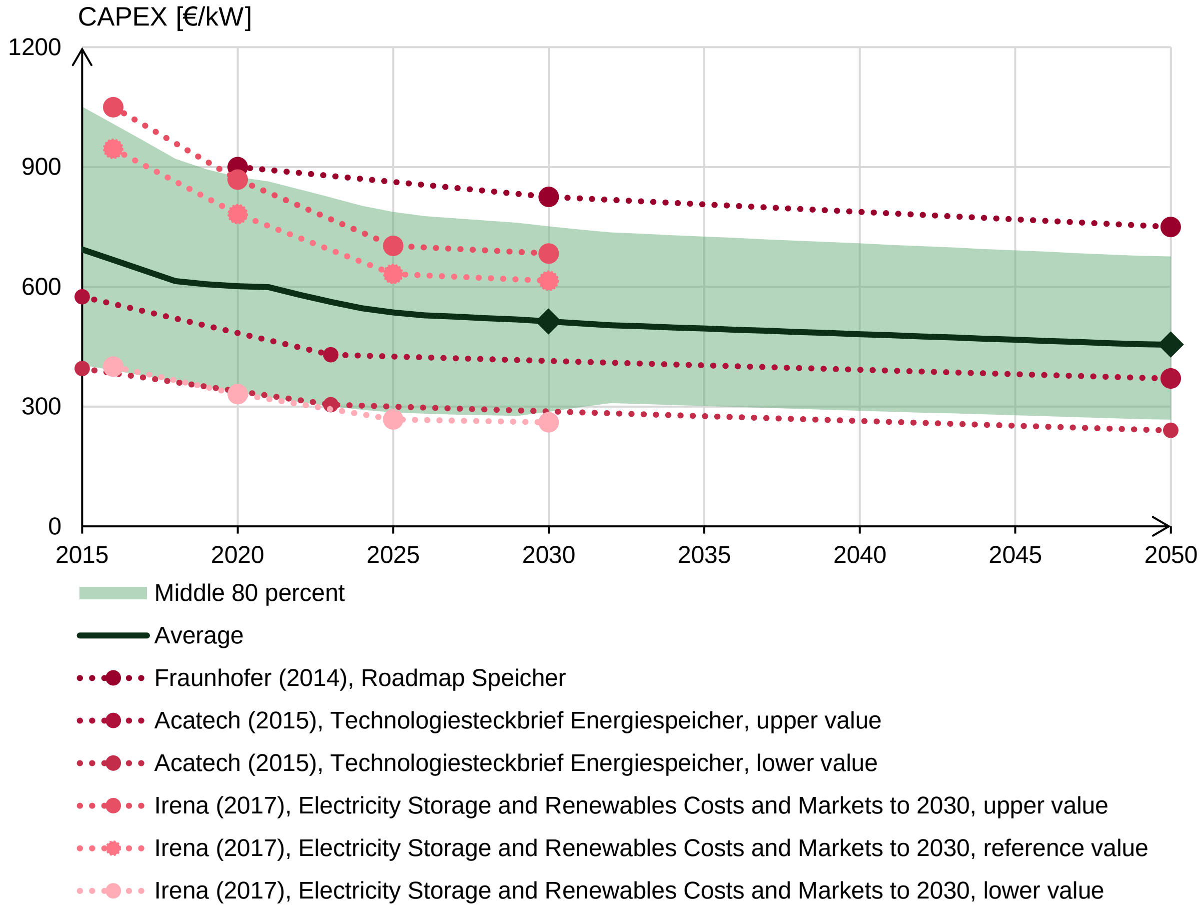

Figure 10: Projection of power costs, AA-CAES

3.2.2 Pumped storage

Of all storage system, pumped storage plants are by far the most and longest established. They consist of two storage basins on different levels. To store energy, water is pumped from the lower to the upper basin and vice versa via a turbine to deliver energy. Some pumped storage systems are integrated into a water reservoir allowing for additional natural inflows into the upper basin. Energy losses caused by pumping up and discharging water lead to roundtrip efficiencies between 70 and 80% and the greatest share of investment costs is incurred by the pump and turbine system. The energy to power ratio of most pumped storages ranges between 2 and 10 hours.

Since pumped storage systems depend on specific geographical conditions, their technical potential is limited and, being a long established technology, the greatest share of this potential in Europe is already being exploited as shown in Figure 11. While the unused technical potential, mainly existing in Scandinavia as well as in the Alps and the Pyrenees, is already small, the politically realisable potential might be even smaller since the construction of a pumped storage plant has a great impact on the surrounding environment.

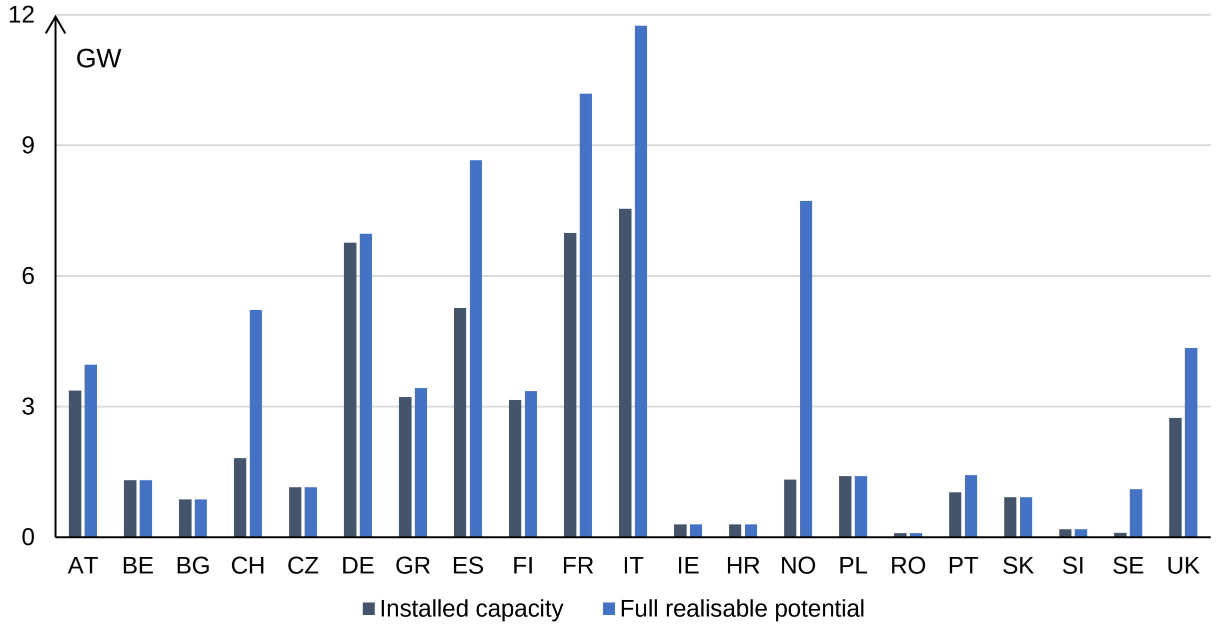

Figure 11: Technical potential of pumped storage

Source: own computations based on [6], overview of potential locations for new pumped storage plants in the EU-15, Switzerland, and Norway

3.2.3 Flywheel storage system

Flywheel storage systems (FSS) are composed of a rotating mass, a bearing for this mass and a motor/generator. The motor sets the mass in rotation to store energy, which can be released again via the generator. So, unlike the other mechanical storage systems introduced, flywheels store kinetic and not potential energy.

FSS reach high roundtrip efficiencies above 85% percent, especially when magnetic instead of mechanical bearings are used to reduce friction. Regardless of the bearing, self-discharge rates amount to at least 20% of stored capacity per hour, which is by far the highest among all storage technologies. On the upside, FSS can do both charging and discharging as well as switching between these modes of operations with high pace and low material wear [7, 8].

These features render FSS unsuited for providing medium- or long-term flexibility, but make them worth considering for providing system inertia to stabilize grid frequencies in the very short-term. Since in today's energy system this function is still fulfilled by the rotating masses of thermal power plants, FSS, although being based on probably the oldest concept of energy storage, are not widely distributed yet.

3.3 Chemical storage

Chemical storage systems use electricity to produce chemicals, which can be converted to electricity again at a later point. Two chemicals suited for such a process are hydrogen and methane.

Hydrogen can be created from water via electrolysis and converted back into electricity by a fuel cell or hydrogen turbine. Methanation builds on water electrolysis but instead of using hydrogen directly, the so-called Sabatier process is applied to create methane from hydrogen and carbon dioxide. Alternative to the Sabatier process, a biochemical conversion is possible as well. Methane can be used similar to natural gas in conventional combined or open cycle power plants. Compared to other storage technologies, the current roundtrip efficiency of chemical storage is comparably small and ranges from 30 to 40%. Although further technological advancements can be expected, the roundtrip efficiency cannot be increased greatly above 50% due to physical limits.

In contrast to other technologies, flexibility from chemical storage is not limited to the temporal dimension, but includes a spatial dimension as well since hydrogen and methane can both be transported. In addition, hydrogen and methane are not only suitable for reconversion to electricity, but could also be used directly for industry, heating, or mobility. While the use of hydrogen in these sectors is very limited so far and extension would require major infrastructural investments, methane can already be mixed into the existing gas grid to a certain extent. Nevertheless, continued use of existing infrastructure will still incur costs for additional grid and storage investment.

In contrast to electrochemical storage, energy costs of chemical storage are small compared to power related costs. While generated hydrogen and methane can easily be stored in storage tanks using already existing infrastructure, systems for electrolysis or methanation require substantial investments. In Figure 12 and Figure 13 the projected capacity costs for electrolysis and methanation based on extensive literature review are displayed respectively. Prices for electrolysis are on average expected to steadily decline until 2050 from almost 1000 €/kW to 370 €/kW.

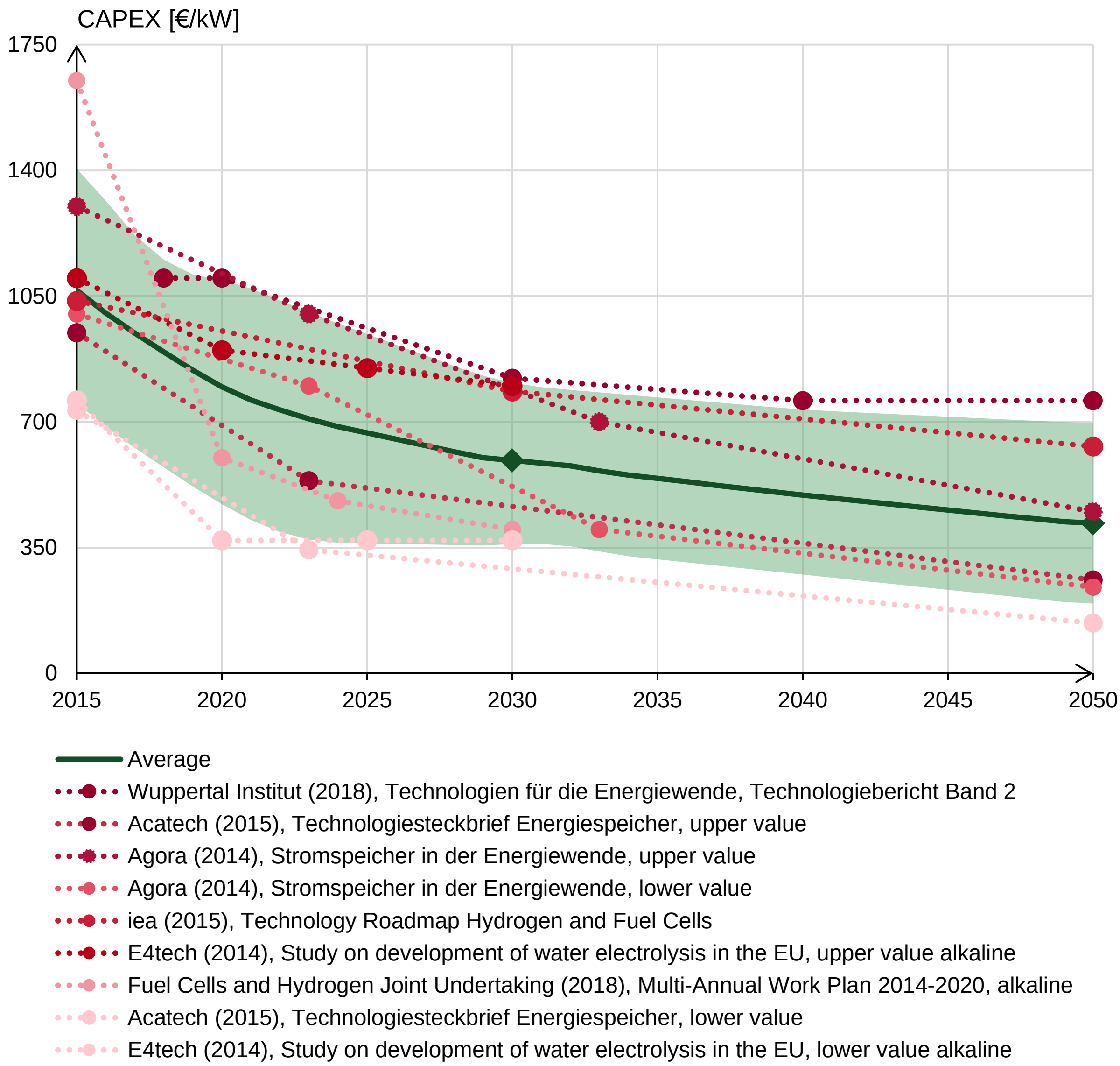

Figure 12: Projection of power costs, electrolysis

Investment costs for methanation, already including costs for the required electrolysis systems as well, are expected to decline sharply until 2030 to 900 €/kW and stay almost constant afterwards until 2030.

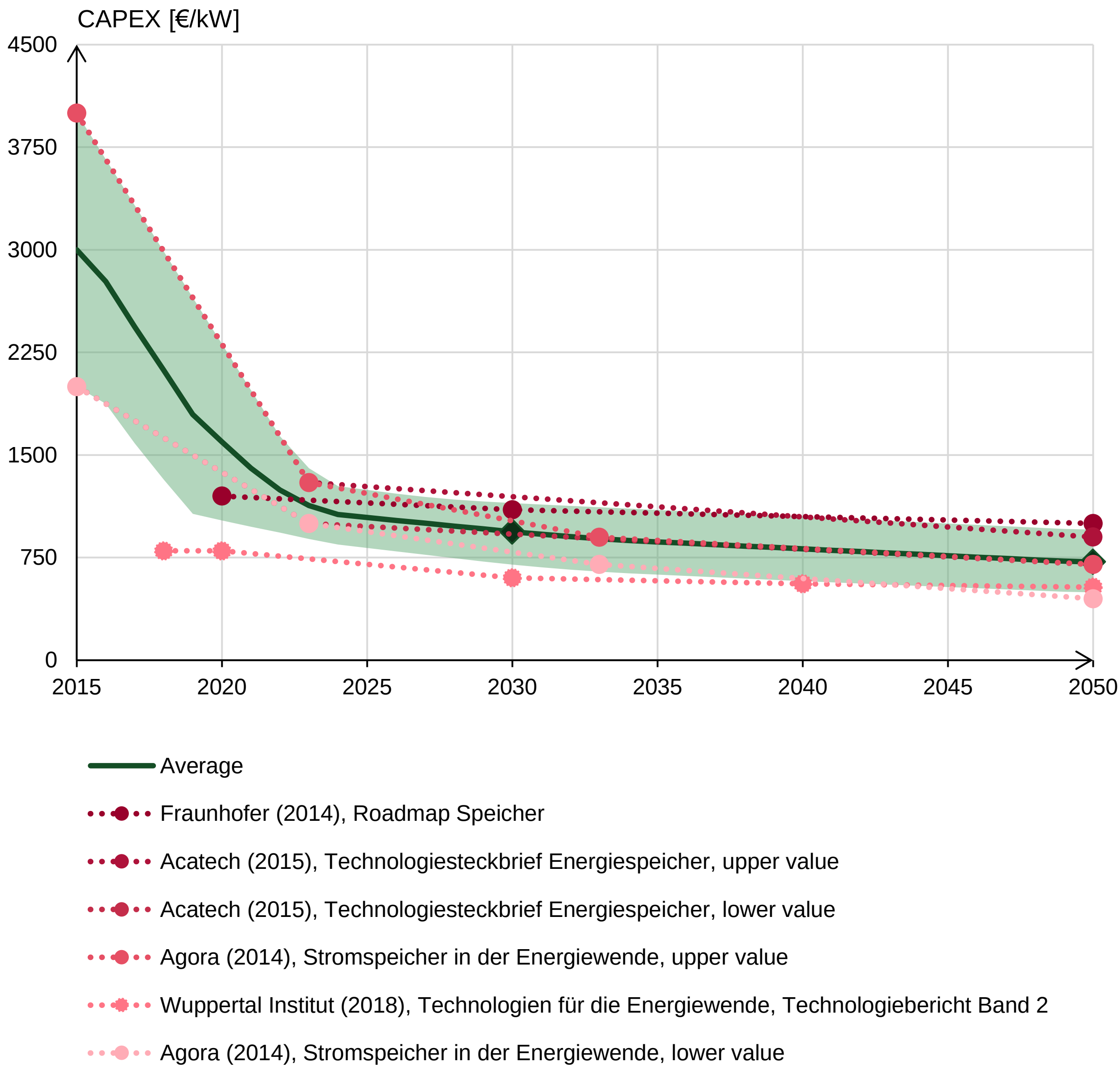

Figure 13: Projection of power costs, methanation

3.4 Comparison of storage technologies

After several types of storage technologies have been introduced, this chapter shortly discusses how these are suited to provide flexibility to the overall power system. Therefore, again it is important to distinguish between energy and power related costs of storage. Among the self-discharge rate, the ratio between energy and power related costs directly determines the feasible energy to power ratio of a storage technology.

For example, electrochemical storage systems have rather high energy related costs, as displayed in Figure 14, so from an economic perspective they are best designed to have a small energy to power ratio. This, and their capability to very quickly adjust their level of consumption or generation, suits electrochemical storage systems best to provide short-term flexibility. Chemical storage systems on the other hand are not able to react as quickly, but can store (and even transport) huge amounts of energy at low costs. As a result, these technologies are probably the most economic storage option to provide long-term flexibility and thus provide power during time periods with low generation from variable renewables, for example in winter. Mechanical storage systems are in between those two. Their energy related costs (and often the respective technological potentials) are not small enough to provide long-term seasonal storage, but they are also not capable to react as quickly as battery systems.

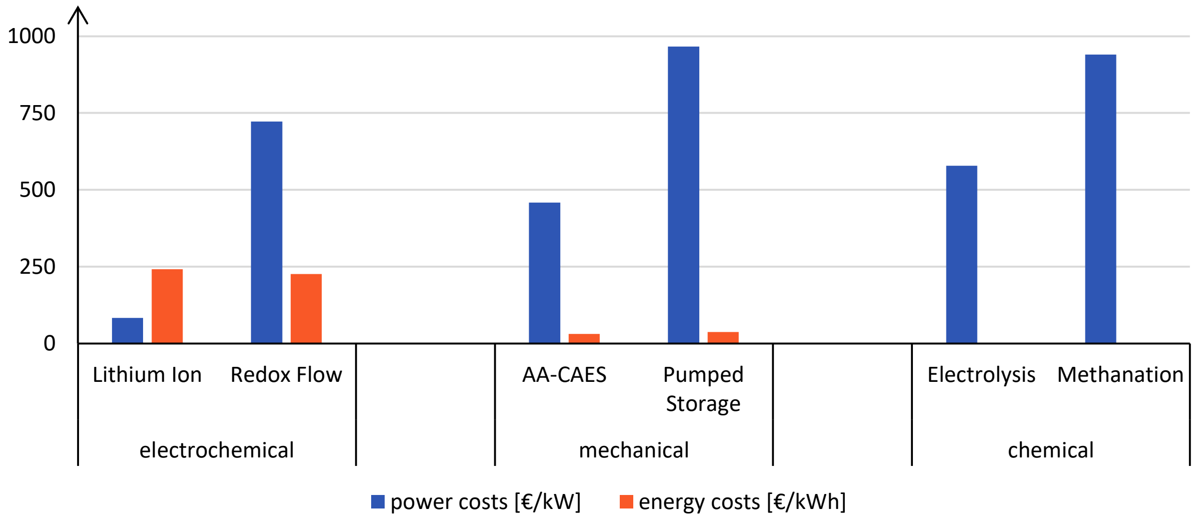

Figure 14: Average cost projections of different storage systems, 2030

Since both electrochemical storage systems presented here have very similar technological properties, next their investment costs are thoroughly compared in order to decide which of both systems future analyses should focus on. For this purpose, the average and the range of cost projections for the whole storage system in 2030 is mapped depending on the energy-to-ratio as displayed in Figure 15.

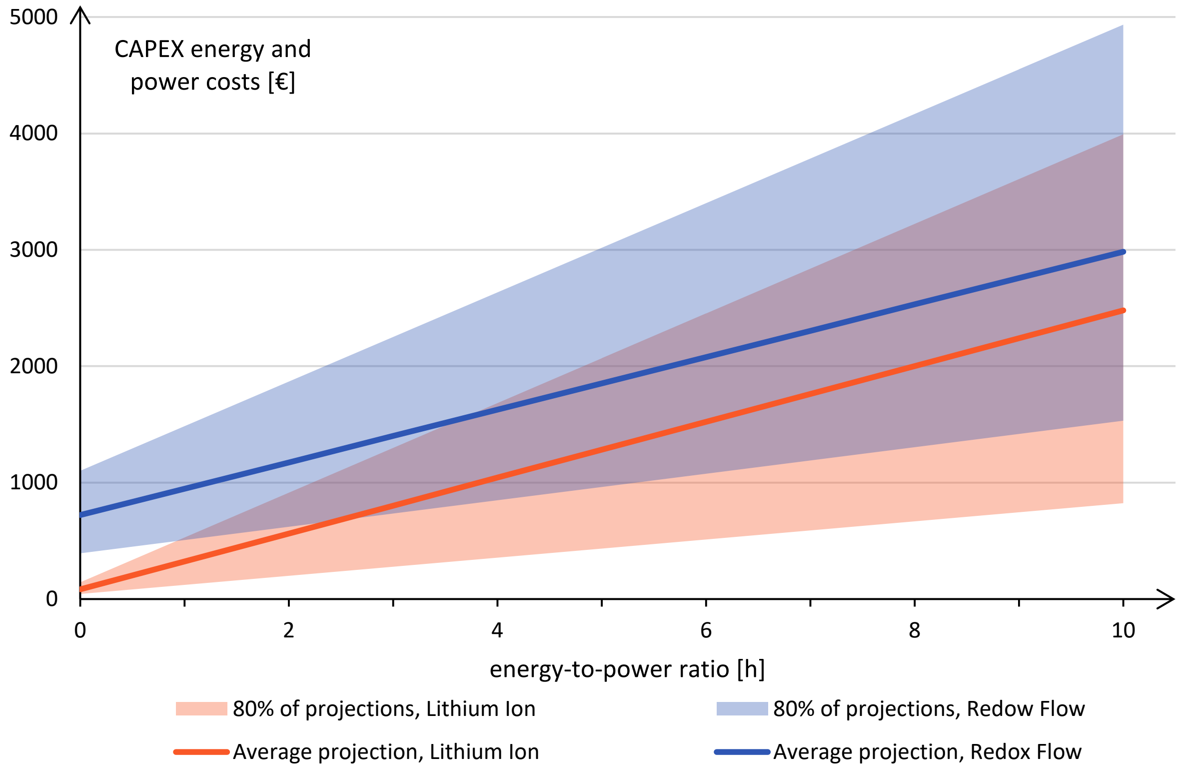

Figure 15: Price projections for battery systems, 2030

The smaller slope of the line representing redox flow reflects that they have smaller energy costs compared to lithium-ion batteries. Yet, within the whole rate of storage sizes reasonable for electrochemical systems, lithium-ion batteries are less expensive since they have much smaller power costs. Only if the cost reductions for redox flow batteries exceed or the ones for lithium-ion fall below expectations, redox flow systems could become economically viable. Given this and the fact that efficiencies of redox flow are about 10 to 20% smaller, based on current information it seems reasonable to focus further analysis on flexibility on lithium-ion systems.

In Figure 16 the levelized costs of electricity storage (LCOS) are displayed for pumped storage (blue) and again a lithium-ion battery (red), both with an energy-to-power ratio of 5 to allow for a meaningful comparison. LCOSs are similar to levelized costs of electricity (LCOE), which are often used to compare different technologies for energy generation, and are defined as total costs of a technology divided by the corresponding electricity provided.[3] These costs do not solely depend on technological properties like efficiency or investment costs, but also on market related parameters like utilisation or, in the case of storage systems, the average power price of stored electricity. Plotting the LCOS as a function of these parameters shows that at least until 2030 pumped storage remains the cheapest storage technology. Especially at low utilization rates, pumped storage remains cheaper due to significantly smaller investment costs

[3] A detailed definition can be found in [44].

for energy. Due to the high round-trip efficiencies of lithium-ion batteries, this gap narrows as utilisation and power pries rises.[4]

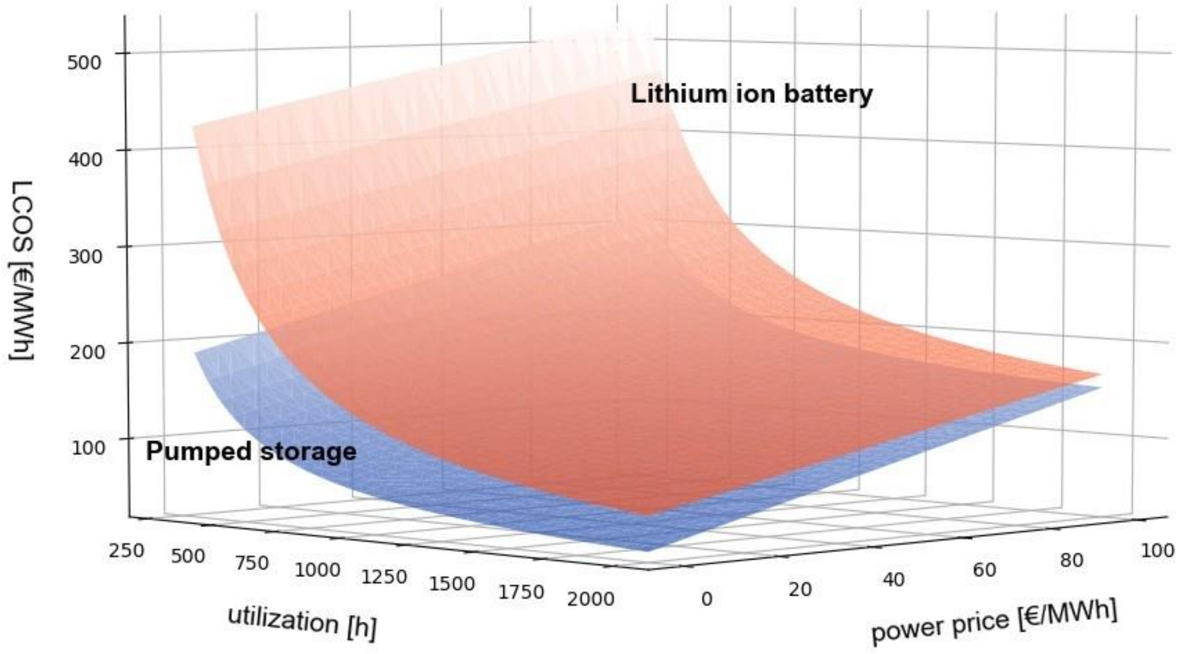

Figure 16: Comparison of LCOS for different power prices and utilizations, 2030

4 Thermal power plants

While storage systems are expected to play an increasingly important role in the future, in today's power system most flexibility is still provided by thermal power plants. This applies to short-term ancillary services, medium-term adjustment to forecasted generation from solar and wind and also the provision of backup capacities for extended periods with small generation from variable renewables. While decarbonisation and expansion of renewables implies a decrease in generation and thus also capacities of thermal power plants, they still might be an important source of flexibility for a transitional phase or if their overall emissions remain sufficiently low. This could best be achieved by gas power plants fuelled with methane created using renewables electricity as described in Section 3.3.

In Figure 17 and Figure 18 the operating restrictions and costs associated with flexible operation for hard coal, closed cycle gas turbine (CCGT) and open cycle gas turbine (OCGT) are displayed.[5] Since all these technologies are well established and fully developed, these values representing the current state of technology can also be assumed for the future. The graphics indicate that of all three technologies considered, hard coal power plants are least

[4] In the abstract lithium-ion batteries might even be favorable over pumped storage at smaller energy-to-power ratios and high utilization. But in practice, such constellations are presumably not viable, because smaller energy-to-power ratios restrict the system's operation and will thus lead to smaller utilization.
[5] Values displayed are an average of different sources [47] [48] [49].

suited to provide medium- or short-term flexibility, but since hard coal plants have comparably high emissions they are not likely to be part of a decarbonised energy system anyway.

Comparing flexibility parameters for CCGT and OCGT however provides valuable insights: OCGT plants are capable to start-up almost immediately and at much smaller costs then CCGT power plants. However, CCGT plants are about 20% more efficient and thus also have smaller emissions than OCGT plants. As a result, deciding between investment in CCGT or OCGT corresponds to a trade-off between smaller emissions and more flexibility, which both is desired in a future energy system characterized by high share of wind and solar power.

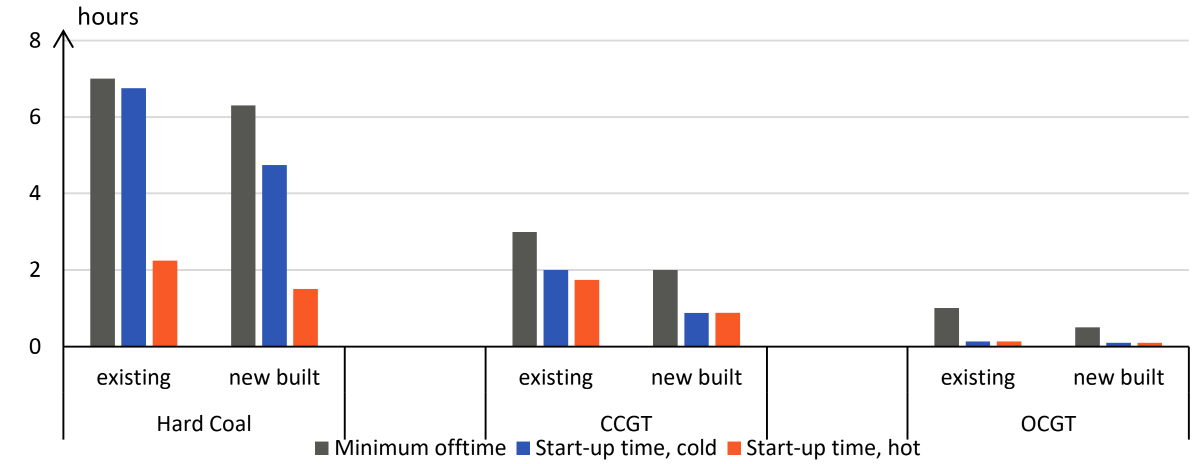

Figure 17: Flexibility parameters of thermal power plants

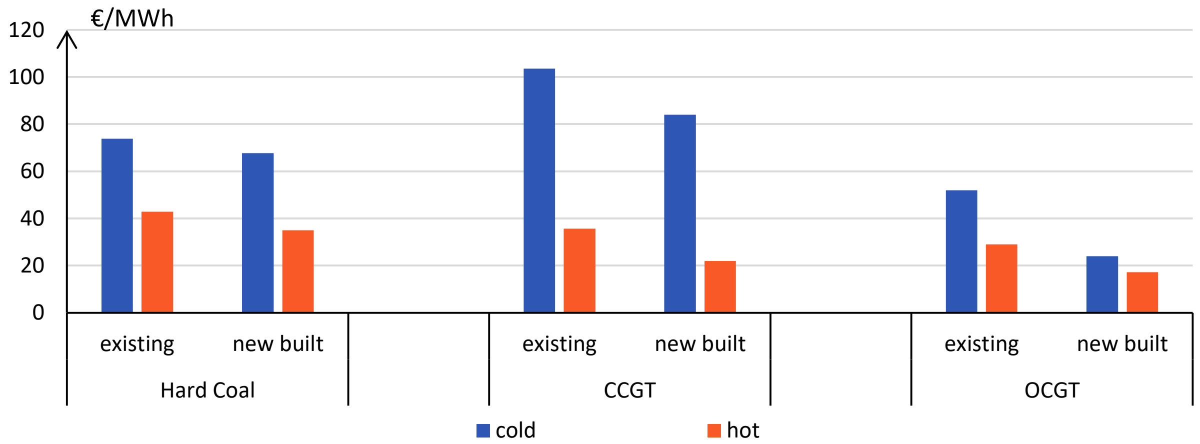

Figure 18: Start-up costs (excluding fuel costs) for thermal power plants

5 Flexible demand

While all flexibility options listed so far focused on technological options on the supply side of markets, encouraging greater participation of the demand side, often referred to as demand side management (DSM), provides another instrument to manage renewable energy systems. In Figure 19 and Figure 20 yearly averages for DSM potentials in decrease and increase according to [9] are displayed. In general, potentials for load reduction are notably smaller than for increasing load and great variation among countries can be observed. DSM can either be implemented by direct market participation of final consumers or indirect programs often launched by national transmission operators. So far, both is limited to huge industrial consumers, where potentials are the easiest to exploit, but two developments make extending DSM to the private and tertiary sector consumers more and more favourable.

First, the technical prerequisite for DSM, a rollout of intelligent metering systems, is heavily promoted by EU legislation. Second, meeting decarbonisation targets not just in the electricity but in the heating and mobility sectors as well, will require the use of renewable electricity in these sectors. The resulting energy system will be more integrated and, thus, offer additional opportunities for involving the demand side.

In the heating sector, electric heating technologies, like heat pumps or electric boilers, can shift their generation according to the needs of the power system within certain limits. These limits are expanded significantly if such technologies are paired with a heat storage system, preferably within a heating network. The deployment of renewable gas, as discussed in Section 3.3, and already established combined heat power plants within these networks is conceivable, too. In the mobility sector, batteries of electric cars, although they are not produced to primarily serve this purpose, can provide flexibility to the power sector similar to batteries discussed in Section 3.1 by adjusting charging power or by injecting into the grid (Vehicle-to-Grid) as long as they are fully charged when required by the consumer.

These examples show both the manifold ways sector integration can provide flexibility to the energy system, but also the difficulty of quantifying potential or meaningful costs of these flexibilities due to the complex and interrelated nature of the sketched energy system. For example, unlike pumped storage, benefits of a heat storage system cannot be assessed from an isolated power or heat perspective, but only by a combination of both.

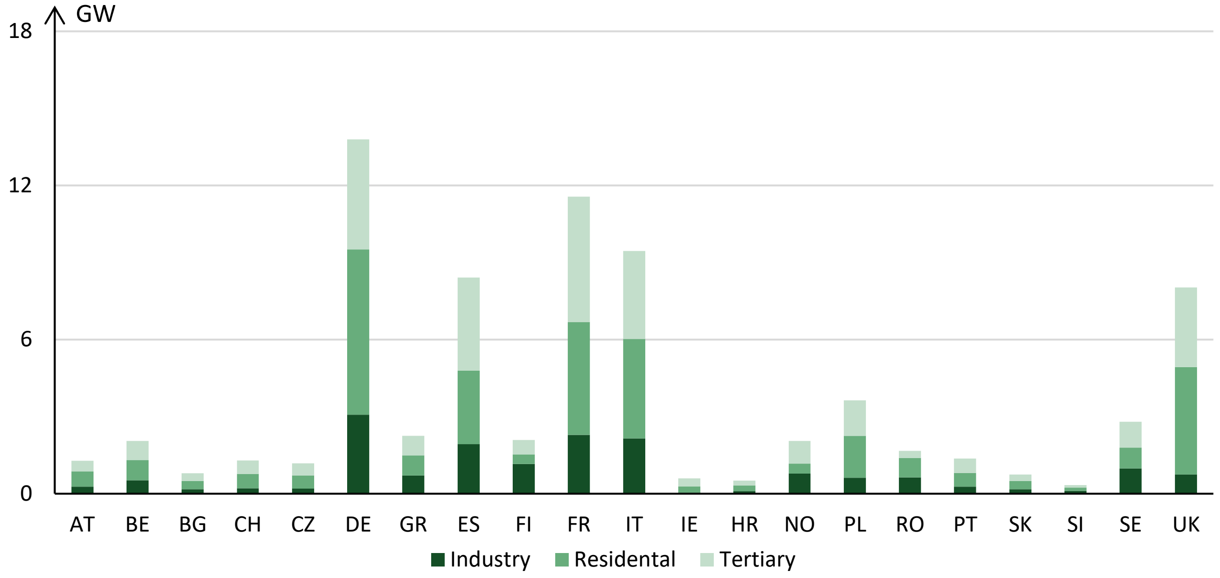

Figure 19: Average potential for load reduction [9]

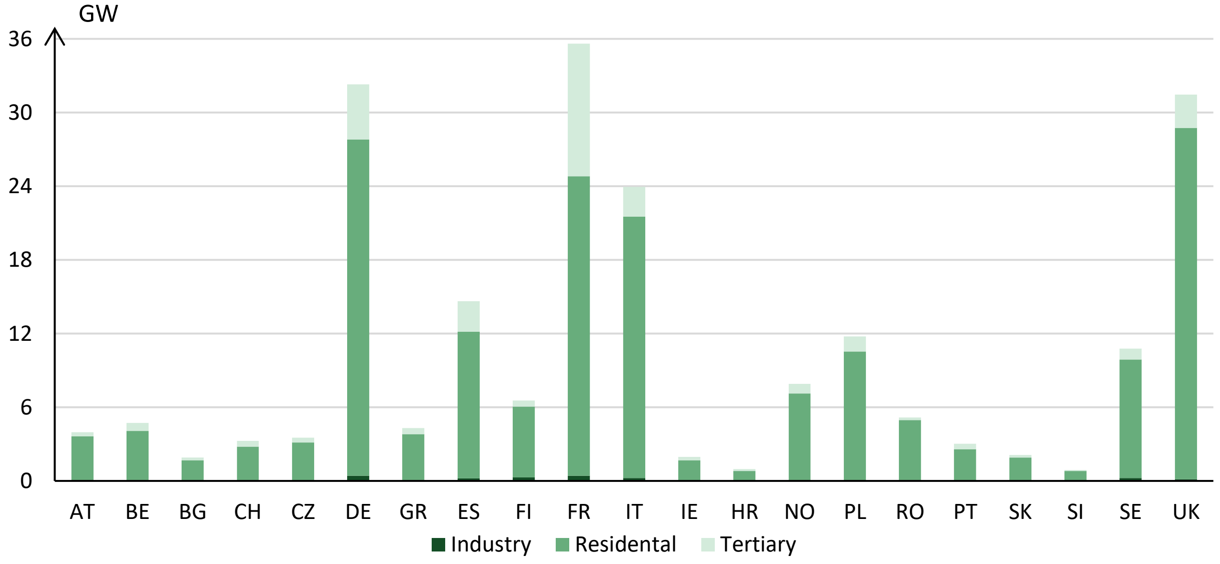

Figure 20: Average potential for load increase [9]

6 Interconnection

Interconnecting nodes in the power grid is fundamentally different from the flexibility options listed so far: These options were capable to offset temporal disparities of supply and demand stemming from increased variability and uncertainty in future energy systems. Strictly (and academically) speaking, interconnection, meaning transport capacities for electricity between regions, cannot offset temporal but only spatial supply-demand-disparities. However, increasing net transfer capacities between regions is still considered a flexibility option in this report, because in practice it can lead to equivalent results. Ideally, instead of being stored, surplus generation can be exported to interconnected regions and vice versa imports can resolve local shortages of supply. As a result, flexibility from interconnection does not primarily depend on the technological properties of transmission capacities, but on the spatial and temporal structure of demand in supply within the energy system. Thus, quantification is a complex process and similar to has been remarked about sector integration earlier.

The costs for AC overhead transmission lines found in the literature range between 400 and 450 € per km and MW of thermal capacity. These values are also applied, when explicitly modelling the power grid on a transmission line level [10, 11]. However, most large-scale models only implicitly represent the power grid as net exchange capacities between regions. In this case, usually a value of 1000 € per km and available exchange capacity is applied [12, 13].

7 Conclusion

In the beginning of the report flexibility was defined as "*a power system's ability to cope with variability and uncertainty in demand and generation*" and subdivided into short-, medium- and long-term flexibility. In the following, storage technologies, thermal power plants, flexible demand and interconnection were accessed regarding their ability to provide these flexibilities in a future energy system characterized by high shares of non-dispatchable renewable sources.

For this purpose, storage technologies were characterized as either electrochemical, mechanical, or chemical storage systems. In conclusion, mechanical and electrochemical storage systems (i.e. batteries) are found mostly suited to cover the need for short- and medium-term flexibility. Electrochemical storage systems or power-to-X technologies on the other hand are one of the few options to provide long-term seasonal storage.

In today's power system, thermal power plants are one of the major sources of flexibility. They provide short- or medium-term flexibility by adjusting their level of supply and long-term flexibility as backup capacities. However, especially the amount of flexibility provided by emissions intensive power plants can be expected to decrease in the future.

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9 Annexes

The technology and cost data described in this report is accompanied by Annex A (Technology and Cost Database).