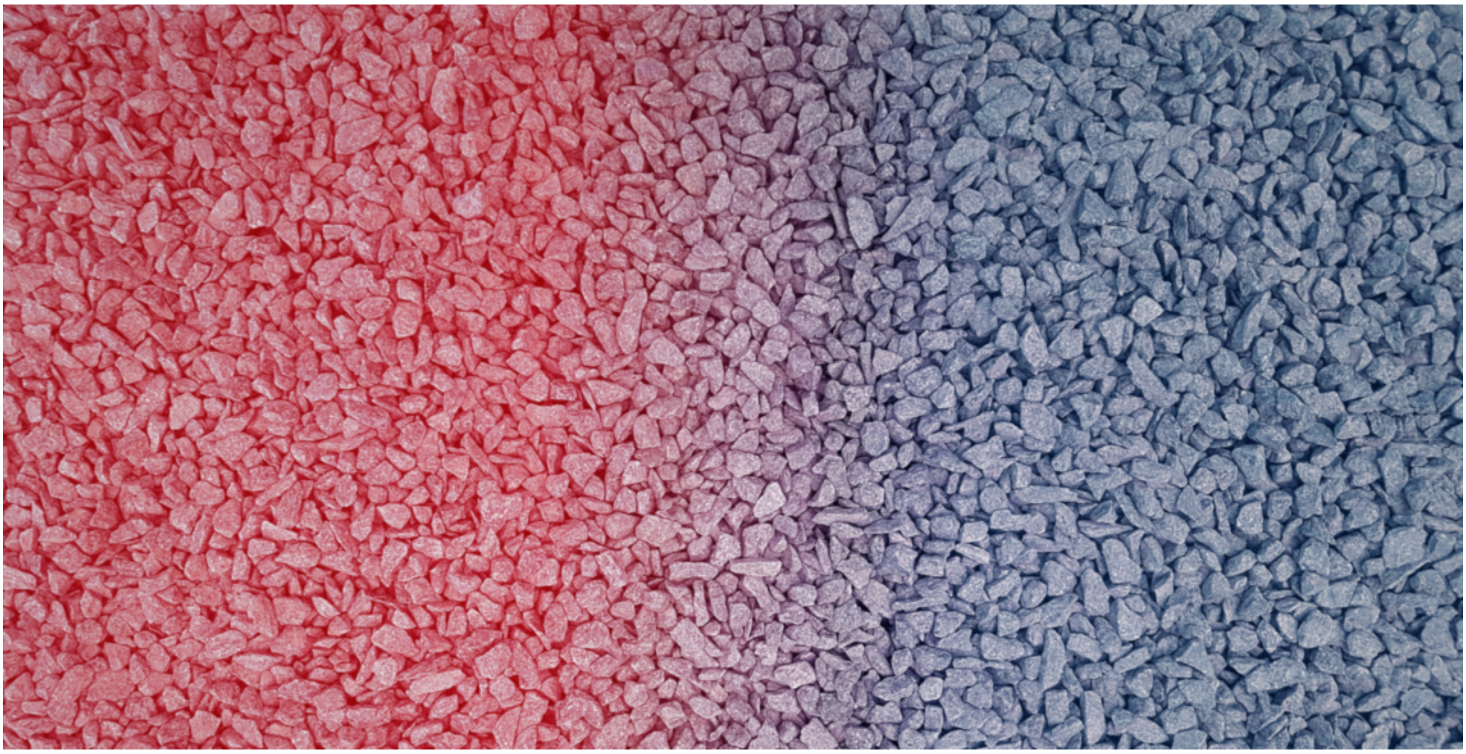
Whitebook
Energy storage technologies in a Danish and international perspective

Department of Energy Conversion and Storage



March 2019

DTU Energy
Department of Energy Conversion and Storage

Contents

1. Acknowledgements

This whitepaper has been prepared with financial support from the Danish National Committee under World Energy Council. Without this support, the work behind the report would not have been possible.

The below-mentioned authors and contributors are gratefully acknowledged for their contributions, inputs and fruitful discussions.

2. Authors and contributors

Main author and editor was Allan Schrøder Pedersen, DTU Energy
The sections about Na-S, VRB and Na-NiCl batteries were written by Rune Christensen, DTU Energy
The section about Li-ion batteries was written by Arghya Bhowmik, DTU Energy
The section about Li-S batteries technology was written by Poul Norby, DTU, Energy.

In addition, valuable and highly appreciated input and comments have been given by:

Anders Bavnhøj Hansen, Energinet, Anders Dyrelund, Rambøll, Christian Veje, Syddansk Universitet, Claus Ditlefsen, GEUS, Frank Elefsen, Teknologisk Institut, Hans Aage Hjuler, Danish Power Systems, Iben Moll Rasmussen, Vindmølleindustrien, Jan Eric Thorsen, Danfoss, Jan Jensen, Dansk Gasteknisk Center, Jens Oluf Jensen, DTU Energy, Jens Pelle, Aalborg CSP, John Bøggild, Haldor Topsøe, John Flørning, Rambøll, Jørgen Jensen, Green Hydrogen, Karen Anthonsen, GEUS, Kim Behnke, Dansk Fjernvarme, Laila Grahl Madsen, IRD Fuel Cells, Lars Barkler, Lithium Balance, Martin Herse-Lyngsø, NIRAS, Martin Speierman, WattsUpp Power, Mathias Kjærgård Christensen, DTU Energy, Michael Paludan-Müller Nylykke, Ørsted, Mikael Sloth, NEL Hydrogen, Mohammad Rezwan Khan, Vestas, Morten Renneberg, HOFOR, Ole Alm, SEAS-NVE, Per Alex Sørensen, EnergiPlan, Per Hessellund Lauritsen, Siemens-Gamesa, Reto Michael Hummelshøj, COWI, Sune Thorvildsen, Dansk Industri, Søren Knudsen Kjær, Aalborg Universitet, Tejs Laustsen Jensen, Hydrogennet, Thomas Mandal Østergaard, Energistyrelsen, Torben R. Jensen, Aarhus Universitet

Many references in the present report are made to the report "Status and recommendations for RD&D on energy storage technologies in a Danish context" and therefore the authors and contributors from then are acknowledged here:

Brian Elmegaard, Claus Hviid Christensen, Claus Kjøller, Frank Elefsen, John Bøgild Hansen, Jørgen Hvid, Per Alex Sørensen, Søren Knudsen Kær, Thomas Vangkilde-Pedersen, Thorkild Feldthusen Jensen. In addition, valuable input was received and used from Aksel Mortensgaard, Anders Bavnhøj Hansen, Jeannette Møller Jørgensen, Bo Nørregaard Jørgensen, Inga Sørensen, Jacob Andreasen, Jan Olsen, Jørgen Boldt, Jørgen Jensen, Laila Grahl-Madsen, Lars Barkler, Mikael Sloth, Morten Hofmeister, Per G. Kristensen, Per Hessellund Lauritsen, Rasmus Lærke, Stig Niemi Sørensen, Thomas Brouer, Torben René Jensen.

3. Foreword

The world is witnessing a global climate change. Average temperatures have been increasing for decades and are foreseen to threaten living conditions and civilization in many places. Weather extremes like heavy precipitation, wild fires, droughts and storms are observed still more often all over the world.

The Paris Agreement sets the goal to limit global warming to well below 2°C, while pursuing efforts to limit the increase to 1.5°C. According to the Intergovernmental Panel on Climate Change (IPCC), to limit warming to 1.5°C will require reduced CO_2 emissions by about 45% by 2030 compared to the 2010 levels and a fully carbon-neutral economy by the middle of this century.

In consequence, we see governments changing their energy policies these years. Black, fossil energy sources are phased out and renewable generation is gaining market shares - strongly assisted by a rapid drop in wind and solar power prices. Thus, completely new and altered energy systems are underway. They will define new roles for suppliers and consumers of energy and what we need to learn is how the new systems can provide supply security, comfort and convenience in our daily life.

Energy storage is an important part of the energy transition – for transport and mobility, it is mandatory. To meet the challenges of affordability and responsivity, energy storage technologies must be further developed and refined. Some storage technologies are already mature and on the market. Some need careful attention to reach the market, but will be necessary in the future energy system.

The present whitebook aims to inform the reader about status, needs and perspectives for energy storage technologies, and set out milestones to guide decision makers, industry and research communities on how to trigger storage as an instrument to achieve the climate goals.

4. English and Danish summary

English summary

In many ways this whitebook can be seen as an update of the report "Status and recommendations for RD&D on energy storage technologies in a Danish context"[1], which was published February 2014 – and then again, this whitepaper is somewhat different in structure and noticeably different in content as well.

The present report is based solely on information available in literature. It mentions why and how the report was prepared, defines and delimits the concept of "energy storage" as used in the work and gives an overview of the most significant development trends of modern energy systems since publication of the above-mentioned report in 2014.

The whitepaper points out major application areas and describes the status of selected storage technologies (with an eye to Danish competences) as well as future application and export potentials. As a natural consequence, the current worldwide market situation for

---

[1] Status and recommendations for RD&D on energy storage technologies in a Danish context, EUDP, ForskEl et al., February 2014

storage technologies is summarized and a projection of the market development over the years to come is cautiously sketched.

Four storage technologies are studied closely in the present report: Batteries, Electrochemical storage, Thermal storage and Mechanical/Thermomechanical storage.

It is interesting to note how the use of batteries has grown since 2014 and how the demand for batteries seems to increase dramatically for yet another period of years driven by several new applications and an increasing population, who can afford buying battery-driven devices including vehicles. In the report Li-ion, Na-S, Na-NiCl and flow battery technologies are described, but other chemistries are included, because they represent new, promising types of batteries potentially able to take over after the Li-ion era.

The report finds that for electrochemical energy storage still some prudent development work has to be done to reach a sufficiently user-friendly state in terms of economy and technical performance. However, electrochemical storage has outstanding properties and fits very well into the sustainable energy system. It links the primary generation of electricity to a variety of highly valuable products and services in the energy sector - and in the materials sector as well.

Thermal energy storage is already a large and important storage area with a huge installed capacity found in hot water containers in buildings and in district heating networks. About 50% of energy consumption is demanded as heat. The demand for cold is also significant, very energy consuming and expected to grow in the years to come. New thermal energy storage techniques therefore need to be developed and demonstrated, and existing techniques – in particular for large scale storage - should be further developed and refined. Denmark has a strong position in development of heating systems and already a considerable export, which could be expanded based on new technologies.

Within mechanical energy storage, flywheel technology is pointed out as a promising topic showing production in Denmark. Furthermore, materials and production techniques have benefitted from the development of rotor blades for wind turbines, since the same or very similar composite materials are in use. In addition, flywheels show performance characteristics to meet some difficult challenges in the sustainable energy system.

The whitepaper finally gives proposals for a revised policy and regulatory framework, which can support energy storage in the energy system, as well as recommendations for actions to consolidate Denmark´s position within energy storage production and export.

Dansk resumé

I flere henseender kan denne hvidbog betragtes som en opdatering af rapporten “Status and recommendations for RD&D on energy storage technologies in a Danish context”[1], som blev publiceret i februar 2014 – og så alligevel ikke. For denne hvidbog er noget anderledes i struktur og ligeledes markant anderledes i indhold.

Hvidbogen er baseret udelukkende på tilgængelig information og data i litteraturen. Det omtales hvorfor og hvordan arbejdet blev udført, definerer og afgrænser det benyttede begreb for energilagring og giver et overblik over de mest betydende udviklingstendenser for moderne energisystemer siden udgivelsen af ovennævnte rapport i 2014.

Hvidbogen udpeger væsentlige anvendelsesområder og beskriver status for udvalgte lagringsteknologier (med et sideblik til danske kompetencer), ligesom fremtidigt potentiale for anvendelser og eksport beskrives.

Fire lagringsteknologier omtales detaljeret i nærværende rapport: batterier, elektrokemisk energilagring (elektrolyse), samt termisk og mekanisk lagring.

Det falder markant i øjnene, hvordan udnyttelse af batterier er steget betydeligt siden 2014 og hvordan efterspørgslen på batterier ser ud til at vokse dramatisk i endnu en årrække fremover drevet af mange nye anvendelser og en på verdensplan stigende befolkning, der kan få råd til at anskaffe batteridrevne brugsgenstande og herunder elektriske biler. I rapporten beskrives Li-ion, Na-S, Na-NiCl og flowbatterier detaljeret, men også andre batterikemier inkluderes, da de repræsenterer nye, lovende batterityper, der kan tage over, når Li-ion æraen ophører.

Hvidbogen finder, at for elektrokemisk energilagring er der endnu et pænt stykke kvalificeret udviklingsrabejde, der skal gøres, for at nå en tilstrækkelig brugervenlig status med hensyn til økonomisk og teknisk ydeevne. Ikke desto mindre har elektrokemisk energilagring nogle enestående egenskaber og passer rigtig godt ind i det vedvarende energisystem. Det kæder den primære el-produktion sammen med en vifte af højværdi-produkter og services i energisektoren – og materialesektoren med, for den sags skyld.

Termisk energilagring er allerede nu et stort og vigtigt lagringsområde i vores energisystem med en enorm installeret kapacitet (energi såvel som effekt) i form af varmtvandsbeholdere i bygninger og i fjernvarmenet. Op mod 50% af den energi, der forbruges, efterspørges som varme. Efterspørgslen på køling er også betydelig, meget energikrævende og må forventes at stige i de kommende år. Nye, effektive termiske lagringsmetoder må derfor udvikles og blive demonstreret, og eksisterende teknikker – specielt med henblik på stor-skala lagring, må udvikles og raffineres yderligere. Danmark indtager en stærk stilling inden for udvikling af komponenter og varmesystemer og denne position vil kunne udbygges baseret på nye teknologier.

Inden for mekanisk energilagring peger rapporten på svinghjul som en lovende teknologi med eksisterende produktion i Danmark. Desuden har både de anvendte materialer og fremstillingsmetoder til svinghjul profiteret af udviklingen inden for fremstilling af rotorblade til vindmøller, eftersom det er de samme eller meget beslægtede kompostmaterialer, der benyttes. Yderligere viser svinghjul fremragende egenskaber, der kan løse væsentlige problemer i fremtidens energisystem.

Hvidbogen giver endelig forslag til, hvordan politik og reguleringer kan revideres med henblik på at støtte introduktion af energilagring, ligesom der gives anbefalinger for tiltag, der kan konsolidere Danmarks position inden for produktion og eksport af energilagringsteknologier

5. Guide to the reader

In this whitepaper reference is often made to the report “Status and recommendations for RD&D on energy storage technologies in a Danish context” published February 2014 or just to the development and changes since 2014. This is because that report gave a status within energy storage by 2014 and because the present whitepaper can be seen to update information to 2019.

However, this whitepaper has a somewhat different structure as it is more strictly following the individual technologies, in the sense that the full technology descriptions are included in the main document. Thus, all technology-specific information is collected under the same heading and there is no need to consult an annex to find it.

Firstly, in Section 6 the background and the reasons for preparing the whitebook are presented and followed (in Sections 7-10) by general discussions of the last 5 years´ energy system development trends, the future needs for storage and the projected market potentials for storage. In addition, two leading simulations of the Danish energy system towards 2030 are also given and show the foreseen role of energy storage.

Secondly, in Sections 11-15 fairly detailed descriptions are given for those technologies, that are found to be most relevant and hold the largest application potential towards 2030. Each technology section gives a technical description followed by sub-sections giving non-technical information about the technologies – i.e. applications, status, players in Denmark and specific recommendations about the technology.

As something new, a short description of virtual energy storage is included in Section 16, since it in some applications offers the same services as physical energy storage.

In Section 17 the challenges about existing storage-relevant legislation and regulation are addressed and recommendations are given on how it could be revised.

Section 18 summarizes conclusions and overall recommendations resulting from the work with the whitebook. The section is a very condensed description of the reasoning, conclusions and recommendations resulting from the report. It is important to underline that this section should not be the reader's only take away from the report, but merely a quick reminder of the main points.

In Annex A, available SET Plan targets for many of the discussed technologies are presented to give the reader a reference with respect to present technology status and future targets in terms of technical and economic performance.

In Annex B and C, tables and figures from external sources are presented and give performance data and economic data for a range of energy storage technologies.

6. Introduction and background

6.1 How and why the work was initiated

In 2014 the report “Status and recommendations for RD&D on energy storage technologies in a Danish context” was published by the public Danish funding authorities within energy-related RD&D. The authorities had identified energy storage as one of three priority areas for reaching the energy-political goals of green energy transition towards 2050 (the other areas were Smart Grid and energy efficiency in buildings).

In support of a focused Danish RD&D effort within energy storage, the funding programme committees needed a status of relevant energy storage technologies and an evaluation of their potentials in a Danish context as well as an overview of Danish players on the scene of energy storage. Such results – collected in a report – should be for internal use within the secretariats and should be published to the benefit of potential, future applicants for funding.

During the latest 5 years much has changed about technology status for energy storage and about the political framework. Thus, in 2018 the Danish government presented a new energy plan to demonstrate how the government´s target about 50% renewable energy in 2030 should be reached. The plan included tax reductions on electricity and electrical heating, support to wind and solar power, establishing a 700-800 MW off-shore wind farm and expanded exploitation of biogas. However, according to the Danish Energy Association the plan will be far from sufficient to secure reaching the climate targets[2].

Setting out from the changed framework conditions since 2014, the Danish National Committee of World Energy Council decided to support the preparation of an updated mapping to reassess and specify the required efforts in Denmark within energy storage and conversion. The mapping should be done on a research-based foundation, but at the same time with increased focus on the development- and market-related challenges the technologies are facing. The outcome of the work should eventually be published as a whitebook aimed at decision makers, industry and the research community.

6.2 Objectives and limitations of the work

This report is basically a whitebook on energy storage. According to Wikipedia[3] a “whitebook is an authoritative report or guide that informs readers concisely about a complex issue and presents the issuing body's philosophy on the matter. It is meant to help readers understand an issue, solve a problem, or make a decision”. Thus the present work has aimed to:

- Present a mapping of Danish strongholds within types of energy storage technologies that are most relevant in Denmark. The mapping should include all sectors of the Danish energy system including electricity, heating and cooling, gas and transport.

---

[2] https://www.danskenergi.dk/nyheder/klimaet-kraever-vindmoller-solceller-vores-baghave Accessed February 2019

[3] https://en.wikipedia.org/wiki/White_paper Accessed November 2018

- Provide a basic assessment of the present and approaching market for energy storage in Denmark and abroad
- Take starting point in existing plans for development of the Danish energy system with particular focus on the period towards 2030.
- Give recommendations for how public, Danish support to RD&D could be optimally invested in the period towards 2030.
- Classify and describe storage technologies according to their technology readiness level.
- Describe relevant energy storage technologies based on their development potential and time perspective as well as applicability in a Danish context.
- Point to Danish competences and players within energy storage, covering research and innovation as well as commercial companies.
- Describe Danish potentials within energy storage in an international perspective.

As for the report published in 2014 the work in the present report has been based on existing knowledge among the participating parties and from information available in open literature, see also references provided in footnotes in the document. Within the given time and economy framework, it has not been possible to generate new independent knowledge, nor to prepare exhaustive descriptions or catalogues of energy storage technologies. In particular, the project group has refrained from giving detailed economic assessments of the future performance of the described technologies. However, in Annex A, the SET Plan targets for the technologies are given (where available), including data on economic performance and more can be found in Annex C.

6.3 Defining and delimiting the concept of energy storage in the present report

What may seem to be straightforward actually turns out to be quite difficult, namely phrasing a clear and sufficient definition of "Energy Storage". Even among the members of the European Association for Energy Storage (EASE), which is solely concerned about aspects of energy storage, it has taken many and lengthy discussions just to reach agreement on how to consider and define energy storage.

In an EC Staff Working Paper[4] from 2017, energy storage was understood as:

> "Energy storage in the electricity system means the deferring of an amount of the energy that was generated to the moment of use, either as final energy or converted into another energy carrier."

In the report[5] preceding the present one, the following definition of energy storage was adopted:

- **Energy Storage is the man-made (artificial) storage of energy in physical or chemical form for utilization at a later time**

---

[4] European Commission Staff Working Document, Energy storage – the role of electricity, European Commission, SWD(2017) 61 final, February 2017.

[5] Status and recommendations for RD&D on energy storage technologies in a Danish context, EUDP, ForskEl et al., February 2014

This definition (which has strong resemblance with the mentioned EC definition) will be used in the present report and thus, the following operations are not included in the present work:

- Natural production of biomass is not included in the concept of energy storage even though power from the sun is indeed stored during production of biomass.
- A fossil-fueled power plant on stand-by is not included, even though in some respects it provides the same service as an energy storage facility.
- Time shifting of electricity demand (sometimes called 'virtual energy storage') is not directly included, although time shifting solves the same kind of problems as energy storage. Nevertheless, a short description of the services virtual energy storage can provide is given in a dedicated section.
- Time shifting electricity production from dam-based hydro power, is also not included, but mentioned, as it has the same impact on the power system as pumped hydro and virtual electricity storage

6.4 Parallel efforts in Europe and abroad

The following national or regional reports concerning future needs for energy storage have been compiled and form part of the background information behind the present work:

EASE/EERA

- In 2017 the report “Joint EASE/EERA recommendations for a European Energy Storage Technology Development Roadmap - 2017 Update” [6] was published. This work was originally initiated by the European Commission and as indicated by the title, it has been prepared in collaboration between the European Association for Storage of Energy (EASE) and the Joint Programme on Energy Storage under the European Energy Research Alliance (EERA). The report gives an exhaustive description of potentials, development needs and recommendations for actions in a European perspective.

IEA

- Late 2014 the IEA published their “Technology Roadmap, Energy storage”, OECD/IEA, Paris, 2014. The report treats the status of energy storage technologies as well as visions for deploymenet towards 2050 and concludes that energy storage technologies are valuable in most energy systems, even with or without high levels of variable renewable generation.

Furthermore, many countries have tried to assess their own national future needs for energy storage. Emphasis has been put on needs in the electricity grids, which is where most workers foresee the first needs to arise. Characteristically, the resulting reports envisage energy storage to become important to the energy system, but only very few reports try to address the need for energy storage in quantitative terms and in particular, they do not take potential interactions between different sectors of the energy system, eg heating/cooling, electricity and gas, into account. Likewise, most reports do not address the question of energy storage for fuelling transport.

IRENA

- Electricity Storage and Renewables: Costs and Markets to 2030, International Renewable Energy Agency, Abu Dhabi 2017

---

[6] Joint EASE/EERA recommendations for a European Energy Storage Technology Development Roadmap - 2017 Update, EASE and EERA, Brussels 2017

EPRI (Electric Power Research Institute)**:**

- The last comprehensive report on energy storage was “Electricity Energy Storage Technology Options - A White Paper Primer on Applications, Costs, and Benefits”, EPRI1020676 from 2010. However, EPRI has since then formed the subgroup “Energy Storage Integration Council” (ESIC) and continuously publishes reports relevant energy storage, e.g. ESIC Energy Storage Implementation Guide and EPRI StorageVET (a software tool that models the value of services that storage projects can provide to the grid and utility customers).

USA, Europe and Germany

- How much electrical energy storage do we need? A synthesis for the U.S., Europe, and Germany, F. Cebulla, J. Haas, J.D. Eichman and W. Novak, Journal of Cleaner Production, 181, February 2018. An analysis of the storage requirements arising from 17 recent storage expansion studies involving over 400 Scenarios for the U.S., Europe, and Germany.

Europe

- Electrical energy storage in highly renewable European energy systems: Capacity requirements, spatial distribution, and storage dispatch,” F. Cebulla, T. Naegler and M. Pohl, J. Energy Storage, vol. 14, pp. 211–223, 2017.
- Large-scale Integration of Renewable Energies and Impact on Storage Demand in a European Renewable Power System of 2050, C. Bussar et al., in Energy Procedia, 2015, vol. 73, pp. 145–153.

Germany:

- Electricity storage systems in the future German energy sector, S. Babrowski, P. Jochem, and W. Fichtner, Comput. Oper. Res., vol. 66, pp. 228–240, Feb. 2016.
- Electricity Storage in the German Energy Transition, An analysis of the storage required in the power market, ancillary services market and distribution grid, Agora Energiewende, December 2014

UK:

- Flexibility Solutions for High-Renewable Energy Systems - United Kingdom, BloombergNEF, Eaton, Statkraft, November 2018

USA:

- Flexibility mechanisms and pathways to a highly renewable US electricity future, B. a Frew, S. Becker, M. J. Dvorak, G. B. Andresen and M. Z. Jacobson, Energy, vol. 101, pp. 65–78, Apr. 2016.
- Identifying Potential Markets for Behind-the-Meter Battery Energy Storage: A Survey of U.S. Demand Charges, J. McLaren, N. Laws, K. Anderson, NREL,
- ESA Vision for 2025, Energy Storage Association, November 2017
- U.S. Battery Storage Market Trends, US Energy Information Administration, U.S. Department of Energy, May 2018.

Australia

- Integrated System Plan - For the National Electricity Market, Australian Electricity Market Operator, July 2018

Denmark:

- IDA's Energy Vision 2050: A Smart Energy System strategy for 100% renewable Denmark, B.V Mathiesen, H. Lund, K. Hansen, I.R. Skov, S.R. Djørup, S. Nielsen, P. Sorknæs, J.Z. Thellufsen, L. Grundahl, R.S. Lund, D.W. Drysdale, D. Connolly, and P.A. Østergaard, 2015. Department of Development and Planning, Aalborg University.
- Overview of current status and future development scenarios of the electricity system in Denmark – allowing integration of large quantities of wind power. P.Sorknæs, H.Maeng, T.Weiss and A.Andersen, Report (Delivery 5.1) in the EU store Project
- Systemperspektiv 2035. Perspektiver for effektiv anvendelse af vedvarende energi i det danske energisystem på længere sigt. Energinet, marts 2018

6.5 Why store energy?

The black, fossil energy system would not have been viable without the access to energy storage. Think of piles of coal at power plants, huge underground natural gas caverns, hot water containers ready to provide convenient, well-tempered water for the morning shower and maybe not the least the gasoline or oil tank onboard our vehicles, whether for land-based, marine or air-borne transport. Thus, energy storage has always been vital to human societies.

However, the energy systems of the future will be dominated by sustainable energy sources primarily based on biomass, surplus heat, geothermal energy, wind, hydro and solar energy. This is the target for many countries all over the world, and for Denmark the transition from fossil fuels is anticipated to be completed by 2050. Figure 1 shows the expected global increase for wind power in the next years to come (see also Figure 3 further below).

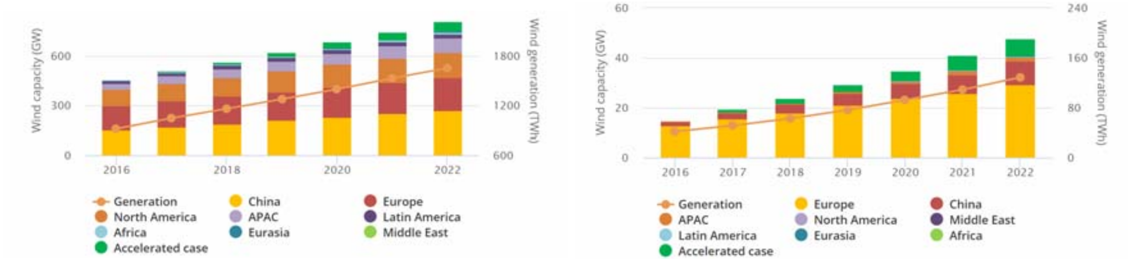


Figure 1. Projected increase in global on-shore (left) and off-shore (right) wind power installations towards 2022 [7]

However, the rapidly fluctuating character of most sustainable energy production (in particular for wind and solar production) implies new challenges to the operation of the energy system because variations in supply and demand are inherently independent of each other leading to considerable mismatches on different time scales ranging from milliseconds to seasons.

This mismatch problem can be solved by energy storage. Other solutions, one often referred to as flexibility options including smart grid operations like demand response, may partly

---

[7] https://www.iea.org/topics/renewables/wind/ Accessed February 2019

solve the same problem, but demand for comfort and convenience strongly favor energy storage as the solution. In addition, energy for transportation, which accounts for about one third of the final energy demand in Western countries, can only be provided if energy storage forms part of the vehicle technology. Grid stabilization, electric power balancing and fuel for transportation are three major cornerstones of future energy systems and can be secured by energy storage.

Different energy storage technologies are suitable for different applications and services. In this report the most relevant technologies will be described, their further development potential will be assessed, and the R&D challenges will be identified.

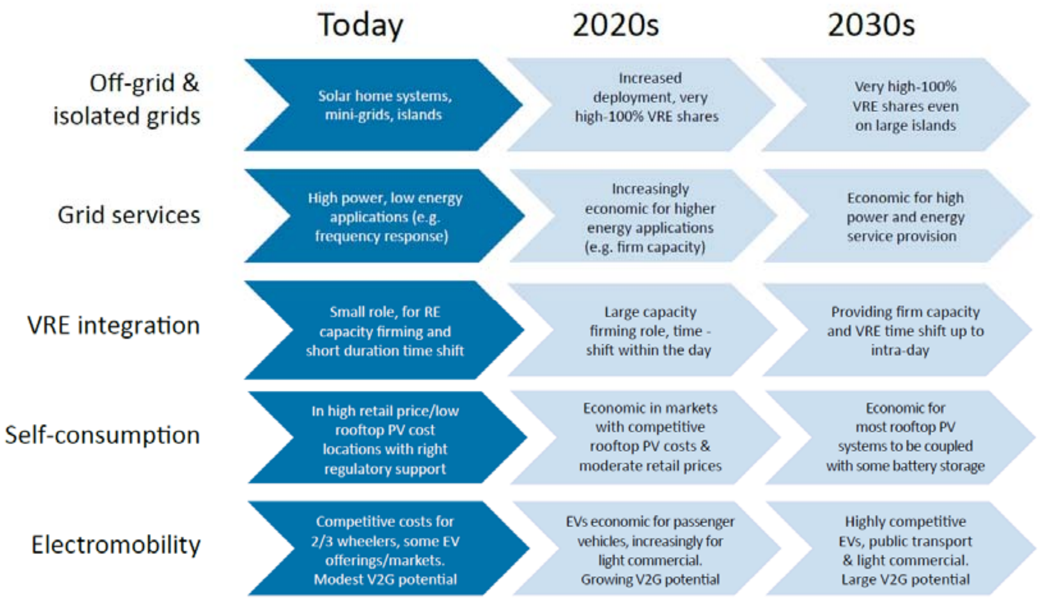


Figure 2. Energy storage needs in the energy transition[8]. The overview concerns electricity grids only, not gas or heating grids.

7. Main development trends since 2014

Much has happened within plans for energy systems and energy supply since the publishing of the report “Status and recommendations for RD&D on energy storage technologies in a Danish context” in February 2014. Firstly, and perhaps most important, the public awareness of climate changes has increased quite markedly as demonstrated by almost daily discussions and reports on TV news and press. In addition, leading politicians in the EU and in Denmark have adopted the agenda. They now pay significant attention to mitigating climate changes and globally increasing temperature. Thus, the overall goal for Denmark is to become CO_2 neutral in 2050 and the EU has set itself a similar long-term goal to reduce greenhouse gas emissions by 80-95%, when compared to 1990 levels, by 2050[9]. Even

---

[8] "Electricity Storage and Renewables: Costs and Markets to 2030," International Renewable Energy Agency, Abu Dhabi, 2017.

[9] Energy Road Map 2050, European Union, Brussels, 2012, doi:10.2833/10759

China – a large but still not completely developed economy – sets goals for decreasing fossil energy consumption, as China is facing heavy pollution from industry, electricity generation and certainly transport in the many Chinese mega-cities.

Increased renewable electricity generation in the Danish and European energy systems

Following the observed global climate changes, energy policies have indeed changed significantly in Denmark, in the European Union and in most of the remaining world in the effort to limit emission of vast amounts of greenhouse gases in consequence of burning fossil fuels.

The latest edition of World Energy Outlook from November 2018[10] considers three scenarios for the development towards 2040:

- ***Current Policy Scenario*** *based solely on existing laws and regulations*
- ***New Policy Scenario****, which provides a measured assessment of where today's policy frameworks and ambitions, together with the continued evolution of known technologies, might take the energy sector in the coming decades. The policy ambitions include those that have been announced as of August 2018 and incorporates*
- ***Sustainable Development Scenario*** *sets out the major changes that would be required to deliver the following goals simultaneously:*
  - *Delivering on the Paris Agreement. The Sustainable Development Scenario is fully aligned with the Paris Agreement's goal of holding the increase in the global average temperature to "well below 2 °C".*
  - *Achieving universal access to modern energy by 2030.*
  - *Reducing dramatically the premature deaths due to energy-related air pollution.*

In the two latter scenarios electricity from renewable energy sources, wind and solar power, plays a prominent role in the future energy system. Thus, already by approx. 2028 – 10 years from now – wind power is projected to be the major source of electricity in Europe.

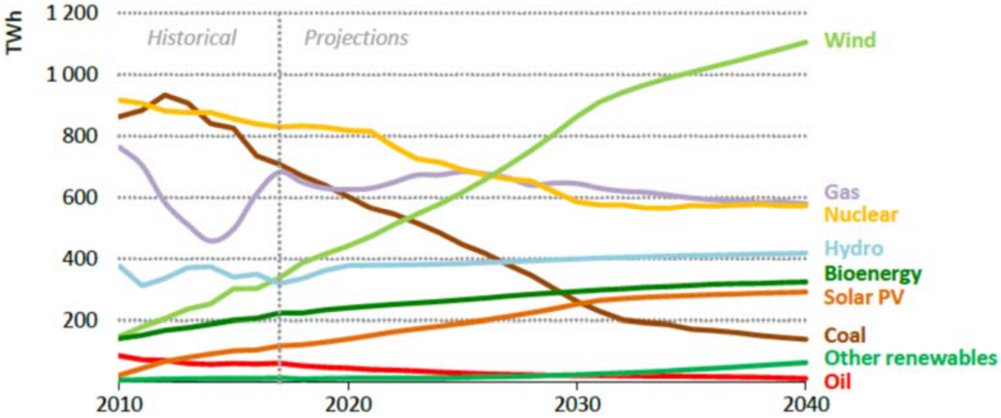


Figure 3. Historical and projected electricity generation distributed on technologies in Europe in the above mentioned New Policy Scenario[10]. Wind is seen to be in front after 2028.

---

[10] World Energy Outlook 2018, p. 29, International Energy Agency, Paris, November 2018

Figure 3 also shows the development of the European generation mix since 2014. Clearly the most CO_2 emitting sources (coal and oil) have declined, whereas renewable input - bioenergy, solar PV and in particular wind power - has increased. This is an encouraging trend and it even seems to continue in the decades to come, at least in the studied scenario.

For Denmark, the tendency for wind is the same as shown for Europe in Figure 3, but even more pronounced. Here the production has increased[11] from 28 PJ in 2010 to 46 PJ in 2016 and wind power is rapidly approaching 50% of final electricity demand. Such uncontrollable and variable production can naturally be very difficult to integrate in a traditional energy system as show in Figure 4, where Denmark is deemed to be placed between Phase 4 and 5.

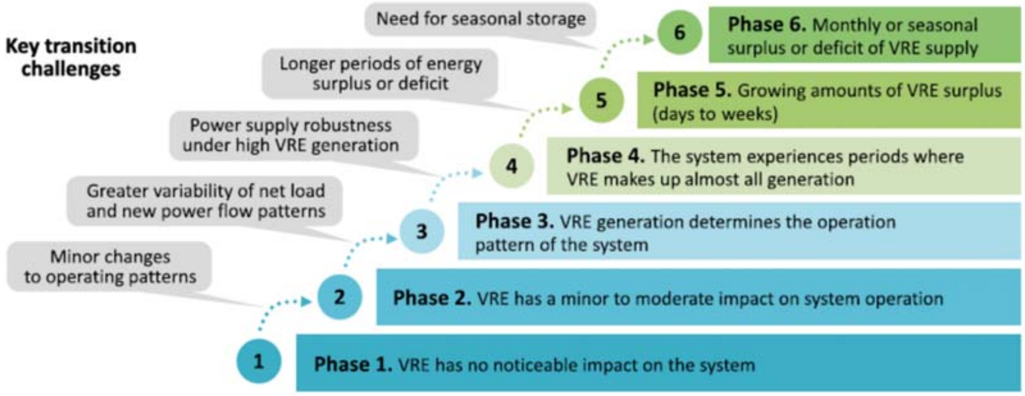


Figure 4[12]. Key challenges by phase in moving to higher levels of integrating variable renewables in power systems

In general, the described problems can be solved by energy storage (as also shown in the challenge between Phase 5 and 6 in Figure 4) and Denmark has excellent connecting cables to neighbor countries including Norway, where water behind hydropower stations can be stored for quite long periods with excess wind power in Denmark and north Germany. Actually, it may be questioned how the Danish electricity system could have been operated without access to the Norwegian water storage capacity.

Expansion of interconnections

Members of the ENTSO-E – the European Network for Transmission Service Operators Electricity – are continuously expanding the electricity transmission grids in Europe. Such expansion is an excellent integrator for renewable energy, since excessive or insufficient local power can often be handled via exchange of power with regions in the “opposite” situation. For Denmark, new interconnecting capacity has been established since 2014 and

---

[11] Energistatistik 2016, Danish Energy Agency, Copenhagen, November 2017

[12] World Energy Outlook 2018, p. 299, International Energy Agency, Paris, November 2018

more is underway[13]. Electrical interconnectors represent a flexibility option and will – isolated seen - decrease the needs for storage capacity

Fuel for transport

Figure 5 below shows historical data since 2010 and projections until 2040 for the worldwide consumption of renewable energy in the transport sector. The use of renewable fuels in transport has increased since 2014 and the increase is expected to continue in the future, where the dominating energy sources will be electricity from wind and solar sources as well as biofuels (from biomass). Biomass as a major source, however, is being disputed because of a number of inherent disadvantages – primarily problems about timing of emission/reabsorption, about land use (competition with food production, forest protection, control of origin). In the case of Denmark more than 25% of biomass for energy use was imported[11] in 2016, which is not a problem if the imported biomass is thoroughly controlled and certified, but the mentioned questions may indicate that electricity for transport could increase more steeply than shown in Figure 5 for the period towards 2040. If this happens, electricity for transport stored in batteries and synthetic fuels will increase even more than foreseen in the figure. In any case, an increase in use of electricity for transport since 2014 can be seen and is expected to increase further in the future.

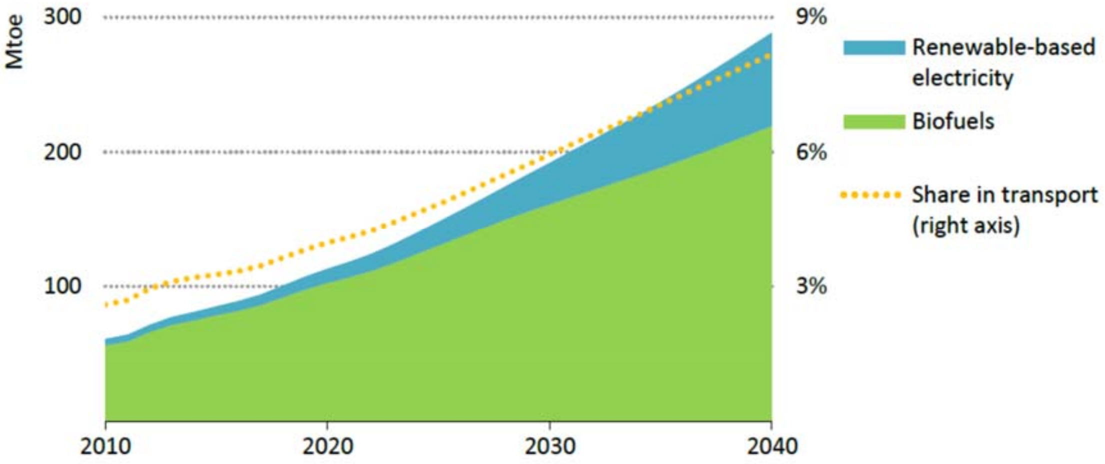


Figure 5. Renewable energy in worldwide transport by type and amount (left axis) and share (right axis)[14]. Historical data since 2010 and projections until 2040.

Integration between energy sectors

An important tool, which can facilitate and even be required for full penetration of renewable sources in the energy system, is cross-sector integration, meaning that different energy sectors should be interlinked. As an example, in the fossil energy system fuel for transport and supply of electricity were totally disconnected and independent of each other. Gasoline and diesel were produced without any relation to generation of electricity. In the renewable system – referring again to Figure 5 – electricity will be used to fuel transport creating a link between the two sectors. The same considerations will be true also for the gas and heating

---

[13] Reinvesterings-, udbygnings- og saneringsplan 2017 (RUS17), Energinet, December 2017
[14] World Energy Outlook 2018, p. 269, International Energy Agency, Paris, November 2018

sectors and this kind of links are expected to be strengthened in the future and form new flexibility options for the energy system as a whole. Thus, in periods with excess electricity generation, energy can be stored in batteries or in synthetic, chemical fuels for later use in transport. This is often called the “integrated energy system” and energy storage has a very important role to play in linking the sectors and contribute to comfortable and convenient use of energy in a system based on renewables. Linking the energy sectors have come much more in focus since 2014 and this development is in strong support of energy storage technologies.

Cost of renewables

The cost of renewable energy is mandatory for its penetration and in particular, wind and solar power have decreased profoundly since 2014. Figure 6 shows the development of the levelized costs of electricity in major regions all over the world and the trend is very common: solar electricity has decreased considerably and is found to be on level with wind power, whether off-shore or on-shore, and also wind power has decreased in price.

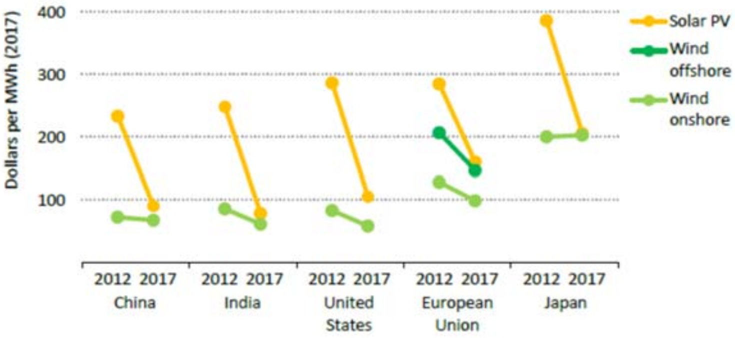


Figure 6[15]. Levelized costs of electricity by selected technologies and regions, 2012-2017

Development of energy storage technologies

Several crucial energy storage technologies have been developed and improved technically as well as economically since 2014. As an example, flywheels have become considerably cheaper and more efficient. Purchase prices have decreased from 2.3 M€/MW in 2009[16] to 0.2 M€/MW in 2017 and 9.3 M€/MWh in 2009 to 2.0 M€/MWh in 2017[17] meaning a reduction of 92% for charge capacity and 79% on storage capacity. This decrease is partly due to a significant decrease in manufacturing prices for polymer composite flywheels, which in turn is driven by a sharp decrease in prices for wind power turbine blades (similar materials and manufacturing methods[17]. Figure 6 above further illustrates the same point.

---

[15] World Energy Outlook 2018, p. 296, International Energy Agency, Paris, November 2018

[16] Quotation from Beacon Power 2009:- Full system price for a 1MW(250kWh) system in the range of \$2.8-3 million/MW; -2 flywheel(200kW) system app. \$1.6 million/MW, both prices without VAT and to be adjusted for relative scope.

[17] Private communication with WattsUp Power 2017: Standard solutions optimized to stabilize transformers in the power grid. The system is sold in modular configurations. Each module has a capacity of 100kWh and a peak discharge capacity of 1 MW capacity. Full system price in the range of 1.5 million Dkkr/MW and for a 2 MW(200kWh) system in the range of 2.5 million DKkr/MW, both prices without VAT and to be adjusted for relative scope.

8. Future applications for energy storage

Applications for energy storage are already numerous. However, most applications – by number and capacity - are served by fossil sources as explained elsewhere in this report (gas stores, piles of coal and fossil fuel stored for transport), but as the fossil sources are phased out, energy storage is the obvious choice as replacement.

The following list points out applications where energy storage will be the suitable and in some cases necessary technical solution. **However, the list is not exhaustive**.

List of applications for energy storage technologies

- Transport
    - Rail
    - Road
    - Air
    - Marine
- Seasonal energy storage
- Electricity grid applications
    - Reserves
        - Substitution foe spinning reserves
        - Voltage stabilization
        - Frequency stabilization
        - Black start
        - Generation capacity firming
    - Demand response
    - Reactive power compensation
    - Arbitrage
    - Weak grids
    - Investment deferral (e.g. in connection with temporary or occasional bottle necks)
- Sector linking
    - Electricity to stored heat and cold
    - Electricity to stored fuel (for re-electrification and supply of transport fuel)
- Renewable support (facilitate integration of renewable energy supply)
- Supply security
- Balancing supply and demand
    - Electricity
        - Local supply including non-connected consumers
        - Charging stations for electric vehicles
    - Heat and cold
        - Hot water storage
        - Cold water storage
- Energy management
    - Solar thermal power optimization
    - Waste heat utilization
- Island or stand-alone operations

9. Simulations of the future energy system in Denmark

The most prominent simulations of the future energy system in Denmark are probably provided by Energinet.dk (the Danish TSO) and IDA (the Danish Society of Engineers). In both reports, energy storage – as gas, as thermal energy and in batteries - is a substantial component of the energy system.

9.1 Energinet´s "Systemperspektiv 2035"

In 2018 Energinet published the report "Systemperspektiv 2035"[18] as well as a background report[19]. The work presents perspectives for efficient utilization of sustainable energy system in a long perspective stretching to 2035 and even to 2050. For 2050 Energinet projects the energy flows for Denmark shown in Figure 7 for simulations based on the Global Climate Actions scenario (ENTSO-E, Ten Years Network Development Plan, 2018-scenario[20]).

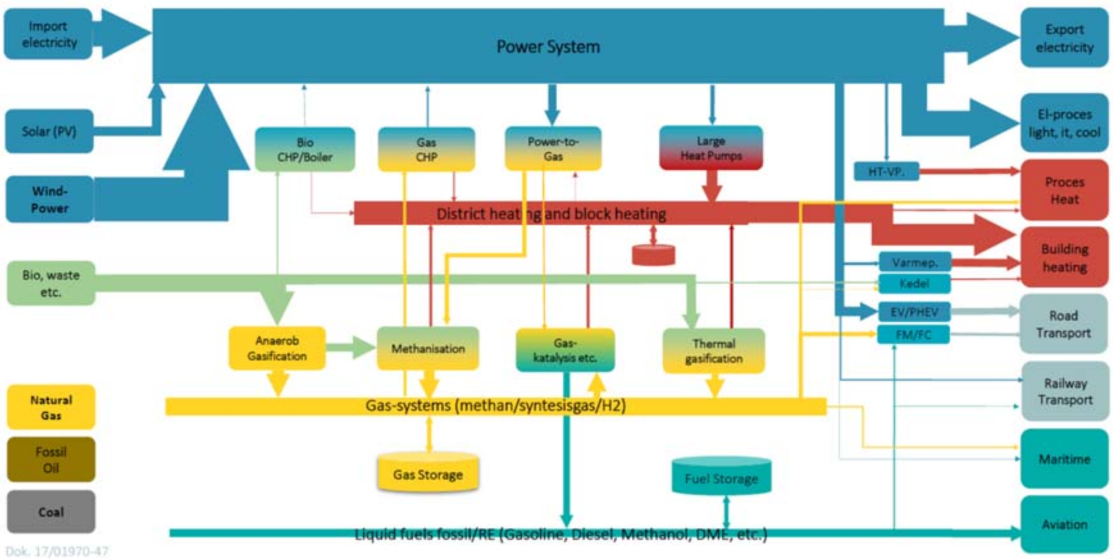


Figure 7 [19]. GCA 2035 – SIMULATED ANNUAL ENERGY FLOW

Energinet underlines that Power-to-gas can be a powerful tool to transfer excess energy from the electricity system to several energy-intensive products of high value. Energinet also notes, that Denmark has significant strongholds within this area and could potentially play an important role as an energy hub for P2X conversions. Energinet also finds (see Figure 8), that battery storage is essential for hourly balancing, but probably too expensive for large scale storage, and that sector coupling (electricity to gas and heat) can provide cost effective

---

[18] Systemperspektiv 2035, Perspektiver for effektiv anvendelse af vedvarende energi i det danske energisystem på længere sigt, Hoverapport, March 2018

[19] Baggrundsrapport Systemperspektiv 2035, Perspektiver for effektiv anvendelse af vedvarende energi i det danske energisystem på længere sigt. Energinet, March 2018, rev. 1.02

[20] https://tyndp.entsoe.eu/tyndp2018/scenario-report/ Accessed February 2019

large scale storage. Energinet notes, that it is essential to analyze cost effective sector couplings.

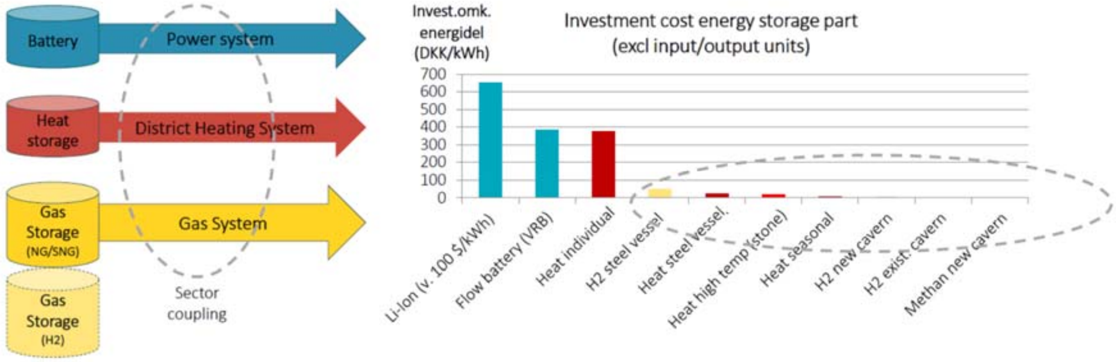


Figure 8[21]. Sector coupling to achieve low cost storage capacity

9.2 IDA's Energy Vision 2050[22]

The vision report was published in 2015 and intends to demonstrate how an intelligent integration of the electricity, heat, gas and transport sectors can create a robust energy supply for Denmark in the future, based on renewable energy[22]. The work has two focus years, 2035 and 2050. The results show that energy storage and conversion is highly needed in the scenarios, which is also shown in an overview of smart energy system components in the work as quoted below (the word storage is highlighted, ed.):

<u>High electrolyser capacities in combination with hydrogenation</u>

- Provide flexible electricity demands (50% operation time for electrolyzers)
- Connect electricity, gas and thermal grids
- **Use gas storages and storages in liquid fuels (electrofuels)**

<u>Smart charge of electric vehicles</u>

- Provides flexible electricity demands
- **Uses battery storage in vehicles**

<u>High large-scale heat pump capacities</u>

- Provide flexible electricity demands
- Provide flexible heat supply
- **Use large thermal storages**

<u>Individual heat pumps</u>

- Provide flexible electricity demands
- **Use small thermal storages**

<u>Flexible electricity demands in households and industry (demand shift)</u>

- Provide flexible electricity demands

---

[21] Systemperspektiv 2035 - Analyse af lagring i energisystemet, Presentation to ATV, March 2018

[22] IDA's Energy Vision 2050: A Smart Energy System strategy for 100% renewable Denmark, B.V Mathiesen, H. Lund, K. Hansen, I.R. Skov, S.R. Djørup, S. Nielsen, P. Sorknæs, J.Z. Thellufsen, L. Grundahl, R.S. Lund, D.W. Drysdale, D. Connolly, and P.A. Østergaard, 2015. Department of Development and Planning, Aalborg University.

Thermal and gas storages

- Provide flexibility between end demands and inputs from baseload and fluctuating heat and gas sources (gasified biomass and biogas)
- Connect electricity, gas and thermal grids

Combined heat and power plants

- Provide flexible electricity supply
- Provide flexible heat supply
- **Use thermal and gas storages**

The required amount of thermal energy storage is assumed to be:

- tank thermal storage capacity: 320 GWh (for district heating and flexibility)
- Pit thermal energy storage capacity: 30 GWh (for solar thermal seasonal storage)

The amount of energy stored for transport purposes in the report is: 130 PJ (36 TWh).

10. Energy storage in a market perspective

A few clicks on a search machine will clearly show that energy storage is highly on the agenda of technologies for use in our future energy system. In line with this, many studies predict significant increase in energy storage markets for the next decade.

In the below Figure 9 an exponential growth in market size is foreseen, mainly driven by a notable growth in the mechanical storage technologies, which will likely be dominated by pumped hydro storage and to some extent flywheels. Compressed Air Energy Storage (CAES) is also a mechanical storage technology, which is frequently discussed for future applications, but looking back, no new plants have been installed nor planned since the nineteen nineties and the author of this report is sceptic if CAES will play a visible role in the period towards 2023.

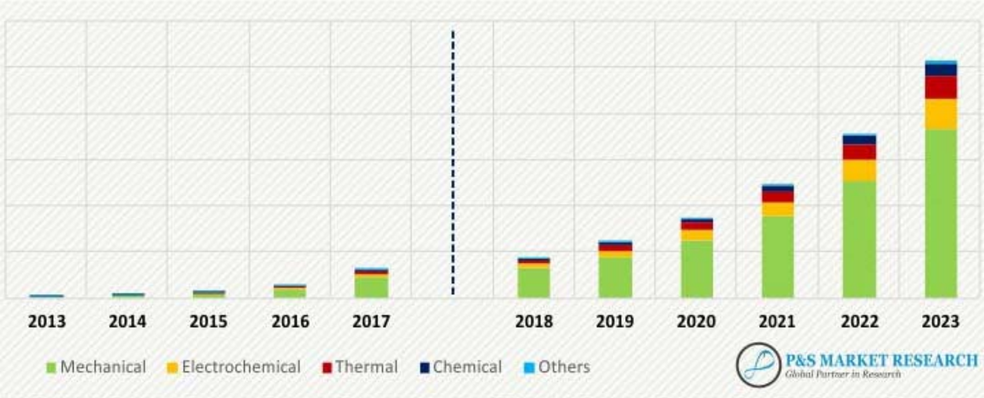


Figure 9. Global energy storage market by type, GW 2013-2023 (Tick marks 10 GW)[23]

---

[23] https://www.psmarketresearch.com/market-analysis/energy-storage-market - Energy Storage Market, Market Research Report, P&S Market Research, June 2018

However, Figure 9 shows that also electrochemical (here batteries), chemical (based on electrolysis) and thermal storage technologies will increasingly gain significance on the market in the future.

Drivers for the market expansion anticipated in Figure 9 are directly related to the changes energy supply undergoes these years, where fossil sources are replaced by renewables. Natural variations in renewable energy production, whether on a daily basis (as for PV) or based on longer periods (like for wind power), must be met by new technologies able to secure sufficient and timely energy supply and here energy storage will play a significant role. Furthermore, energy for transport, which – as mentioned – is about one third of total final energy demand in developed societies, requires energy storage suitable for mobile applications with emphasis on high energy density (volumetric as well as gravimetric), versatility and compatibility with the surrounding energy system, which will most often in the future be based on electricity generation.

In particular for Denmark, the transition to renewables is progressing fast. The wind power share of electricity generation is already about 50%, which is viable because of strong interconnections and a common electricity market with neighbor countries. Here Norway provides significant flexibility in hydropower. Hydropower can be turned off and on depending on the amount of electricity offered on the market, which in South Scandinavia is increasingly often determined by the wind power production. However, as the wind power capacity is increasing in Denmark as well in its neighbor countries and because other countries (like the Netherlands and the UK) will establish new interconnections to Norway, the Norwegian flexibility may not suffice to secure stable electricity supply in the future in Denmark. This obviously calls for Danish access to new energy storage capacity.

10.1 Asia, Africa and the Middle East

Another recent study[24] has looked at the emerging markets for energy storage including regions like Asia, Africa and the Middle East – cf. Figure 10 below. Here too, a significant deployment of storage capacity is foreseen towards 2025. The study also estimated the potential revenues from operating storage in the energy systems and as can be seen from the figure, significant business opportunities are predicted. In the same study it is interesting to note, that in some regions (like China and particularly India) a considerable share of the storage capacity is anticipated to be installed behind the meter (even in non-remote areas), meaning that households and private enterprises may see their economic advantage in applying own and self-administered storage capacity. For the moment being, the most obvious technology to provide such capacity would be batteries, but that may change in the future depending on the development of competing technologies able to provide the same kind of service.

For the case of India, the Prime Minister in 2014 announced a national target to install 100 GW of solar PV capacity by 2022. In addition, according to footnote [24], a July 2016 tender for several hundred megawatts of new solar PV capacity included the requirement that every 50 MW of PV capacity must have 5 MW / 2.5 MWh of associated energy storage. This kind of regulation will naturally support markets for energy storage and the Indian electricity supply security as well. The Indian electricity supply is still characterized of weak grids and poor grid stability.

---

[24] Energy Storage Trends and Opportunities in Emerging Markets, A. Eller and D. Gauntlett, ESMAP and IFC, 2017

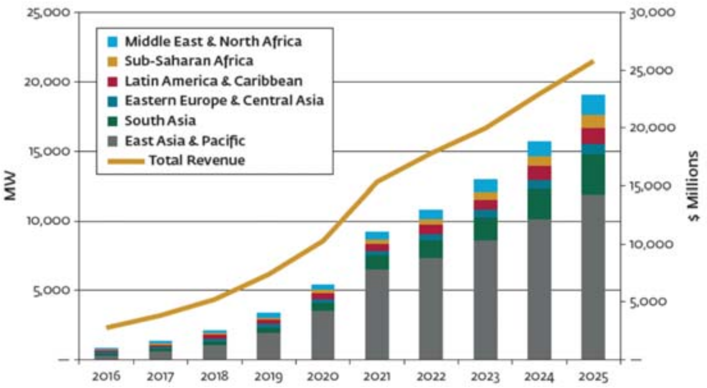


Figure 10. Projected Annual Stationary Energy Storage Deployments, Power Capacity and Revenue by Region, Emerging Markets: 2016–2025

10.2 North America

In the US a significant demand for batteries is already present and a further growth is foreseen by the U.S. Energy Information Administration[25] - see Figure 11.

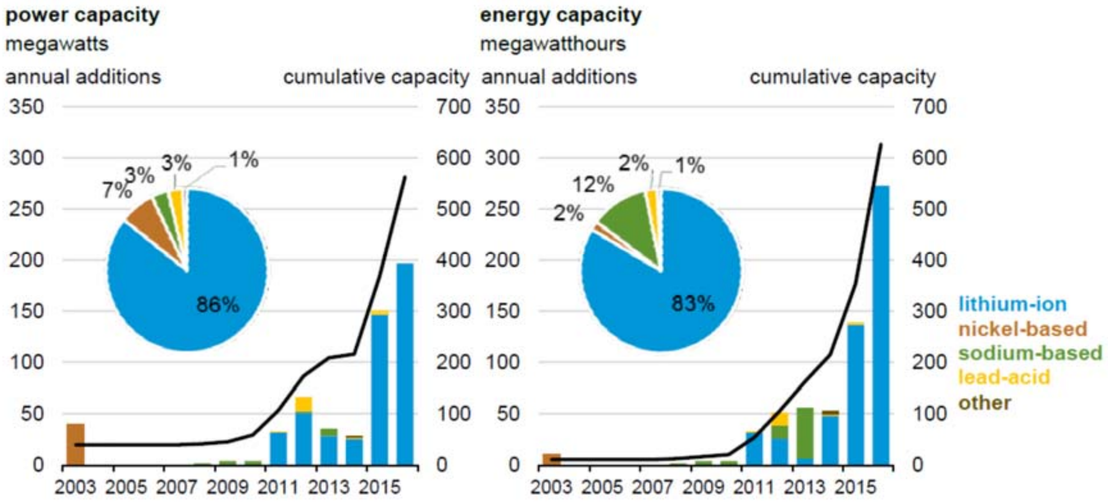


Figure 11. US Large-Scale Battery Storage Capacity by Chemistry (2003–2016)

It can be seen from the figure, that by far, the latest installations have been dominated by Li-ion technology, although other battery chemistries may seem to gain market shares.

The reference in footnote [26] gives a projection of the installed wind, photovoltaics and large scale energy storage capacity in the US towards 2050 as shown in Figure 12. Thus the expected energy storage capacity by and large reflects the installed variable generation capacity proportionally. The reference states that:

---

[25] U.S. Battery Storage Market Trends, May 2018, U.S. Energy Information Administration, Form EIA-860, Annual Electric Generator Report

- Battery-based storage costs are expected to continue to decline as utility-scale energy storage markets grow.
- Policies such as storage mandates in California and market participation rules in the PJM electricity market support near-term growth in storage systems to stabilize grid operations, improve utilization of existing generators, and integrate intermittent technologies such as wind and solar into the grid.
- In the longer term, wind and solar growth are projected to support economic opportunities for storage systems that can provide several hours of storage and enable renewables generation produced during the hours with high wind or solar output to supply electricity at times of peak electricity demand.

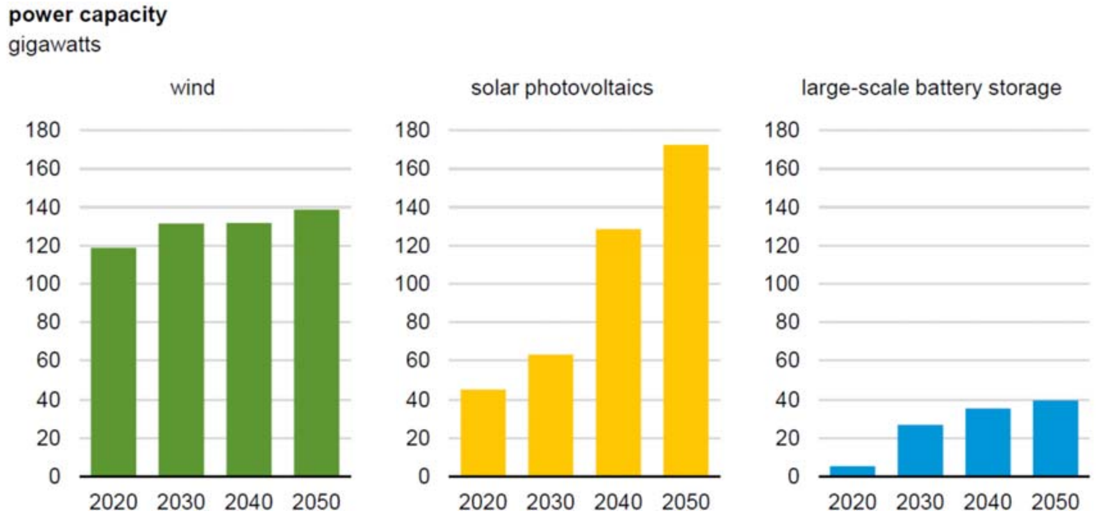


Figure 12. U.S. Large-Scale Wind, Solar, and Battery Storage Capacity Projections 2020–2050 [26].

10.3 Europe

Late 2018 an agreement on new rules and regulations for the European electricity market was reached[27]. By the time of writing, the agreement still remains to be approved by the European Parliament and Council before final implementation in the national legislation of member states can take place. However, the agreement holds a large potential for new business opportunities for energy storage technologies.

Several parts of the new rules are important to energy storage and give promises to support and further energy storage:

- **Coal Power Plants in Stand-By mode**. Subsidies to generation capacity emitting 550 g CO2/kWh or more will be phased out under the new rules. In some EU member states financial support has been given to coal fired power plants operated in stand-by mode to provide capacity firming in periods where other (predominantly renewable) generation capacities are insufficient to meet the electricity demand. This kind of operation will be difficult for coal fired plants (1 kWh electricity generated from coal emits more than 900 g CO_2 somewhat depending on thermal efficiency) without

---

[26] Annual Energy Outlook 2018 with projections to 2050, February 2018, U.S. Energy Information Administration, Office of Energy Analysis, U.S. Department of Energy, Washington, DC 20585

[27] "Commission welcomes political agreement on conclusion of the Clean Energy for All Europeans package", European Commission - Press release, Brussels, 18 December 2018. Available on http://europa.eu/rapid/press-release_IP-18-6870_en.htm (Accessed December 2018)

support. However, the need for capacity firming will naturally persist and is likely to grow and this is where energy storage can gain market openings providing such firming services.

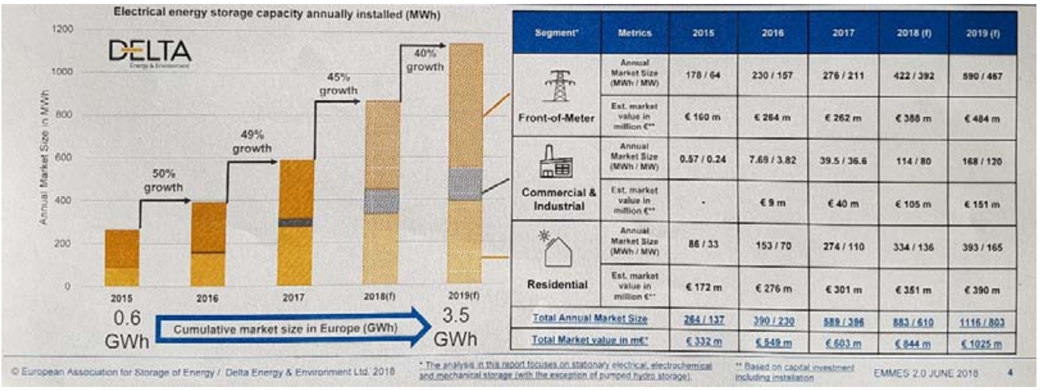
- **Smart meters**. Consumers will have the right to get smart meters to control their consumption, unless analysis in a given member state shows that the cost outweighs the benefits. The right can incentivize consumers, who produce electricity, to utilize low electricity prices and store energy “behind the meter” for own later utilization when electricity prices are high. Battery storage can be highly relevant for this application.
- **Dynamic price contract**s. The consumer is put at the center of the clean energy transition. Customers will be able to participate directly in the market[28] as active customers, for example by selling self-generated electricity, participating in demand response schemes or joining citizens energy communities. Thus, the new rules enable the active participation of consumers whilst putting in place a strong framework for consumer protection. Consumers will be able to have a dynamic electricity price contract from energy companies with more than 200.000 clients. Such dynamic price contracts will rely on smart meters and incentivize installation of “behind the meter” energy storage, buying electricity in periods with low prices and selling back when prices are high. Battery storage or more bulk technologies can be relevant for this application.

These are important and optimistic messages to energy storage operators and manufacturers and they seem to represent a clear position of the European Commission steering after the coming needs in the European energy system.

The European Association of Energy Storage (www.ease-storage.eu) together with DELTA Energy and Environment (www.delta-ee.com) in June 2018 prepared a report “European Market Monitor on Energy Storage (EMMES) - Snapshots of latest trends in Europe”. The report is classified as confidential and for the use of EASE members and other purchasers only but “extracts may occasionally be used externally”. The report gives very useful and comprehensive data on the European energy storage market with particular emphasis on stationary electrical, electrochemical and mechanical (excluding pumped hydro, though) for significant EU member states or regions. Major findings of the report are summarized in Figure 13 and shows a steadily increasing market into 2019 based on historical data for the period 2015-2017. Market data is split into Front-of-Meter, Commercial & Industrial and Residential applications, all showing their own contributions to the accumulated market development. The market foresight is considerable and is expected to reach more than one billion EUR in 2019. It is interesting to note, that for front-of meter installations the report finds significant fluctuations between countries due to national differences, in particular policy and regulations. This clearly demonstrates the importance of accommodating policies and regulations to welcome energy storage in the energy system.

---

[28] “Europe’s electricity market rules get ready for the energy transition: provisional agreement between Presidency and Parliament”, EP Today, 19 December 2018. Available on https://eptoday.com/europes-electricity-market-rules-get-ready-for-the-energy-transition-provisional-agreement-between-presidency-and-parliament/ Accessed December 2018



Segment*	Metrics	2015	2016	2017	2018 (f)	2019 (f)
Front-of-Meter	Annual Market Size (MWh / MW)	178 / 64	230 / 157	276 / 211	422 / 392	590 / 467
	Est. market value in million €**	€ 160 m	€ 264 m	€ 262 m	€ 388 m	€ 484 m
Commercial & Industrial	Annual Market Size (MWh / MW)	0.57 / 0.24	7.69 / 3.82	39.5 / 36.6	114 / 80	168 / 120
	Est. market value in million €**	-	€ 9 m	€ 40 m	€ 105 m	€ 151 m
Residential	Annual Market Size (MWh / MW)	86 / 33	153 / 70	274 / 110	334 / 136	393 / 165
	Est. market value in million €**	€ 172 m	€ 276 m	€ 301 m	€ 351 m	€ 390 m
Total Annual Market Size		264 / 137	390 / 230	589 / 396	883 / 610	1116 / 803
Total Market value in m€*		€ 332 m	€ 549 m	€ 603 m	€ 844 m	€ 1025 m

© European Association for Storage of Energy / Delta Energy & Environment Ltd. 2018

* The analysis in this report focuses on stationary electrical, electrochemical and mechanical storage (with the exception of pumped hydro storage).

** Based on capital investment including installation

EMMES 2.0 JUNE 2018 4

Figure 13. Electrical energy storage capacity annually installed in the EU (MWh and MW)[29]

10.4 Australia

The Australian Energy Market Operator (AEMO) released an Integrated System Plan for the National Electricity Market (NEM) by July 2018[30]. The plan is a cost-based engineering optimization plan dealing with transmission system requirements for the NEM over the next 20 years. A number of likely scenarios for the energy system of Australia were considered and all of them turned out to include energy storage pursuant to out-phasing coal-fired power plants. Under the “Neutral ISP planning scenario”, the analysis projects the lowest cost replacement (based on forecasted costs) for retiring coal-fired generation capacity.

Figure 14 shows the required energy storage capacity over the next 20 years distributed on states and applications (utility or distributed) for two variations of the Neutral scenario. The curves clearly show the need and feasibility for energy storage as seen from the Australian Energy Market Operator´s position. The report finds, that “In contrast to the history of this sector (electricity supply, ed.), overall economic and population growth, and associated growth in demand for power, does not result in increased requirements for supply from the power system. Rather, the demand for power on the grid is flattening, due to the growth of rooftop photovoltaic (PV) and increasing use of local storage, as well as overall increases in energy efficiency)”[30]. Thus for Australia, like mentioned above for several other regions and countries, the capacity of distributed energy sources is increasing significantly primarily due to an increasing number of rooftop PV installations, which are still more often combined with local energy storage, primarily in the form of batteries. Actually, a dedicated study[31] assessing market participation opportunities for behind-the-meter PV/battery systems in the Australian electricity market based on historical electricity prices foresees attractive economic future opportunities for this kind of combined installations in Australia.

---

[29] European Market Monitor on Energy Storage (EMMES) - Snapshots of latest trends in Europe, EASE and DELTA-ee, June 2018, Edition 2.0

[30] Integrated System Plan, Australian Energy Market Operator, July 2018. Available on https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Integrated-System-Plan. Accessed January 2019.

[31] Assessment of market participation opportunities for behind-the-meter PV/battery systems in the Australian electricity market, E. Franklin, D. Lowe and M. Stocks, Energy Procedia 110 (2017) 420 – 427

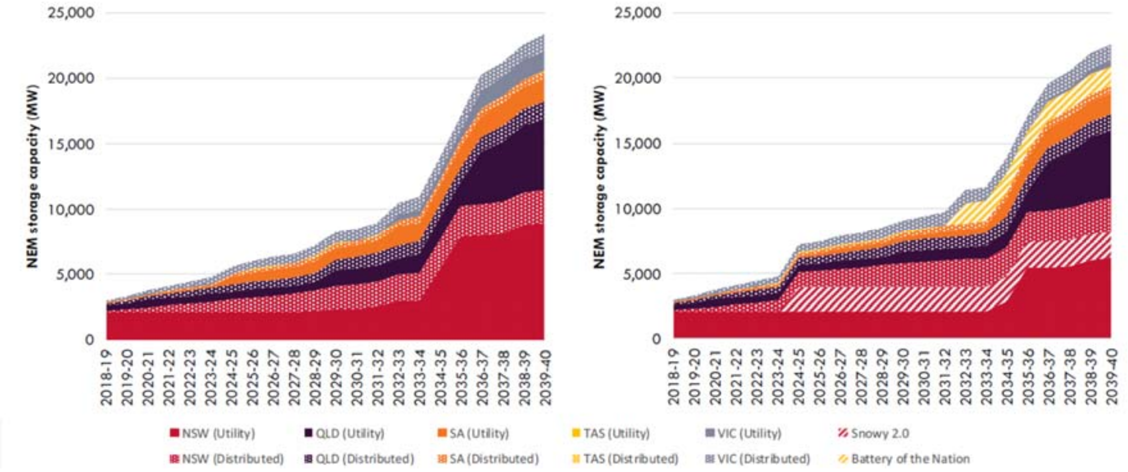


Figure 14[30]. Projected build of storage for Neutral (left) and Neutral with storage initiatives (right). The mentioned storage initiatives are two large pumped hydro plans (Snowy 2.0 and Battery of the Nation).

10.5 Business cases for energy storage

As energy systems change and energy storage finds its role(s) in the future systems, new business case will emerge. Some have already appeared and some are underway supported by anticipated changes in rules and regulations for energy systems.

The world-wide dominating energy storage technology is pumped hydro storage[32]. Plants have been installed on commercial basis and it is interesting to note in Table 1, that China and India are on the top ten list of countries with most installed pumped hydro storage in terms of power.

Country	Total power GW
China	32.0
Japan	28.3
United States	22.6
Spain	8.0
Italy	7.1
India	6.8
Germany	6.5
Switzerland	6.4
France	5.8
Republic of Korea	4.7
Total	128.1

Table 1. Pumped Hydro Power storage capacity (GW) by country, operational by mid-2017[32]

Similar to pumped hydro, also batteries have for a long time been used commercially and the use is growing fast in electric vehicles and mobile electronic devices like cell phones and

---

[32] IRENA (2017), Electricity Storage and Renewables: Costs and Markets to 2030, International Renewable Energy Agency, Abu Dhabi.

computers. The same can be said about hot water storage used in sanitary and district heating applications.

However, new business cases are about to emerge although several are anticipated to be driven by emotions rather than economy for yet a while.

An interesting example of such new business cases is show in Figure 15[33]. Energy storage is not shown in the figure but the depicted principles could include storage in several levels e.g. by the smart meter consumers or in the local generation pool. The basic idea of the concept is that consumers in smaller clusters or societies go together and optimize their energy economy on a joint basis by shared utilization of devices and local exchange of payments.

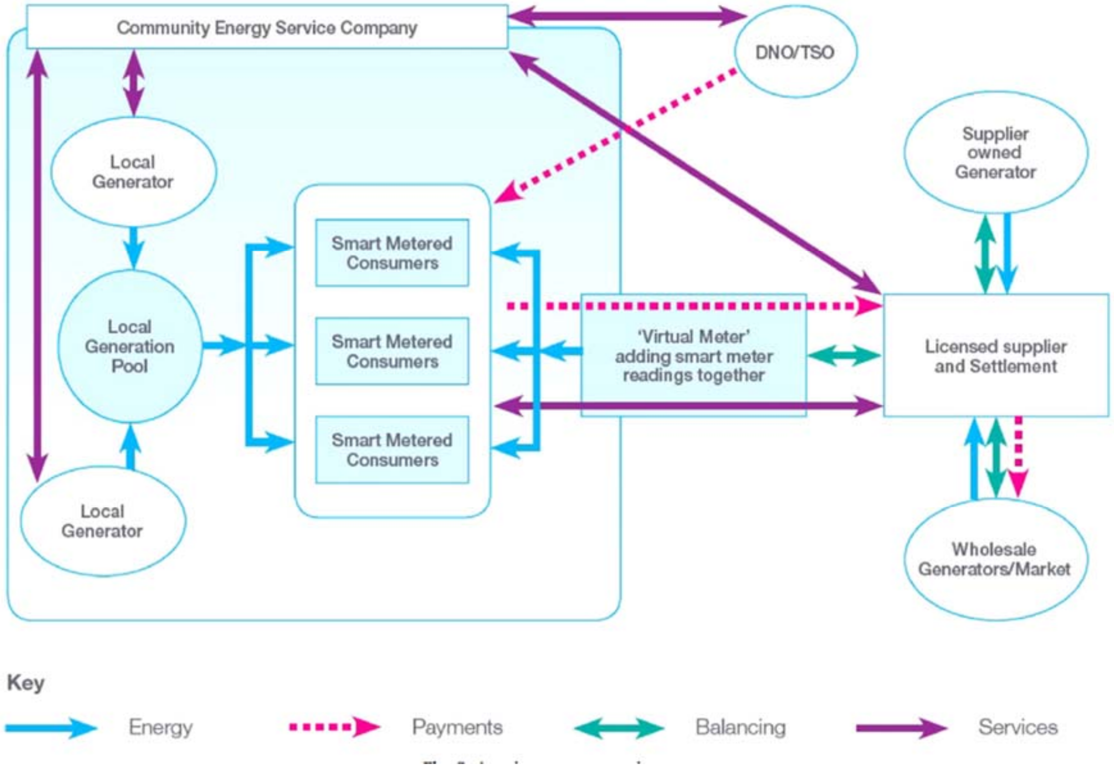


Figure 15. Aggregated consumers (shown as "Smart Meter Consumers") acting in an environment of local generation/consumption and optimized exchange with external energy service companies.

Many other business cases for energy storage are appearing these years in substitution of special energy services based on fossil energy. Examples are:

- **Uninterrupted power supply** (UPS) for e.g. hospitals, communication systems, military defense systems, data storage, surveillance, vital ongoing work, traffic regulations and many others
- **Power outages** which are somewhat related to UPS above
- **Power quality** securing frequency and voltage on grids as well as minimizing reactive power

---

[33] Business model innovation in electricity supply markets: The role of complex value in the United Kingdom, S. Hall and K. Roelich, Energy Policy 92 (2016) 286–298

- **Transport** where improved batteries or more efficient use of existing battery technology is needed
- **Capacity firming** (backing up generation capacity)

10.6 Conclusions on markets and drivers

The examples of coming need for energy storage described above are all pointing in the same direction of **increased demand for energy storage all over the world**. Apart from pumped hydro, much emphasis is currently put on batteries in a wide range of applications from µW to MW. However, many other types of storage technologies will be demanded and just need the last push of development before being matured for commercial applications. Such development is already taking place.

Technologies

11. Batteries

Demonstration of the first real battery is usually ascribed to the Italian scientist Alessandro Volta in the years around 1800. His battery was based on a pile of alternating Cu and Zn disks physically separated by an electrolyte as shown in Figure 16. Such assemblies are called voltaic piles after the inventor and their function can be attributed to different redox potentials of Cu and Zn relative to a standard electrode.

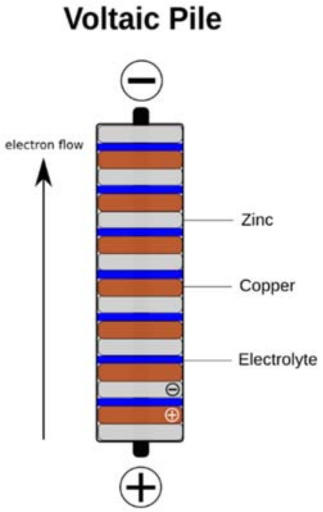


Figure 16[34]. The voltaic pile invented by Alessandro Volta. The pile consist of several battery cells, each consisting of a Cu disc, a separator (e.g. cloth) soaked with electrolyte and a Zn disc.

Since their appearance, batteries have gained tremendous and still increasing importance in a variety of applications and the limit does not seem to be reached yet.

11.1 General description, working principle and categorization

The basic component of a battery is the electrochemical cell, which is able to convert chemical energy to electrical energy and vice versa. Many different chemical reactions hold this property and the example shown above is explained here:

(1) $Zn + Cu^{++} \rightarrow Zn^{++} + Cu$

In the cell the overall reaction can be considered as two half-reactions:

---

[34] https://www.wpclipart.com/science/tools/electronic/voltaic_pile.png.html Accessed February 2019.

(2) $Zn \rightarrow Zn^{++} + 2e^-$ (oxidation of Zn) and

(3) $Cu^{++} + 2e^- \rightarrow Cu$ (reduction of Cu ions)

Another physical setup of this cell (compared to Figure 16) is shown in Figure 17 and consists of two half-cells. A crucial point of the device is that electrons can only pass from one half-cell to the other via the electron-conducting wire and ions can only pass through the ion-conducting salt bridge. If reaction (1) is associated with a negative change of Gibbs free energy (which it is as expressed by the different standard potentials of half-reactions (2) and (3)) the overall reaction (1) will proceed freely and the electrons will do electrical work as they pass through a voltage difference.

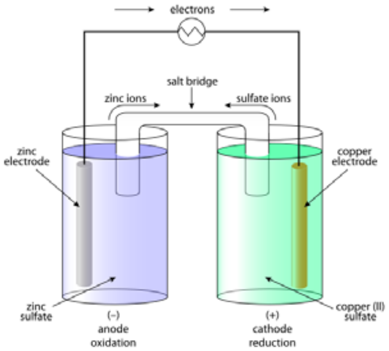


Figure 17. Drawing showing the principles of the electrochemical cell described above[35]

Numerous other reactions can be – and are - brought into electrochemical utilization. In the next sections, selected battery systems will be presented.

Battery cells can be divided in two groups: non-rechargeable cells – called primary – and chargeable cells – called secondary - and hence, secondary batteries can be used for electricity storage.

Battery cells can be characterized by their nominal voltage and their energy capacity. The cell voltage is low (usually below 4 V) but by connecting several cells in series the voltages are added, forming a battery pack to reach up to several hundred volts. In the same way, battery cells connected in parallel will add up the capacity.

Batteries can only be operated with direct current (DC), whereas nearly all power generators except solar power generate alternating current (AC). Therefore, mains AC electricity must be rectified and transformed to a suitable voltage level before applied for charging a battery. If the battery is used to power an AC-application, an inverter must transform the DC current from the battery. Both transformations result in energy losses.

The most common batteries on the market are lead-acid batteries, nickel metal hydride batteries and lithium-ion batteries.

---

[35] https://en.wikipedia.org/wiki/Galvanic_cell Accessed November 2018

11.2 Lithium ion batteries

Technology description

Most common lithium ion batteries (LIB) contain a graphitic anode (mesocarbon micro beads, MCMB), a cathode (lithium metal oxide or phosphate e.g. $LiCoO_2$) and an electrolyte consisting of a solution of a lithium salt (e.g. $LiPF_6$) in a mixed organic solvent (e.g. ethylene carbonate–dimethyl carbonate, EC–DMC) embedded in a separator felt[36]. Copper and aluminum current collectors are used at the anode and cathode for connecting to the external circuit. The external circuit carries electrons as charge and an internal circuit (electrolyte) have lithium ions as a charge carrier. During discharge, lithium ions intercalated in graphite anode is taken out, moved through the electrolyte and finally intercalated in the host material in the cathode (here $Li_{(1-x)}CoO_2$) as shown in Figure 18. The chemical bond between the cathode material and lithium is stronger than that between anode material and lithium. Thus, the chemical energy stored in the battery is reduced. The excess energy is released as electrochemical potential during discharge. This amounts to 3.7 V for the cathode-anode pair depicted in Figure 18 but would be different for other electrode pair (2.5-5 V)[37]. It drives one electron for each Li^+ ion moved from anode to cathode, through the external circuit. On the contrary, during the charging process, we provide electrical energy to drive lithium ions from cathode to anode, increasing the chemical energy of the system.

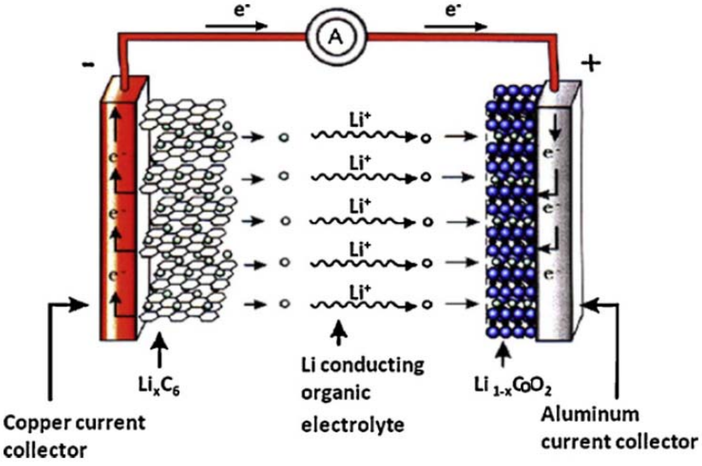


Figure 18: Schematic diagram of a common LIB system36.

Discharging:

$Li_xC_y \rightarrow yC + xLi^+ + xe^-$ (anode)

$Li_{(1-x)}CoO_2 + xLi^+ + xe^- \rightarrow LiCoO_2$ (cathode)

Charging:

---

[36] B. Scrosati and J. Garche, “Lithium batteries: Status, prospects and future,” J. Power Sources, vol. 195, no. 9, pp. 2419–2430, 2010.

[37] R. Marom, S. F. Amalraj, N. Leifer, D. Jacob, and D. Aurbach, “A review of advanced and practical lithium battery materials,” J. Mater. Chem., vol. 21, no. 27, p. 9938, 2011.

$yC + xLi^+ + xe^- \rightarrow Li_xC_y$ (anode)

$LiCoO_2 \rightarrow Li_{(1-x)}CoO_2 + xLi^+ + xe^-$ (cathode)

The charging and discharging of the LIB at the atomic level is linked to the shuttling mechanism of lithium ions between the anode and cathode side. The reversible insertion of lithium ions into the host materials at the anode and cathode is called intercalation.

The extent to which lithium ions are allowed to migrate from one electrode to another during charge/discharge processes is often referred to as state of charge (SoC)/depth of discharge (DoD). This is often controlled during battery operation to maintain structural stability of electrode materials i.e. maintain the cyclability. Phosphate based cathode materials can show better stability and longer cycle life compared to oxide cathode based LIB[38]. On the anode site, lithium titanium oxide can provide very high cycle life (~20000 cycles) compared to traditional graphite anode[39]. Long cycle life can provide better techno economics for LIB. Figure 19 visualizes different Li-ion battery configurations and the components within each configuration.

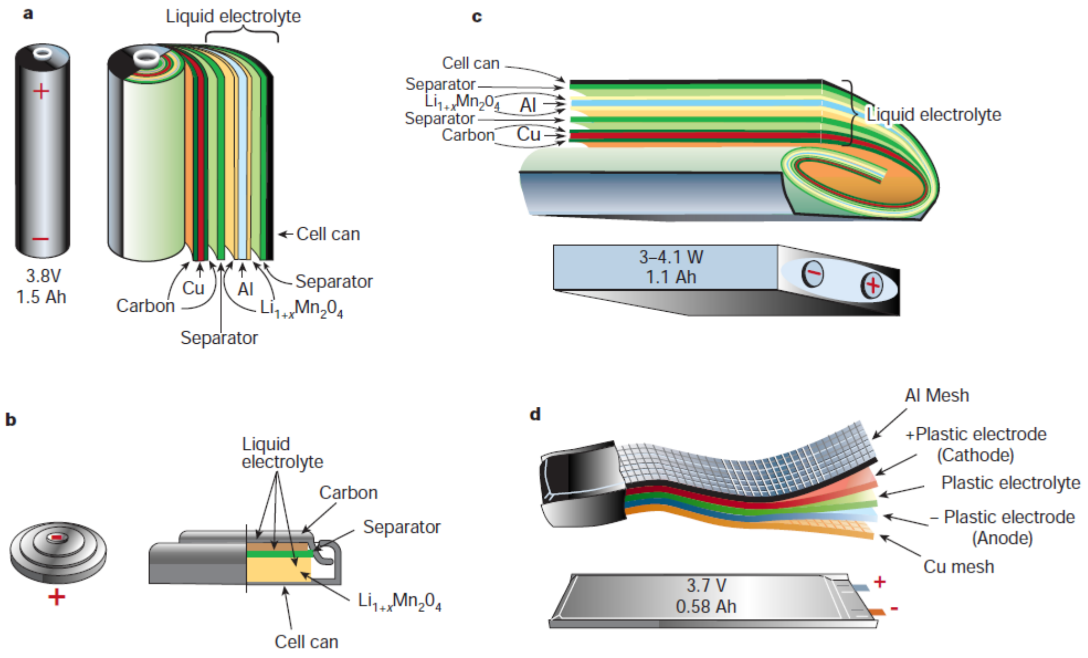


Figure 19. Schematic drawing showing the shape and components of various Li-ion battery configurations. (a) Cylindrical; (b) coin; (c) prismatic; and (d) pouch[40].

Applications

LIB based grid scale storage solutions are being used for a variety of operations including frequency regulation, load following, voltage support, time shifting, capacity firming of renewables etc. Among these, frequency regulation is of the highest priority and economic

---

[38] B. Diouf and R. Pode, “Potential of lithium-ion batteries in renewable energy,” Renew. Energy, vol. 76, no. 2015, pp. 375–380, 2015.

[39] http://kokam.com/data/Kokam_Cell_Brochure_V.3.pdf

[40] J. M. Tarascon and M. Armand, “Issues and challenges facing rechargeable lithium batteries.,” Nature, vol. 414, no. 6861, pp. 359–67, 2001

benefit. Storing energy for delivery during the time of usage with the highest electricity cost is also profitable and often termed as electric bill management (mainly applicable for households and smaller clusters of consumers). To synchronize generation assets for electrical grid operation, the alternating current (ac) frequency is regulated within tight tolerance bounds. This is achieved by adjusting supply to demand precisely within a matter of milliseconds. LIB is suitable due to the fast response, high power capability, long cycle lifetime at short partial cycles and low self-discharge rate). These are the fundamental requirements for primary frequency regulation service[41]. One of the best examples for such usage is the 13 MW/53 MWh system at Toronto prepared by Leclanché S.A. for Toronto Hydro Corp. This system is installed in 2016 and expected to provide service for 15 years. Figure 20 provides an example of supply regulation of a solar production facility using LIB based ESS.

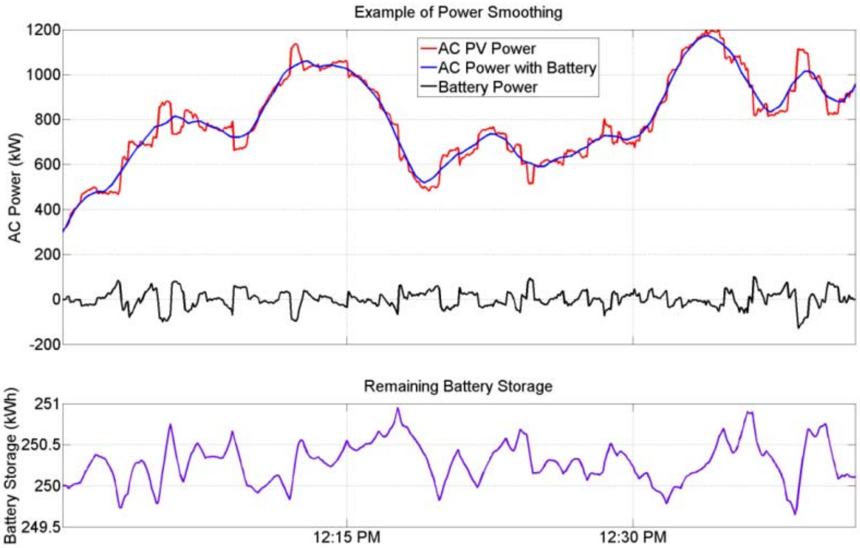


Figure 20. Supply regulation of solar production using LIB based ESS as studied by Sandia national laboratory[42].

The mismatch between demand cycle in the grid and the wind and solar power generation is adjusted by storing energy during low demand and supplying during peak demand (also here for smaller consumptions). Such usage of ESS leads to longer (usually 24 hours) and deeper charge discharge cycle. In Figure 21, ESS helps absorb excess solar energy production in daytime and discharging to meet the demand 12 hours later in the evening. While traditional sources feed to the baseload, ESS provides time shift capability to renewable resources to meet peak load in the morning and evening.

---

[41] D. Stroe, V. Knap, M. Swierczynski, A. Stroe, and R. Teodorescu, “Operation of a Grid-Connected Lithium-ion Battery Energy Storage System for Primary Frequency Regulation : A Battery Lifetime Perspective,” Ieee Trans. Ind. Appl., vol. 53, no. 1, pp. 430–438, 2017.

[42] J. Johnson, B. Schenkman, A. Ellis, J. Quiroz, and C. Lenox, “Initial Operating Experience of the La Ola 1.2 MW Photovoltaic System,” Sandia Rep., no. October, 2011.

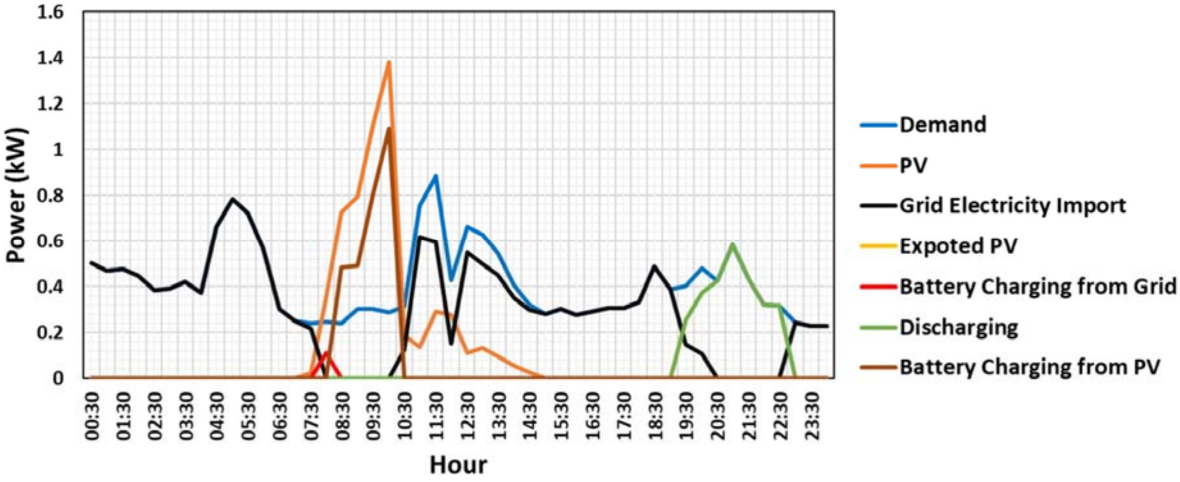


Figure 21. Daily time shift (simulated) using ESS[43].

At the generation side, wind and solar energy firms can benefit from ESS as it smoothes the output and controls the ramp rate (MW/min) to eliminate rapid voltage and power swings on the electrical grid. By onsite capacity control through buffer storage, generation firms can abide by delivery projection guidelines and avoid financial losses from fluctuation penalty. As presented in Figure 22, the storage systems either can be tied to each unit (many small battery systems) or centrally operated large ESS for the whole generation site. The economics of scale for the ESS, the feasibility of the control modules and the actual observed fluctuation needed to be considered for designing such ESS. It has been proven that a semi distributed (a combination of unit based and central storage) option is most optimal for ramp control[44].

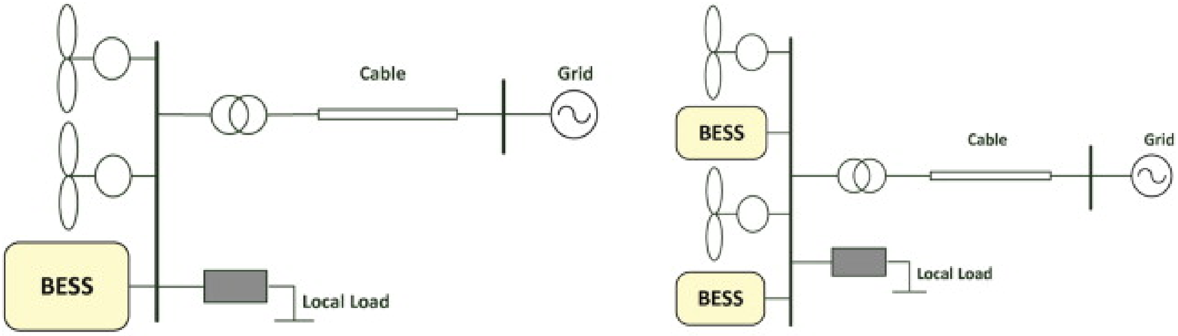
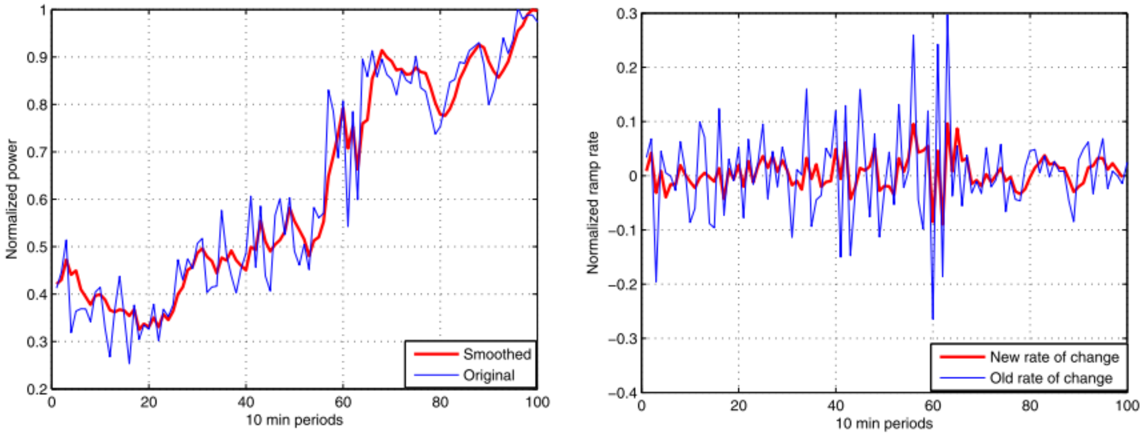


Figure 22. Two different models for generation side battery ESS44.

---

[43] A. Sani Hassan, L. Cipcigan, and N. Jenkins, “Optimal battery storage operation for PV systems with tariff incentives,” Appl. Energy, vol. 203, pp. 422–441, 2017.

[44] M. Khalid and A. V. Savkin, “Minimization and control of battery energy storage for wind power smoothing: Aggregated, distributed and semi-distributed storage,” Renew. Energy, vol. 64, no. 2014, pp. 105–112, 2014.



(a) Wind power smoothing (b) Ramp rate

Figure 23. Battery based ESS for wind power smoothing with a distributed architecture44.

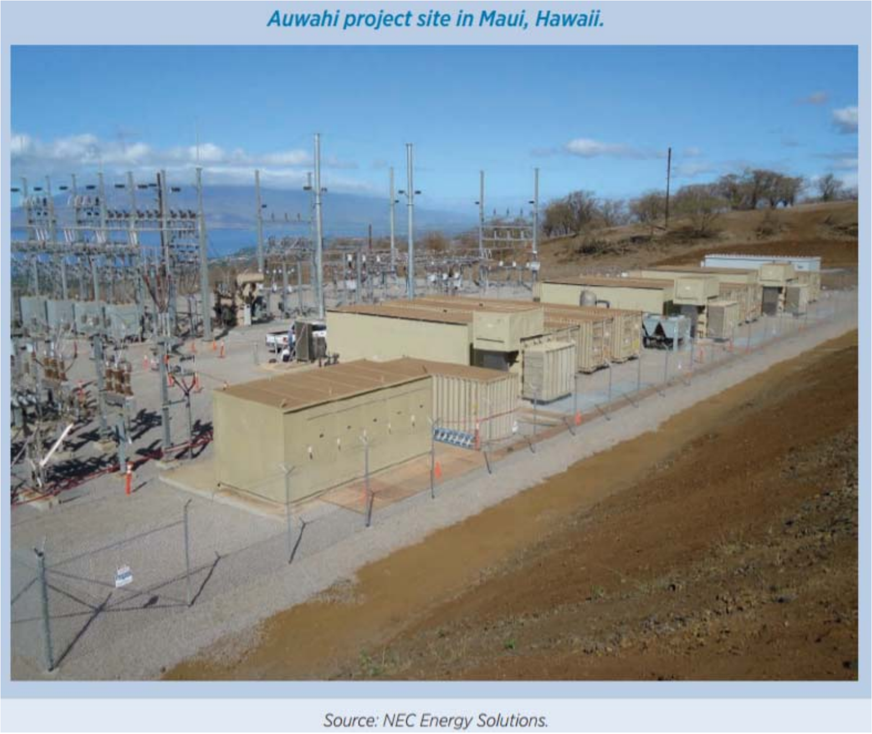
Existing policy and regulations impose a restriction on variability by requiring generator firms to provide accurate short term predictive delivery schedules with variability bounds. Large unexpected ramping leads to penalty, financial losses, and grid failure if it is heavily renewable energy dependent. Along with wind speed simulation forecasting, ESS with quick response time like LIB, can control the ramp very significantly and provide very good predictability of power generation capacity (Figure 23). As a specific case study, NEC Energy Solutions provided a lithium-iron phosphate battery in Maui, Hawaii (Figure 24), to smooth ramp rates in a 21 MW wind farm. The battery has a capacity of 11 MW/4.4 MWh. It was installed to manage wind farm ramp rates to comply with local interconnection requirements. The ramp rate limitation on Maui is in place to ensure local power grid stability by limiting feed-in variability of generating resources.

The efficiency of Li-ion battery cells can reach close to 100 %, which is especially useful for short cycle usage of the ESS[45],[46]. However AC-DC conversion and energy demand from the control electronics leads to a grid-grid efficiency (AC-AC) of about 85 % as observed in Maui, Hawaii site, where LIB is used for wind power smoothing. Frequency regulation or capacity management usage require fast short cycle charge-discharge and reduces round trip efficiency. While time shift application (cycling once in 24h) provides better efficiency.

---

[45] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, “Progress in electrical energy storage system: A critical review,” Prog. Nat. Sci., vol. 19, no. 3, pp. 291–312, 2009.

[46] K. C. Divya and J. Østergaard, “Battery energy storage technology for power systems—An overview,” Electr. Power Syst. Res., vol. 79, no. 4, pp. 511–520, Apr. 2009.


Auwahi project site in Maui, Hawaii.

Source: NEC Energy Solutions.

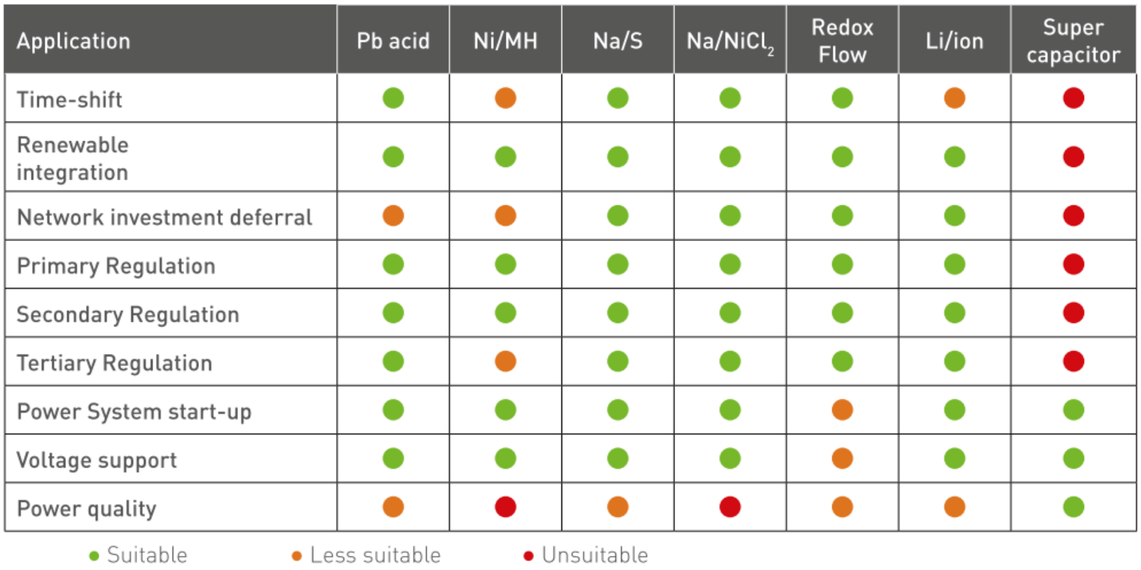
Figure 24. LIB based storage for onsite wind energy smoothing in Hawaii.

Lithium ion battery systems can be engineered to suit many grid services, due to the versatile nature of the power/energy/ramp characteristics. Full depth of discharge can be achieved within 10 minutes and power delivery ramping happens in millisecond time. This allows both power quality and power management usage. Also, scale up of 100 MW or more is possible as installed by AES energy and TESLA. Thus LIB based ESS is currently used for (a) black start (b) demand response (c) renewable distribution upgrade deferral (d) electric bill management (e) time shift (f) capacity firming (g) frequency regulation (h) load following (i) micro grid operation (j) ramping (k) voltage support etc.

Many of these functionalities and requirements have already been explained previously. Grid with generation assets that ramp slowly can greatly improve on the demand response by utilizing the fast power delivery capacity of LIB. Black start is the process of restoring an electric grid to operation without relying on the external transmission network after a failure. LIB based ESS in El Centro (30 MW) is the largest LIB installation for this purpose (Table 1) and is sometimes used to kick start large combined cycle natural gas plants. Wind generators at peak provide 5-8 times higher power than the average generation capacity. This might require an expensive upgrade in transmission and distribution infrastructure. Ramp management utilizing high power capacity of LIB leads to minimization of such expenses.

The possibility of proving full range of grid services through only LIB based ESS (Table 2. Comparison of different battery storage systems for key grid applications.) paves the path for self-sufficient renewable based micro grid operation in rural or areas of geographical isolation. For example, Blue Lake Rancheria a Native American reservation operates a micro grid with 950 kWh Tesla battery storage system and solar plants.

Table 2. Comparison of different battery storage systems for key grid applications[47].



Application	Pb acid	Ni/MH	Na/S	Na/NiCl$_2$	Redox Flow	Li/ion	Super capacitor
Time-shift	🟢	🟠	🟢	🟢	🟢	🟠	🔴
Renewable integration	🟢	🟢	🟢	🟢	🟢	🟢	🔴
Network investment deferral	🟠	🟠	🟢	🟢	🟢	🟢	🔴
Primary Regulation	🟢	🟢	🟢	🟢	🟢	🟢	🔴
Secondary Regulation	🟢	🟢	🟢	🟢	🟢	🟢	🔴
Tertiary Regulation	🟢	🟠	🟢	🟢	🟢	🟢	🔴
Power System start-up	🟢	🟢	🟢	🟢	🟠	🟢	🟢
Voltage support	🟢	🟢	🟢	🟢	🟠	🟢	🟢
Power quality	🟠	🔴	🟠	🔴	🟠	🟠	🟢

🟢 Suitable 🟠 Less suitable 🔴 Unsuitable

For very large scale and long-term storge (longer than hours to a few days), lithium battery systems remain very expensive (compared to solutions like pumped hydro), limiting the suitability. Grid power quality is dependent on the voltage, frequency, and the waveform. LIB as ESS is advisable for voltage and frequency regulation. Voltage distortion from the generators and current distortions from the loads create undesirable harmonics in the power supply network. Removing such harmonics require extremely high power density. Some LIB used at extreme discharge rates degrade the cell quickly. For this purpose, high power/low energy storages devices like supercapacitors are more suitable.

With LIB demand increasing exponentially every year, the supply of raw material and cost increment is a main concern. Lithium extraction has the potential for geopolitical risks because the world's known resources of easily extractable lithium are largely concentrated in three South American countries: Chile, Bolivia, and Argentina[48], but the limited availability of cobalt resources remains the biggest concern but is only relevant for NMC cells. LFP cells and LTO cells, which are lithium-ion battery chemistries also used for grid scale batteries, do not use cobalt.

Life time

Currently, commercial systems from Samsung SDI have 8000-cycle 15-year lifetime. More stable electrode materials (e.g. polyanion cathode and titanate anode) and better big data based management of battery systems are poised to bring at least 50% increase in cycle life and lifetime.

Cost

As the C-rate capacity of batteries increases to 10C by 2030, the regulation capacity will increase linearly (10C ramp vs C/2 operation) and power capacity investment cost will drop. Although module cost will decrease as suggested by Elon Musk CEO of TESLA Inc[49],

---

[47] O. Teller et al., "Joint EASE/EERA Recommendations for a European Energy Storage Technology Development Roadmap Towards 2030," p. 26, 2013.

[48] "Securing Materials for Emerging Technologies - THE APS PANEL ON PUBLIC AFFAIRS & THE MATERIALS RESEARCH SOCIETY," Mater. Res. Soc., vol. 103, no. 103, pp. 1–28, 2011.

[49] Elon Musk, https://twitter.com/elonmusk/status/840096176678420481

counterbalancing effects from more expensive engineering and further automation would keep installation cost and O&M cost (currently US$79/kWh) at a similar level or slightly higher. Power density will follow the improved energy capacity at same C-rate.

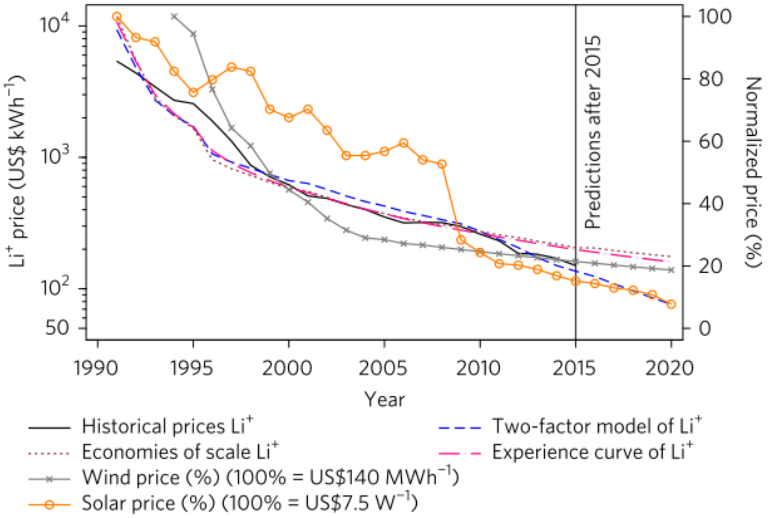


Figure 25. Exponential decrease in LIB prices along with renewable generation[50].

Better-negotiated prices than shown are most possibly accessible to project managers. On the other hand, charge discharge character might not be accessible at scale, when connected to the grid due to technical limitations.

Research and development perspectives

Due to the economic and technological impact, a wide range of government and industry-sponsored research is taking place across the world towards the improvement of LIB at material and system level. The following points in particular need attention:

- Higher energy density is achievable by discovering new cathodes with higher electrochemical potential and anode/cathode materials, which can intercalate more lithium per unit volume/weight.
- Higher electrochemical potential for the cathode material also need to be matched by the electrochemical stability of the electrolyte used with it. Thus, research in new electrolyte system is also needed. Electrolytes with better chemical stability also leads to lower chances of thermal runaway.
- Improved power capacity is obtained if lithium ion movement is faster inside the electrode and the electrolyte materials. In short, cathodes with high electrochemical potential, anode with low electrochemical potential, cathode/anode with high lithium capacity, electron/lithium transport, electrolyte with large electrochemical stability window and fast lithium transport is the desirable direction in LIB research.

Great progress has been made in the direction of new cathode materials and significant improvement has been achieved in terms of voltage and energy density (Figure 26). A nickel phosphate[51] based cathode can operate at 5.5 V (compared to 3.7 V of cobalt oxide cathodes),

---

[50] N. Kittner, F. Lill, and D. M. Kammen, "Energy storage deployment and innovation for the clean energy transition," Nat. Energy, vol. 2, no. July, p. 17125, 2017.

[51] J. Wolfenstine and J. Allen, "LiNiPO4-LiCoPO4 solid solutions as cathodes," J. Power Sources, vol. 136, no. 1, pp. 150–153, 2004.

but a complimentary electrolyte is not available. This limitation for overall battery chemistry is exemplified in Figure 26. On the anode side, silicon based anode can improve upon carbon based anodes for intercalation capacity by up to 10 times. But stability for long term operation has remained an issue[52]. On the electrolyte side, ionic liquids are being researched upon for safer high potential operation[53].

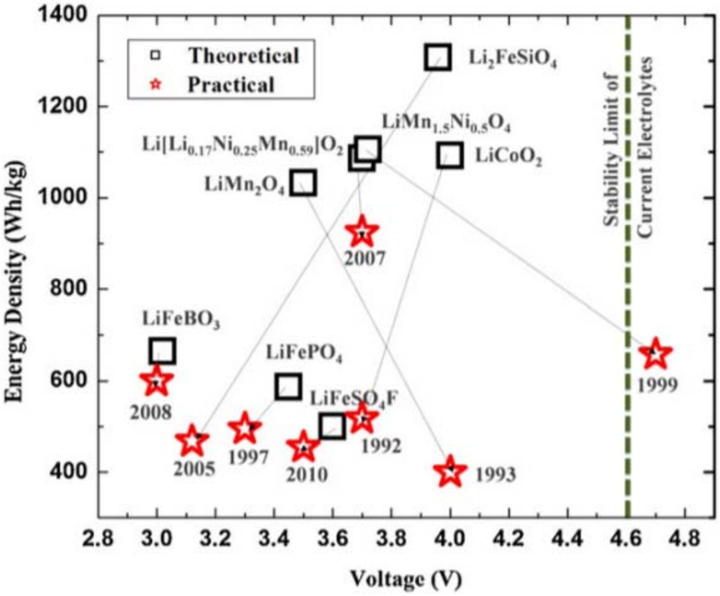


Figure 26. Development of new LIB cathodes and limitations from available electrolytes[54].

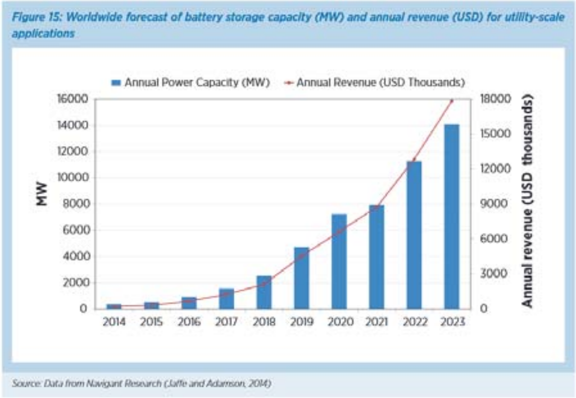


Figure 15: Worldwide forecast of battery storage capacity (MW) and annual revenue (USD) for utility-scale applications

Source: Data from Navigant Research (Jaffe and Adamson, 2014)

Figure 27**.** Worldwide forecast of battery storage capacity (MW) and annual revenue (USD) for utility-scale applications[55]

---

[52] C. K. Chan et al., “High-performance lithium battery anodes using silicon nanowires,” Nat. Nanotechnol., vol. 3, no. 1, pp. 31–35, 2008.

[53] M. Armand, F. Endres, D. R. MacFarlane, H. Ohno, and B. Scrosati, “ionic-liquid materials for the electrochemical challenges of the future,” Nat. Mater., vol. 8, no. 8, pp. 621–629, 2009.

[54] B. Xu, D. Qian, Z. Wang, and Y. S. Meng, “Recent progress in cathode materials research for advanced lithium ion batteries,” Mater. Sci. Eng. R Reports, vol. 73, no. 5–6, pp. 51–65, 2012.

[55] IRENA, “Battery Storage for Renewables : Market Status and Technology Outlook,” Irena, no. January, p. 60, 2015.

11.3 Na-S batteries

Technology description

Na-S batteries are secondary (i.e. rechargeable) batteries and are designed for system level applications. They are both power-intensive and energy-intensive. Na-S battery cells consist of a molten sodium anode, a molten sulfur cathode, and a β-alumina oxide solid state electrolyte (BASE) incased in a single tube. A schematic of a Na-S battery cell can be seen in Figure 28.

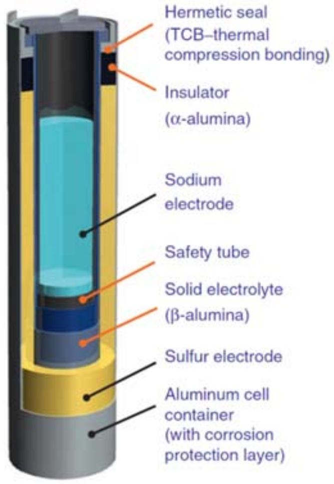


Figure 28: Schematic of a Na-S battery cell[56].

The reactions taking place during discharge on the cathode and anode sides of the battery are [57], [58]

$$2\ \mathrm{Na} - 2e^- \rightarrow 2\ \mathrm{Na}^+ \text{ (Anode)}$$

$$x\mathrm{S} + 2\ \mathrm{Na}^+ + 2e^- \rightarrow \mathrm{Na_2S_x}\ (x=3\sim5)\ \text{ (Cathode)}$$

During charge the reverse reaction occurs. A graphical schematic of the reaction process and the full cell reaction can be seen in Figure 29.

---

[56] NGK Insulators LTD, “Case Studies.” pp. 1–13, 2016.

[57] B. Dunn, H. Kamath, and J.-M. Tarascon, “Electrical Energy Storage for the Grid: A Battery of Choices,” Science (80-.)., vol. 334, no. 6058, pp. 928–935, 2011.

[58] J. Cho, S. Jeong, and Y. Kim, “Commercial and research battery technologies for electrical energy storage applications,” Prog. Energy Combust. Sci., vol. 48, pp. 84–101, Jun. 2015.

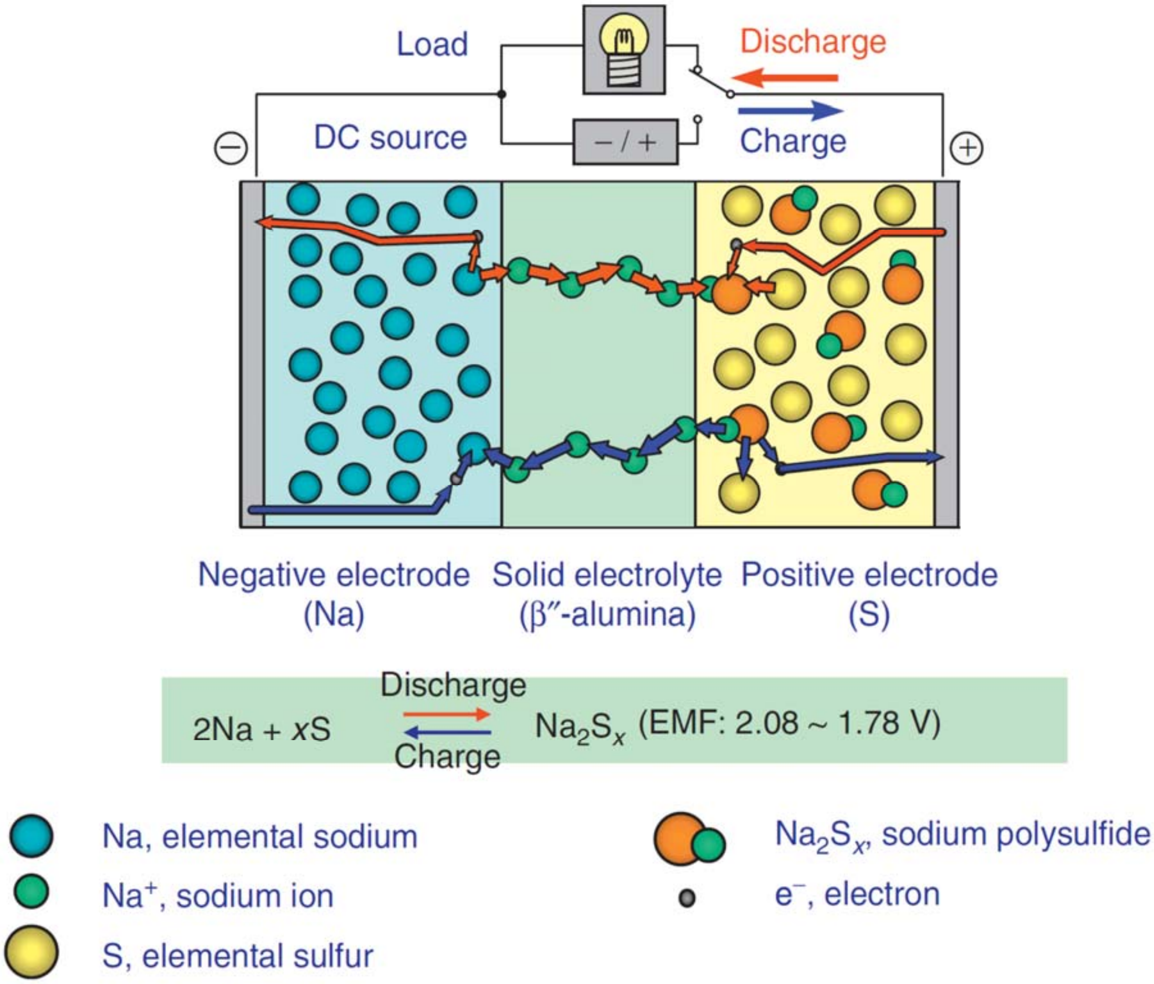


Figure 29: Graphical schematic of the reaction process and the full cell reaction. EMF: electromotive force56.

During continued discharge the value of x in Na_2S_x will gradually decrease and more sodium rich discharge products will be formed. The reaction occurs at a potential of 1.78 – 2.08 V at 350 °C depending on the state of battery charge. Relatively high temperatures (300-350 °C) are required for the reaction to take place. Elevated temperatures are required to keep the electrodes molten (98 °C for Na, 115 °C for S, and > 250 °C for Na_2S_x products[59]). A temperature of 300 °C or more is required to ensure sufficient Na ion conductivity through the BASE. The production of BASE has large impact on both battery performance and cost 58.

Cells are arranged in modules with thermal enclosures to minimize heat loss. An illustration of a module can be seen in Figure 30.

---

[59] J. Garche and C. K. Dyer, Encyclopedia of electrochemical power sources. Academic Press, 2009.

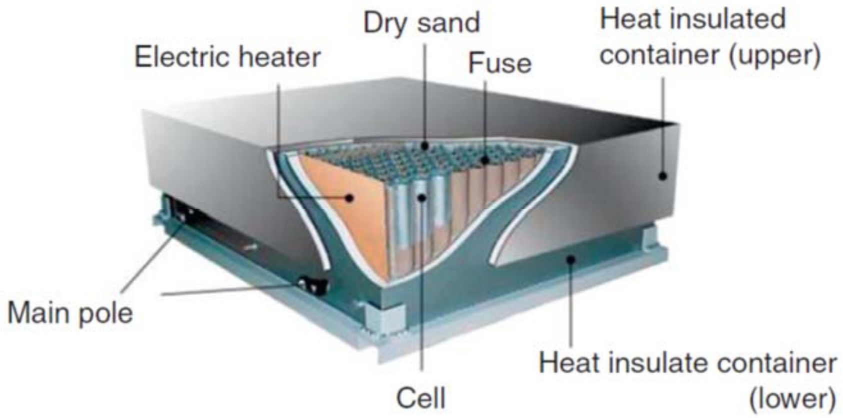


Figure 30: Illustration of Na-S battery module56

A Na-S battery installation consists of one or more Na-S battery units containing the battery modules (shown in Figure 30), a battery management system, and a power conversion system required to connect the batteries to the grid. A schematic and a picture of an older 1 MW Na-S battery installation can be seen in Figure 31.

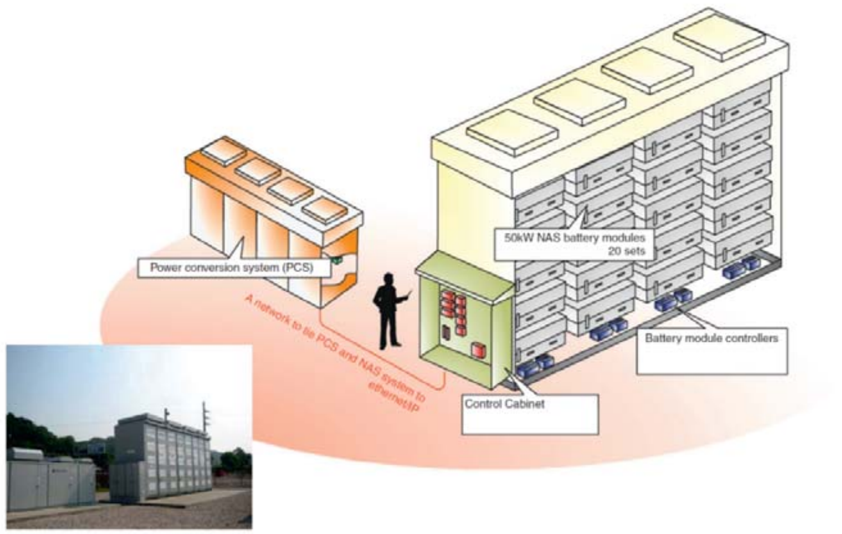


Figure 31: Schematic and picture of a 1 MW Na-S battery installation56

For a more detailed technology description the reader is referred to “Encyclopedia of Electrochemical Power Sources” [60].

Applications

Larger installations (34 MW – 50 MW and multi-MWh) are used for time shifting of production from renewable or conventional production plants. Smaller installations (400 kW

---

[60] R. Holze, “SECONDARY BATTERIES – HIGH TEMPERATURE SYSTEMS: Sodium-Sulfur,” in Encyclopedia of Electrochemical Power Systems, vol. 200, 2009, pp. 302–311.

– 8 MW) are used as back-up power, for off-grid applications, and for ancillary services [61], [62], [63].

Energy efficiency and losses

The heat loss from each battery module will be 2.2 – 4.0 kW56. This loss amounts to approximately 1 % per hour, and the Na-S batteries are thus not ideal for long term storage. During continued operation, which can include some hours of idle time, the Ohmic losses in the charge/discharge reaction will balance the heat loss 60. The heat loss should thus not be treated as an independent source of energy loss during operation as it is included in the battery efficiency. Simple air cooling is sufficient for maintaining temperature and build into standard battery units. The battery temperature should be maintained to prevent the electrodes from solidifying since freeze-thaw cycles significantly reduce battery lifetime[64].

Individual battery cells have been measured with efficiencies at 89 %64. The efficiency of a grid size battery unit including auxiliary losses has been measured to be 83 % for an Italian installation primarily used for time shifting 64. Reliable data for the efficiency in operation mode with constant power adjustment is not available for recently produced Na-S battery units.

Regulation ability and other system services

The response time (i.e. the time it takes for the battery to supply requested charge or discharge power) is according to the manufacture <1 ms at operation temperature [65]. Measurements find that the battery can change from full rated charging power to full rated discharging power in less than 50 ms 64. This is possibly limited by the power conversion system (PCS). Na-S batteries are able to provide energy pulses above rated discharge power for up to minutes at a time63. Pulses can be as large as 6 times rated power capacity for 30 s[66]. The other systems in the total installation, e.g., the PCS, and the grid connection must, however, be dimensioned accordingly for the pulse power capability to be utilized. This will increase cost.

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

Due to its short response time combined with relatively large storage and power capacity, Na-S batteries can provide a range of system services. NGK Insulators states: ”The NAS battery systems also provide additional functions, including primary reserve, secondary reserve, load balancing and voltage control.”61 .

---

[61] NGK Insulators LTD, “Case Studies.” pp. 1–13, 2016.

[62] “DOE Global Energy Storage Database.” [Online]. Available: https://www.energystorageexchange.org/. [Accessed: 29-Mar-2017].

[63] IEC, “Electrical Energy Storage,” 2011.

[64] M. Andriollo et al., “Energy intensive electrochemical storage in Italy: 34.8 MW sodium-sulphur secondary cells,” J. Energy Storage, vol. 5, pp. 146–155, Feb. 2016.

[65] NGK Insulators LTD, “Structure of NAS Energy Storage System,” 2016. [Online]. Available: https://www.ngk.co.jp/nas/specs/.

[66] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, “Progress in electrical energy storage system: A critical review,” Prog. Nat. Sci., vol. 19, no. 3, pp. 291–312, 2009.

Typical characteristics and capacities

Na-S battery installations come in two typical sizes. The larger installations used for time shifting have 34-50 MW capacity with 6-7.2 hours of storage capacity at full load (245-300 MWh). Information for three such installations are shown in Table 3.

Table 3. Smaller installations of up to 8 MW capacity have been installed during the last 20 years in 200 different locations61. In all cases the storage capacity corresponds to 6-8 hours of full power output capacity. As the batteries are highly modular, the installation size can easily be varied according to demand. The power capacity to storage capacity is, however, for currently available commercial products fixed at a ratio of 1:6-8 65.

Table 3: Larger Na-S battery installations 61, 64, [67].

Location	**Rokkasho village, Aomori, Japan**	**Campania Region (3 sites), Italy**	**Buzen City, Fukuoka, Japan**
			
Commissioned	2008	2015	2016
Storage capacity	245 MWh	250 MWh	300 MWh
Power capacity	34 MW	34.8 MW	50 MW
Energy density		<41.6 kWh/m^3*	26 kWh/m^3
Specific energy		<76 Wh/kg**	56 Wh/kg
Total land use	17.5 m^2/MWh	77 m^2/MWh	47 m^2/MWh

*Value for individual battery assembly units. ** Value for individual battery modules

New installations will for economic reasons likely consist of the standard commercially available units mentioned in [68]. NGK Insulators states that container type units as those used for the Buzen City installation will decrease construction time and cost compared to previous installations.

The lifetime in number of cycles for Na-S batteries depend on the usage. The number of cycles can be increased by utilizing less than the full storage capacity in each cycle as can be seen

---

[67] NGK Insulators LTD, "The World's Largest NAS Battery Installation Commences Operation Short Installation Period Achieved through Containerized, Compact Format," 2016. [Online]. Available: http://www.ngk.co.jp/english/news/2016/0303.html.

[68] NAS, Sodium Sulphur battery Energy Storage System, https://www.ngk.co.jp/nas/ Accessed January 2019

in Figure 32. The ratio of energy discharged from the battery relative to the fully charged state is referred to as the Depth of Discharge (DoD). At 0 % DoD the battery is fully charged. At 100 % DoD the battery is fully discharged.

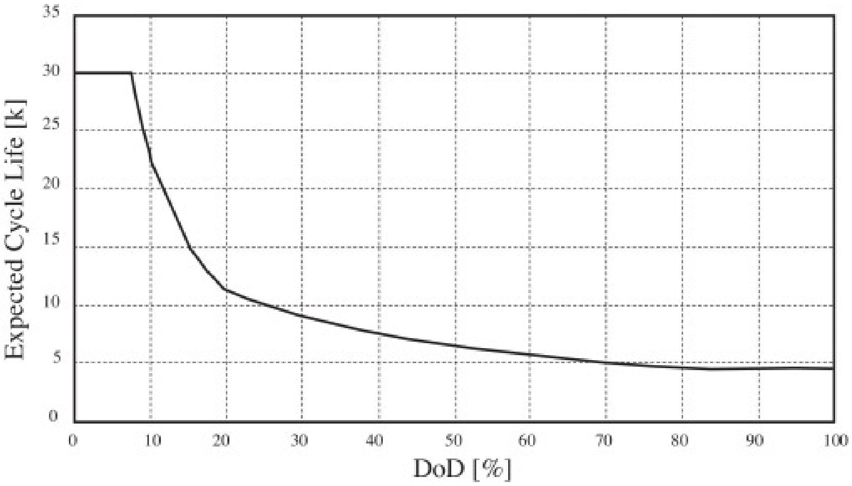


Figure 32: Expected number of cycles (in thousands) as function of Depth of Discharge (DoD) during cycles 64.

A Na-S battery used for time shifting with daily cycles of >80 % DoD will have an expected lifetime of 4500 cycles. If used for grid services, the average DoD will likely be smaller increasing the expected cycle lifetime. The technical lifetime is expected to be 15 years at a usage of 300 cycles at >80 % DoD per year [69], [70]. Longer technical lifetimes have not been reported. This is potentially due battery lifetime being limited by cycle lifetime during standard battery operation. An extended technical lifetime might not be obtainable by simply reducing the number of annual cycles or DoD for various reasons such as corrosion.

Advantages/disadvantages

Compared to many other batteries, Na-S batteries have the advantage that they a composed of inexpensive and abundant raw materials. Therefore, they have the potential to be very low cost and be manufactured on very large scale. Na-S batteries are well proven and developed for grid scale applications and have been commercially available for grid scale purposes for 15 years. They are well suited for energy intensive storage applications but can also be used for power intensive purposes. The cost per MW power capacity is, however, larger than for batteries mainly intended for power intensive applications. Na-S batteries have significant pulse power capabilities, i.e. they can operate at higher power than rated for short durations of time 60, 66.

Na-S batteries require high temperatures and should remain heated, as the battery can only survive a limited (in the order of 20) freeze-thaw cycles in which the temperature is lowered and the molten electrodes solidify 64. They are thus not suited for longer periods of idle storage with resulting heat losses but should ideally always be charging or discharging for optimal

---

[69] G. Huff et al., “DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA,” Rep. SAND2013- …, no. July, p. 340, 2013.

[70] NGK Insulators LTD, “Comparison of Battery Technologies | Why NAS? | NAS.” [Online]. Available: https://www.ngk.co.jp/nas/why/comparison.html. [Accessed: 13-Sep-2017].

utilization. The market for Na-S batteries is currently limited, due to only one commercial manufacturer existing. Due to the elevated temperatures and the highly reactive molten electrode materials, safety concerns and requirements are also higher for Na-S batteries than most other types of batteries. However, only one safety incident has been reported as a battery caught fire in 2011 58.

Research and development perspectives

It is not possible to quantify the full potential for improvements through R&D at the given time. The potential is however, estimated to be substantial in terms of both technical and financial specifications [71].

All critical components of the battery are undergoing active research. These include the BASE, the sealing materials, the sodium electrode, the sulfur electrode, and battery interfaces [72]. Research efforts are especially focused on geometry optimizations [73], [74] and improvement of Na ionic conductivity through the BASE [75]. New solid electrolytes to replace BASE are also being considered 71.

An alternative research route is to use the Na-S chemistry in a flow battery [76], [77].

Due to the similarity with Na-$NiCl_2$ batteries, synergies in research and development efforts can be expected.

Additional remarks

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

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

---

[71] O. Teller et al., “Joint EASE/EERA Recommendations for a European Energy Storage Technology Development Roadmap Towards 2030,” 2013.

[72] Z. Wen, Y. Hu, X. Wu, J. Han, and Z. Gu, “Main Challenges for High Performance NAS Battery: Materials and Interfaces,” Adv. Funct. Mater., vol. 23, no. 8, pp. 1005–1018, Feb. 2013.

[73] G. Kim, Y.-C. Park, Y. Lee, N. Cho, C.-S. Kim, and K. Jung, “The effect of cathode felt geometries on electrochemical characteristics of sodium sulfur (NaS) cells: Planar vs. tubular,” J. Power Sources, vol. 325, pp. 238–245, Sep. 2016.

[74] S. I. Kim, W. Il Park, K. Jung, and C.-S. Kim, “An innovative electronically-conducting matrix of the cathode for sodium sulfur battery,” J. Power Sources, vol. 320, pp. 37–42, Jul. 2016

[75] K. . Ahlbrecht, C. Bucharsky, M. Holzapfel, J. Tübke, and M. J. Hoffmann, “Investigation of the wetting behavior of Na and Na alloys on uncoated and coated Na-β”-alumina at temperatures below 150 °C,” ionics (Kiel)., pp. 1–9, Mar. 2017.

[76] X. Yu and A. Manthiram, “Ambient-Temperature Sodium-Sulfur Batteries with a Sodiated Nafion Membrane and a Carbon Nanofiber-Activated Carbon Composite Electrode,” Adv. Energy Mater., vol. 5, no. 12, pp. 1–6, 2015.

[77] X. Yu and A. Manthiram, “Performance Enhancement and Mechanistic Studies of Room-Temperature Sodium–Sulfur Batteries with a Carbon-Coated Functional Nafion Separator and a Na 2 S/Activated Carbon Nanofiber Cathode,” Chem. Mater., vol. 28, no. 3, pp. 896–905, Feb. 2016.

11.4 Na-NiCl$_2$ batteries

Technology description

Na-NiCl2, or Sodium-nickel chloride, batteries are secondary (i.e. rechargeable) batteries. They are also known as ZEBRA (Zeolite Battery Research Africa Project) batteries. They are applicable for both power-intensive and energy-intensive electrical energy storage. They can be used on both grid level and for mobile applications such as electric and hybrid vehicles.

Na-NiCl$_2$ batteries are similar to the more mature Na-S batteries. The key components of a Na-NiCl$_2$ battery cell are the molten sodium anode, a ceramic β-alumina oxide solid state electrolyte (BASE), and a porous cathode, where the reactant is NiCl$_2$. The cathode also contains liquid NaAlCl$_4$ to obtain sufficient ionic conductivity[78], [79]. A schematic of a cell can be seen in Figure 33.

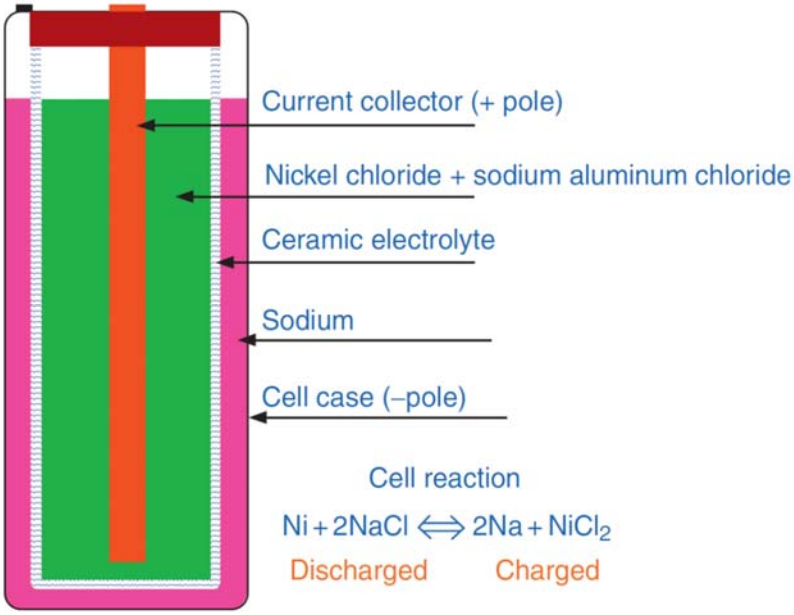


Figure 33: Schematic of Na-NiCl$_2$ battery cell. The “Ceramic electrolyte” is BASE[80].

A picture of five connected cells and the components used to manufacture a cell can be seen in Figure 34.

---

[78] J. L. Sudworth and R. C. Galloway, “SECONDARY BATTERIES – HIGH TEMPERATURE SYSTEMS | Sodium–Nickel Chloride,” in Encyclopedia of Electrochemical Power Sources, 2009, pp. 312–323.

[79] Z. Yang et al., “Electrochemical Energy Storage for Green Grid,” Chem. Rev., vol. 111, no. 5, pp. 3577–3613, May 2011.

[80] J. L. Sudworth and R. C. Galloway, “SECONDARY BATTERIES – HIGH TEMPERATURE SYSTEMS | Sodium–Nickel Chloride,” in Encyclopedia of Electrochemical Power Sources, 2009, pp. 312–323.

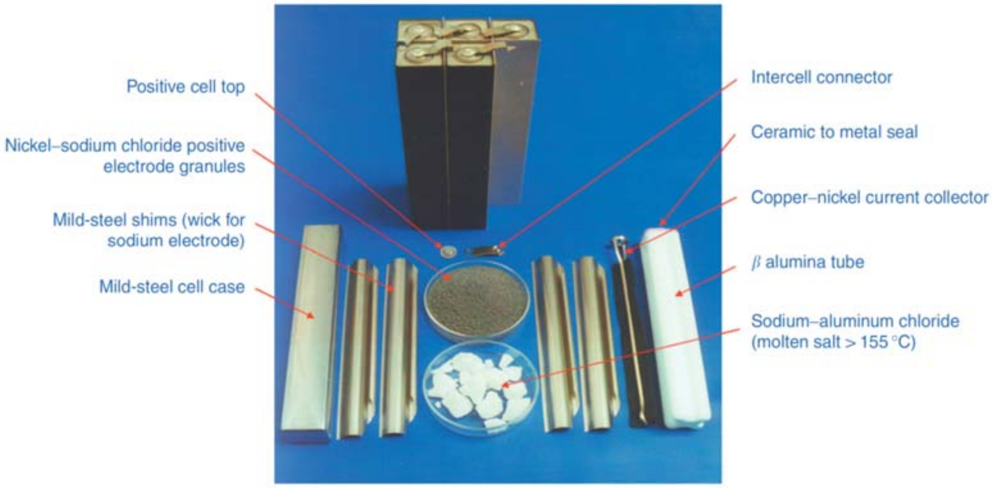


Figure 34: Na-NiCl$_2$ battery cell components80.

Cells are assembled in a fully discharged state. This allows the sodium to be supplied in the form of NaCl as can be seen from the discharge reaction:

$$2\ \mathrm{Na} - 2e^- \rightarrow 2\ \mathrm{Na}^+\ \text{(Anode)}$$

$$\mathrm{NiCl_2} + 2\ \mathrm{Na}^+ + 2e^- \rightarrow 2\ \mathrm{NaCl} + \mathrm{Ni}\ \text{(Cathode)}$$

$$2\ \mathrm{Na} + \mathrm{NiCl_2} \rightarrow 2\ \mathrm{NaCl} + \mathrm{Ni}\ \text{(Full Cell)}$$

During charge the reverse reaction occurs. The reaction has a full cell potential of 2.58 V at 300 °C. The operating temperature is 250 °C to 350 °C to ensure sufficient Na ionic conductivity through the BASE[81]. A lower limit operation temperature of 150 °C is required to maintain liquid NaAlCl$_4$80. An illustration of the charging reaction can be seen in Figure 35.

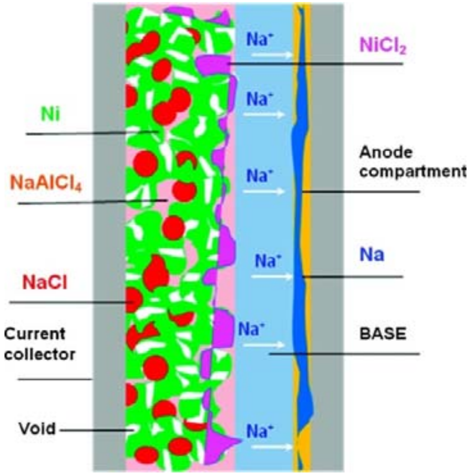


Figure 35: Illustration of Na-NiCl$_2$ charging process78.

---

[81] R. Benato et al., “Sodium nickel chloride battery technology for large-scale stationary storage in the high voltage network,” J. Power Sources, vol. 293, pp. 127–136, 2015.

The battery cells are connected in battery units with thermal insulation, heating and cooling systems, and various control systems. Battery modules can be combined in larger battery units for grid scale applications. Current commercial grid scale units are shown in Section "Examples of market standard technology". A grid scale Na-$NiCl_2$ battery installation consists as a minimum of a unit containing the battery modules, a battery management system, and a power conversion system required to connect the batteries to the grid.

For a more detailed technology description the reader is referred to "Encyclopedia of Electrochemical Power Sources" 80.

Energy efficiency and losses

Heat loss is reported to be less than 0.6 % of total energy storage capacity per hour for a 17.8 kWh battery module and less than 0.3 % of total storage capacity per hour for a 35.7 kWh battery module80. The heat loss depends on the specific assembly unit. Heat loss in large battery installations consisting on multiple assembly units, e.g. identical container assembly units, each containing multiple battery modules is expected to scale approximately linearly with installation size. The heat loss in percentage of total energy storage capacity is thus approximately independent of total installation size. During continued operation, which can include some hours of idle time, the Ohmic losses in the charge/discharge reaction will balance the heat loss. The heat loss should thus not be treated as an independent source of energy loss during operation as it is included in the battery efficiency. Simple air cooling is sufficient for maintaining temperature during operation and build into standard battery units.

Na-$NiCl_2$ batteries can be repeatedly cooled to ambient temperatures and reheated, i.e. undergo so-called freeze-thaw cycles, without any decrease to battery lifetime80, 81, [82]. Typical time scales are days to solidify during cooling and tens of hours to liquidize during reheating[83]. Na-$NiCl_2$ batteries should remain heated during shorter idle periods.

At grid scale battery operation, the DC efficiency of a Na-$NiCl_2$ module has been measured to 90 %[84]. A 0.5 MW Na-$NiCl_2$ battery unit has been measured to 89 %81. Auxiliary losses, e.g., from cooling account for approximately 2 %84.

Regulation ability and other system services

Standard recharging is slower than discharging the battery, i.e. the standard charging input will be lower than the rated output capacity. Commercial data states 6-8 hours to recharge a battery with 3 hour capacity at rated discharge capacity81, [85]. Fast recharge at a rate equal to or above the rated output power is possible at the cost of decreased energy efficiency and accelerated battery degradation86. At low charge/discharge rates (approximately 1/3 of rated

---

[82] G. L. Soloveichik, "Battery Technologies for Large-Scale Stationary Energy Storage," Annu. Rev. Chem. Biomol. Eng, vol. 2, pp. 503–27, 2011.

[83] B. Parkhideh, "Project : Storage Technologies for Hybrid Electric Buses - Subject : ZEBRA Battery," 2006.

[84] M. Pietrucci, "Progetti Pilota Power Intensive: Descrizione degli impianti e delle tecnologie," 2017.

[85] FZSoNick, "DATASHEETS," 2017. [Online]. Available: http://www.fzsonick.com/en/emea/energy-storage/prodotti/spring,-mod-164,-324.aspx.

power) the full battery energy storage[86] capacity can be used. At rated power output only 80 % of storage capacity should be utilized to prevent accelerated degradation81.

The response time (i.e. the time it takes for the battery to supply requested charge or discharge power) is stated to be 20 ms[87] and measured to be less than 1 second when the battery is operational81. The response time from non-operational mode with the battery at operating temperature takes 45 seconds81.

Given the necessary power conversion system (PCS) equipment etc. is installed, Na-$NiCl_2$ batteries are able to provide energy pulses of up to at least 3 times rated power capacity for periods measured as long as 30 min but with storage capacity reduced by a factor of two compared to rated discharge rate81. The effect of such operation on battery lifetime is not known.

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

Na-$NiCl_2$ batteries can provide a range of system services. The manufacturer FZSoNick states the following applications: Load levelling, power quality, renewable resource optimization, and utility grid ancillary services85.

Typical characteristics and capacities

The energy density and specific energy calculated for the Energy Spring 164 system from FZSoNick85 (See Figure 37) is 32.8 kWh/m^3 and 56 Wh/kg, respectively.

The storage period for Na-$NiCl_2$ batteries depends on the operation of the batteries and can range from minutes to hours.

Research and development perspectives

It is not possible to quantify the full potential for improvements through R&D at the given time. The potential is however, estimated to be substantial in terms of both technical and financial specifications [88].

All critical components of the battery are undergoing active research. These include the BASE, the sealing materials, the sodium electrode, the cathode, and battery interfaces. Research efforts are especially focused on geometry optimizations and improvement of Na ionic conductivity through the BASE. New solid electrolytes to replace BASE are also being considered88.

---

[86] M. Hosseinifar and A. Petric, “Effect of High Charge Rate on Cycle Life of ZEBRA (Na/NiCl 2) Cells,” J. Electrochem. Soc., vol. 163, no. 7, pp. A1226–A1231, 2016.

[87] T. V Rachel Carnegie Douglas Gotham David Nderitu Paul Preckel, “Utility Scale Energy Storage Systems,” 2013.

[88] O. Teller et al., “Joint EASE/EERA Recommendations for a European Energy Storage Technology Development Roadmap Towards 2030,” 2013.

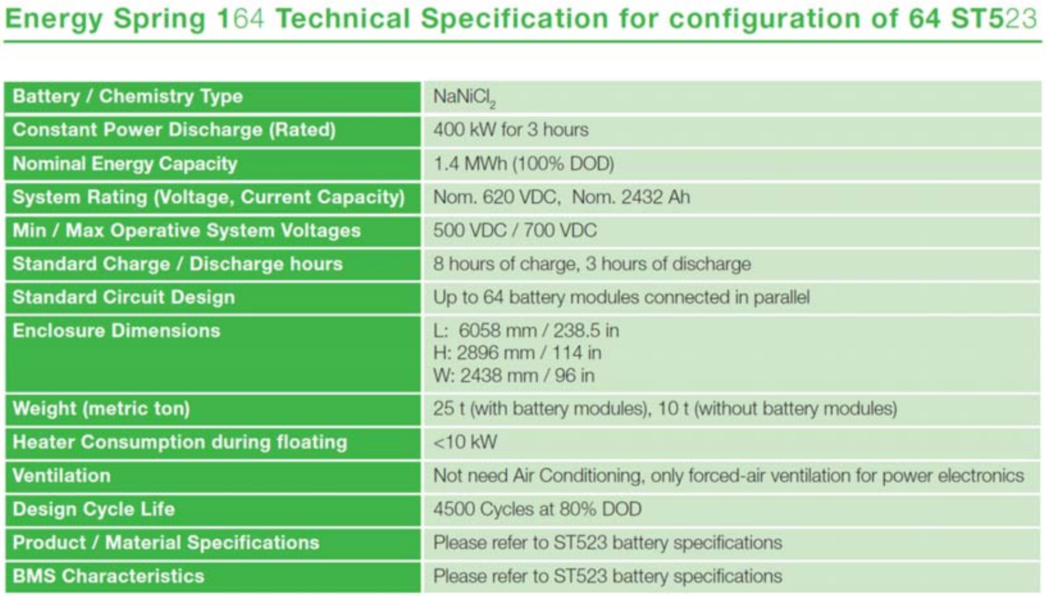
Research is also going into slightly changed chemistries which would change the battery characteristics significantly79, [89].

Due to the similarity with Na-S batteries, synergies in research and development efforts can be expected.

Examples of market standard technology

FZSoNick, a subsidiary of FIAMM, is the only currently trading commercial manufacturer of Na-NiCl$_2$ batteries85. Illustration and technical specifications available at below referenced URL are presented for a grid scale assembly unit in Figure 36 - Figure 37. Units are highly modular and can be combined to an installation of desired size.

Figure 36: Energy Spring 164 system from FZSoNick85.



Energy Spring 164 Technical Specification for configuration of 64 ST523

Battery / Chemistry Type	NaNiCl$_2$
Constant Power Discharge (Rated)	400 kW for 3 hours
Nominal Energy Capacity	1.4 MWh (100% DOD)
System Rating (Voltage, Current Capacity)	Nom. 620 VDC, Nom. 2432 Ah
Min / Max Operative System Voltages	500 VDC / 700 VDC
Standard Charge / Discharge hours	8 hours of charge, 3 hours of discharge
Standard Circuit Design	Up to 64 battery modules connected in parallel
Enclosure Dimensions	L: 6058 mm / 238.5 in H: 2896 mm / 114 in W: 2438 mm / 96 in
Weight (metric ton)	25 t (with battery modules), 10 t (without battery modules)
Heater Consumption during floating	<10 kW
Ventilation	Not need Air Conditioning, only forced-air ventilation for power electronics
Design Cycle Life	4500 Cycles at 80% DOD
Product / Material Specifications	Please refer to ST523 battery specifications
BMS Characteristics	Please refer to ST523 battery specifications

Figure 37: Specifications for Energy Spring 164 system from FZSoNick85.
http://www.fzsonick.com/media/369733/20161221_energy-spring-164_datasheet-a4.pdf

---

[89] X. Lu et al., “Liquid-metal electrode to enable ultra-low temperature sodium–beta alumina batteries for renewable energy storage,” Nat. Commun., vol. 5, pp. 5884–5901, Aug. 2014.

Additional remarks

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

Even though Na-$NiCl_2$ batteries have high commercial potential, rapid cost reduction of alternative storage solutions, e.g. Li-ion batteries could halter commercial deployment and technological development of Na-$NiCl_2$ batteries. This can prevent Na-$NiCl_2$ batteries from reaching full commercial potential.

11.5 Vanadium Redox Flow Battery (VRB)

Technology description

Vanadium redox flow batteries also known simply as Vanadium Redox Batteries (VRB) are secondary (i.e. rechargeable) batteries. VRB are applicable at grid scale and local user levels.

VRB are the most common flow batteries. A flow battery consists of a reaction cell stack, where the electrochemical reactions occur, at least one storage tank filled with electrolyte (anolyte) consisting of reactants in solution for the negative battery electrode, i.e., the anode, at least one storage tank filled with electrolyte (catholyte) consisting of reactants in solution for the positive battery electrode, i.e., the cathode, piping connecting the storage tanks with the reaction cell stack, and mechanical pumps to circulate the electrolytes in the system. A schematic of a traditional flow battery can be seen in Figure 38. The region bordered by the grey electrodes is the reaction cell stack.

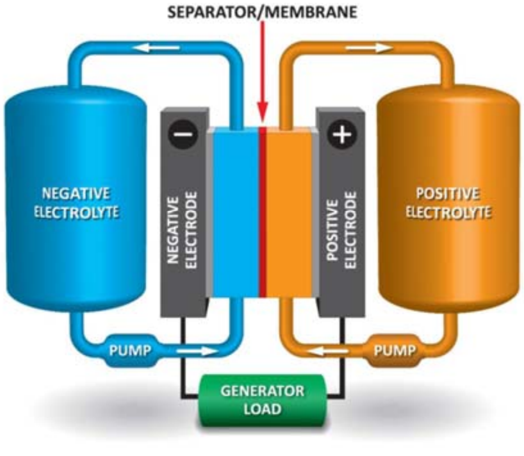


Figure 38: Schematic of flow battery[90].

---

[90] M. Manahan, N. Jewell, D. Link, and B. Westlake, “Program on Technology Innovation: Assessment of Flow Battery Technologies for Stationary Applications,” EPRI, 2016.

The anolyte reactive species are V^{2+} and V^{3+} ions. The catholyte reactive species are VO_2^+ and VO^{2+} ions with the V atom in oxidation state +5 and +4, respectively. Traditionally, the reactive species have been dissolved with concentrations of 1.5 - 2 M in aqueous sulfuric acid solutions with an acid concentration of 2-5 M [91].

When pumped into the reaction cell the anolyte and catholyte will be separated by a proton conducting (polymer) membrane. An illustration of reaction cell components and a full reaction stack can be seen in Figure 39.

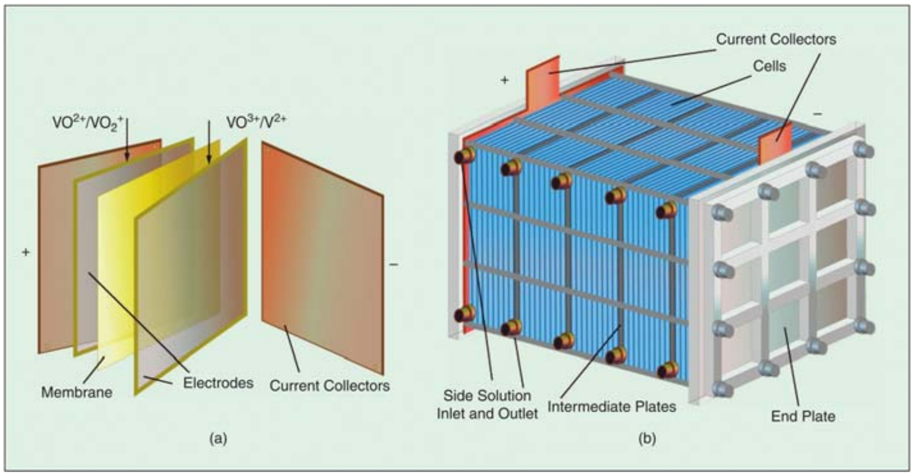


Figure 39: a) Reaction cell. b) Typical stack91.

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

$$V^{2+} \rightarrow V^{3+} + e^- \qquad \text{(Anode side reaction)}$$

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

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

During charge the reverse reaction occurs. The full reaction provides a cell voltage of 1.26 V. The battery operates at ambient temperatures.

Flow batteries are different from other batteries by having physically separated storage and power units. The volume of liquid electrolyte in storage tanks dictates the total battery energy storage capacity while the size and number of the reaction cell stacks dictate the battery power

---

[91] M. Guarnieri, P. Mattavelli, G. Petrone, and G. Spagnuolo, “Vanadium Redox Flow Batteries: Potentials and Challenges of an Emerging Storage Technology,” IEEE Ind. Electron. Mag., vol. 10, no. 4, pp. 20–31, 2016.

capacity. The energy storage capacity and power capacity can thus be varied independently according to desired application and customer demand91.

Applications

A VRB installation consists, as a minimum, of a VRB unit as described above, a battery management system, and a power conversion system connecting the battery unit to the grid. For a more detailed technology description the reader is referred to "Encyclopedia of Electrochemical Power Sources"[92].

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

Due to its short response time combined with the ability to independently vary installation size of energy storage capacity and power capacity, VRB installations can provide a range of system services. The manufacturer UniEnergy Technologies lists the following applications for grid and utility installations: T&D deferral (avoid need to upgrade transmission and distribution equipment), flex capacity/ramping, load shifting, and ancillary services[93] .

Examples of recently commissioned grid-scale VRB installations are listed Table 4

Location	**Yokohama, Japan**	**Hokkaido, Japan**	**Braderup, Germany**	**Pullman, Washington, USA**
Commissioning year	2012	2016	2014	2015
Energy Storage Capacity	5 MWh	60 MWh	1 MWh	4 MWh
Power Capacity	1 MW	15 MW	325 kW	1 MW
Technology provider	Sumitomo Electric Industries	Sumitomo Electric Industries	UniEnergy Technologies	UniEnergy Technologies

Table 4: Selected grid-scale VRB installations 93, [94], [95].

At least 21 different installations of minimum 100 kW have been commissioned since 201195. The 21 installations have been supplied by at least 8 different manufactures. A 200 MW/800 MWh installation is currently under construction in Dalian in China.

---

[92] M. Skyllas-Kazacos, "SECONDARY BATTERIES – FLOW SYSTEMS | Vanadium Redox-Flow Batteries," in Encyclopedia of Electrochemical Power Sources, 2009, pp. 444–453

[93] UniEnergy Technologies, Product material: Maximizing Value Thorugh UET Energy Storage. 2015.

[94] Sumitomo Electric Group, REDOX FLOW BATTERY: Product material. 2016.

[95] "DOE Global Energy Storage Database." [Online]. Available: https://www.energystorageexchange.org/ Accessed: November 2018.

In comparison to other grid-scale batteries, VRB and other flow batteries have the significant advantage that the energy storage capacity and power capacity can be varied independently and optimized for a specific application. In contrast to molten sodium batteries (Na-S and Na-$NiCl_2$) also applicable for grid scale applications, VRB operate at ambient temperatures. The reactants in a VRB are in a solution. This allows the full energy storage capacity of the battery to be utilized without battery degradation in contrast to batteries where charge/discharge products are solid state90 . VRB have long technical lifetime in comparison to other batteries. Current batteries are reported by multiple manufactures to have unlimited cycle lifetime within the technical lifetime (up to 20 years). Due to the large technical and cycle lifetime compared to other batteries, VRB have the lowest levelized cost of storage (€/kWh per cycle) among grid scale batteries91. VRB also have the advantage that the electrolytes can easily be recycled and reused90. As vanadium is the active specie in both anolyte and catholyte, leakage of reactants from one electrolyte into the storage container of the other electrolyte will, in contrast to other flow batteries, not result in electrolyte contamination but only loss of energy storage capacity. The energy storage capacity can be regained by re-balancing the volume and vanadium content of the two electrolyte solutions90. VRB are by manufacturers promoted as being very safe[96].

VRB and other flow batteries have relatively low grid-to-grid energy efficiencies in comparison to other batteries. This is a consequence of losses related to mechanical pumping of electrolyte, undesired electrical currents known as shunt currents, which allows electrons to bypass the external circuit, and leakage of reactant vanadium ions through the reaction cell membrane. Even though the energy density and specific energy for VRB have recently increased, they remain relatively low in comparison to other batteries 90, [97].

Research and development perspectives

VRB are under rapid development. There is significant potential for R&D to reduce cost of all battery components[98], [99]. An example is research in use of non-aqueous electrolytes91. The minimum cost will, however, likely be limited by the vanadium cost. The vanadium cost is not fixed in the sense that there is a potential for use of lower cost vanadium sources in production than those traditionally used 90 .

There is a significant potential for cost reduction of flow batteries by using alternative reaction chemistries, i.e., other redox couples than vanadium. Grid scale redox flow batteries could potentially be based on, e.g., organic compounds or zinc-bromide, bromide-polysulphide, iron-chromium, and zinc-chloride99.

---

[96] UniEnergy Technologies, Product material: Maximizing Value Thorugh UET Energy Storage. 2015.

[97] J. Cho, S. Jeong, and Y. Kim, “Commercial and research battery technologies for electrical energy storage applications,” Prog. Energy Combust. Sci., vol. 48, pp. 84–101, Jun. 2015

[98] L. Baumann and E. Boggasch, “Experimental assessment of hydrogen systems and vanadium-redox-flow-batteries for increasing the self-consumption of photovoltaic energy in buildings,” Int. J. Hydrogen Energy, vol. 41, no. 2, pp. 740–751, 2016.

[99] O. Teller et al., “Joint EASE/EERA Recommendations for a European Energy Storage Technology Development Roadmap Towards 2030,” 2013.

11.6 Other flow batteries

Inorganic flow batteries

VRB as mentioned above is the most used flow battery chemistry, but other chemistries can be used in other types of inorganic flow batteries. Thus, the Iron-Chromium system can be utilized for flow batteries according to:

the discharge reactions: $Cr^{2+} \rightarrow Cr^{3+} + e^-$ and $Fe^{3+} + e^- \rightarrow Fe^{2+}$

and the charge reactions: $Cr^{3+} + e^- \rightarrow Cr^{2+}$ and $Fe^{2+} \rightarrow Fe^{3+} + e^-$

American EnerVault operates a large Fe-Cr battery (250 kW/1 MWh) in California[100]. A photo indicating the size of the electrolyte containers is seen in Figure 40.

Figure 40. Photo of the EnerVault installation in California 100.

Similarly the Zn-Br system can be utilized according to:

the discharge reactions: $Zn_{(s)} \rightarrow Zn^{2+}_{(aq)} + 2\ e^-$ and $Br_{2\ (aq)} + 2\ e^- \rightarrow 2\ Br^-_{(aq)}$ and

the charge reactions $Zn^{2+}_{(aq)} + 2\ e^- \rightarrow Zn_{(s)}$ and $2\ Br^-_{(aq)} \rightarrow Br_{2\ (aq)} + 2\ e^-$

Zn-Br flow batteries are provided by several manufacturers and footnote [101]

- Primus Power - Hayward, California, USA
- RedFlow Limited - Brisbane, Australia
- Smart Energy - Shanghai, China
- EnSync (Formerly ZBB) - Menomonee Falls, Wisconsin, USA
- ZBEST Power - Beijing, China

---

[100] http://enervault.com/turlock/ Accessed January 2019

[101] https://en.wikipedia.org/wiki/Zinc%E2%80%93bromine_battery Accessed January 2019

Organic Flow Batteries

Also organic materials have been used for flow batteries. The aim is to use cheap organic materials and thereby lower overall battery costs. An example of such organic materials used in a flow battery system is shown in Figure 41.

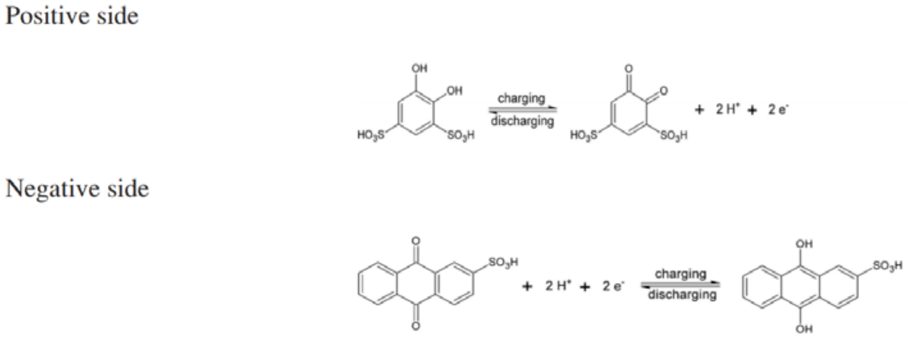


Figure 41. Aqueous all-organic Redox Flow battery based on the quinone molecular structure[102]

11.7 Lithium-sulfur batteries

The lithium-sulfur battery is one of the very promising new battery chemistries, which are currently being developed.

The lithium-sulfur battery has a voltage around 2.2V and is interesting because of the potentially high practical specific energy, estimated to 400-600 Wh/kg at cell level. This is around twice the capacity of present-day lithium ion batteries. The volumetric energy density will be similar to lithium-ion batteries[103].

---

[102] An Inexpensive Aqueous Flow Battery for Large-Scale Electrical Energy Storage Based on Water-Soluble Organic Redox Couples, B. Yang, L. Hoober-Burkhardt, F. Wang, G. K. Surya Prakash and S. R. Narayanan, Journal of The Electrochemical Society, 161 (9) A1371-A1380 (2014)

[103] “Metal-based nanostructured materials for advanced lithium–sulfur batteries”, J. Balach, J. Linnemann, T. Jaumann and L. Giebeler, J. Mater. Chem. A, 2018, 6, 23127–23168

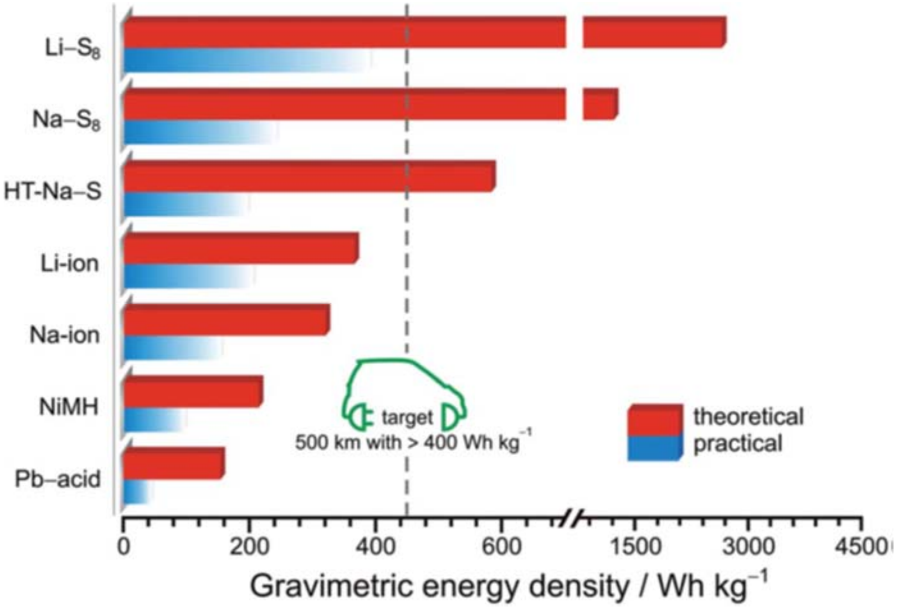


Figure 42. Schematic comparison of the theoretical and practical gravimetric energy densities of various rechargeable battery systems. Expected mid-class to small electric car range based on reported Tesla Model S and Audi e-tron performances[103].

The Li-S battery is a conversion type battery (in contrast to a lithium-ion intercalation type battery) and work by reaction between elemental lithium and sulfur:

$S_8 + 16\ Li \leftrightarrow 8\ Li_2S$

utilizing the half reactions: $S_8 + 16\ Li^+ + 16\ e^- \leftrightarrow 8\ Li_2S$

$16\ Li \leftrightarrow 16\ Li^+ + 16\ e^-$

The electrolyte in the lithium-sulfur battery is typically ether-based organic with e.g. LiTFSI as the electrolyte salt. The reactions in the Li-S battery are similar to the high temperature sodium-sulfur battery, however, the lithium-sulfur battery works at room temperature in a battery cell. The cell design is comparable to that for lithium-ion battery cells.

One of the challenges in development of Li-S batteries is self-discharge and capacity loss due to migration of lithium polysulfide species which are formed as intermediate products during discharge and which are highly soluble in the organic electrolyte, Figure 43. The polysulfides may diffuse from the positive to the negative electrode where they are reduced, resulting in a reversible or irreversible loss of capacity. Development of improved electrolyte formulation, electrode structuring, confinement of sulfur and the use of solid state electrolytes are some of the efforts for counteracting the polysulfide shuttle effect.

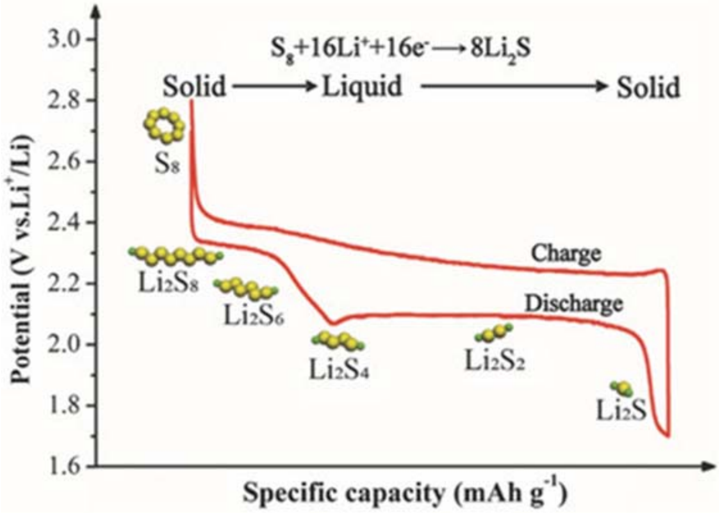


Figure 43. A typical charge/discharge profile for a Li-S battery[104]. During discharge polysulfide species are formed.

11.8 Metal-air batteries

Metal-air batteries can obtain very high theoretical energy densities and capacities, since they do not rely on heavy intercalation electrodes, but instead on pure metal anodes. On the positive side of the metal air battery there is only an air cathode that contributes to the weight, as the oxygen participating in the cathode reactions can be supplied from outside the battery. The resulting electrochemical device is very light in its charged state but will gain weight during discharge as it consumes oxygen. Capacities are therefore generally given as open or closed, with the latter including the weight of oxygen.

The Al- and Mg-air batteries have very high theoretical energy densities, as seen in Figure 44, due to the relatively low weight of these metals and the fact that the number of electrons transferred is 3 and 2, respectively.

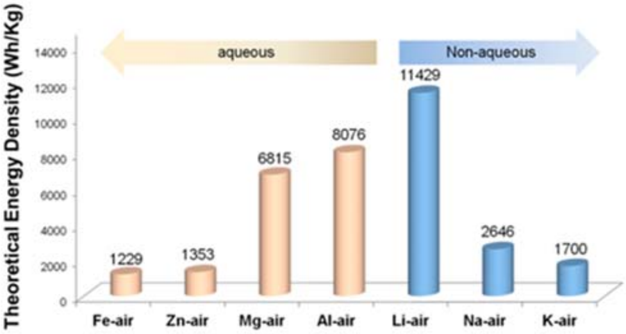


Figure 44[105]. Theoretical energy densities of different metal-air batteries

---

[104] "More Reliable Lithium-Sulfur Batteries: Status, Solutions and Prospects", R. Fang, S. Zhao, Z. Sun, D.-W. Wang, H.-M. Cheng, and F. Li, Adv. Mater. 2017, 29, 1606823

[105] Metal-air batteries: Will they be the future electrochemical energy storage device of choice? Yanguang Li and Jun Lu. ACS Energy Letters, 2(6):13701377, 2017

The Li-O_2 battery has a capacity which is nearly comparable to gasoline's, and has attracted a lot of attention. Even with the promising properties of these batteries, they are not available commercially.

The zinc-air battery can be considered as one of the most successful metal-air batteries, as it has seen widespread application as a primary battery for hearing aids and other low-current devices. The Zn-material has a theoretical specific energy of 1086 Wh/kg including oxygen and 1353 Wh/kg for the pure material, which is almost 3 times higher than current lithium-ion batteries. Practical applications of Zn-air batteries report values between 350-500 Wh/kg105. Furthermore, Zn is very abundant, has a low cost of 2USD/kg, compared[106] to Li at 8 USD/kg (in 2010), and it can be fully recycled. The theoretical discharge potential is 1.65V, but practical values are lower due to overpotentials.

Thus far, electrical recharging of these batteries is a challenge that can be circumvented by mechanically replacing the anode or using a flow system, in which case it could be considered as a zinc-air fuel cell[107].

Zn-air batteries convert O_2 and Zn during discharge to create ZnO. During charge the ZnO is split, oxygen is emitted from the battery and Zn is redeposited. This process requires the use of an air electrode that employs a catalyst to split O_2. The overall reaction is:

$$2\ Zn + O_2 \leftrightarrow 2\ ZnO$$

One reason that rechargeable zinc-air batteries have not yet reached commercial applications is that the charging process poses difficulties, which cannot easily be bypassed.

11.9 Batteries based on cheap and abundant materials

The more batteries are used and the wider the application areas, the more are concerns about scarcity of materials and environmental issues popping up. Until now, real problems have probably not been seen. Even for Li-ion systems batteries the Li is still supplied from natural sources and re-use of Li simply does not yet pay off.

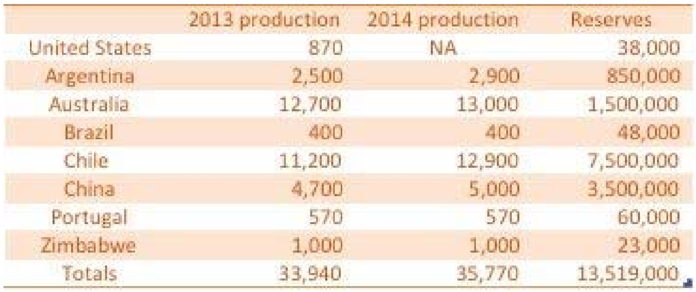
Early 2015 the U.S. Geological Survey made an estimation of the world´s lithium reserves. The conclusion was that there is enough known reserves for about 365 years of current (2014) global production of about 37,000 tons per year - see Figure 45[108].

---

[106] Note that Zn/Li atomic weight ratio is approx. 9.4 and that Zn utilizes two an Li only one electron in the reactions and thus the “price per electron” is almost the same for the two materials

[107]. Zinc-air fuel cell, a potential candidate for alternative energy. Prabal Sapkota and Honggon Kim, Journal of Industrial and Engineering Chemistry, 15(4), 445-450, 2009.

[108] https://www.greentechmedia.com/articles/read/Is-There-Enough-Lithium-to-Maintain-the-Growth-of-the-Lithium-Ion-Battery-M Accessed February 2019



	2013 production	2014 production	Reserves
United States	870	NA	38,000
Argentina	2,500	2,900	850,000
Australia	12,700	13,000	1,500,000
Brazil	400	400	48,000
Chile	11,200	12,900	7,500,000
China	4,700	5,000	3,500,000
Portugal	570	570	60,000
Zimbabwe	1,000	1,000	23,000
Totals	33,940	35,770	13,519,000

Figure 45. USGS Mining and Reserves Data (Metric Tons)

Taking the vigorous expansion of Li-ion battery use since 2014 into consideration, this projection is naturally no longer reliable, but – as mentioned – reuse of Li has not yet found substantial commercial application and thus a considerable “reserve” is available from Li-ion batteries after end of life.

Nevertheless, researchers are searching for new battery chemistries based on cheap and abundant materials and actually, some of the chemistries mentioned above comply to this – e.g. Na-S, Zn-air and organic flow batteries. Yet other members of this class are (e.g.):

- Aqueous Hybrid Ion (AHI) Batteries (saltwater battery) based on intercalation of alkali metals in manganese oxide and marketed by Aquion Energy
- Edison battery based on Ni and Fe. Invented about 1900 and maybe finding new applications[109]. However, it should be noted that “revolutionary” results from battery research are frequently published without practical impact so far.

11.10 Battery case story: Tesla mega-battery in Australia

Batteries installed to provide ancillary services to electricity grids are penetrating all over the world in grids with high share of intermittent, fluctuating electricity supply. A well-known example is the 100 MW/129 MWh battery installed near Jamestown, South Australia, with Tesla as the battery technology provider. The installation is based on commercial agreements112. Two photos of the installation are seen in Figure 46.

Figure 46. The Tesla mega-battery in Australia [110] and [111].

---

[109] https://www.wired.co.uk/article/ultrafast-nickel-iron-battery Accessed February 2019
[110] https://www.bbc.com/news/world-australia-42190358 Accessed January 2019
[111] https://electrek.co/2017/12/19/tesla-battery-save-australia-grid-from-coal-plant-crash/ Accessed January 2019

The battery is more precisely rated[112] at 100 MW discharge and 80 MW charge, and has a storage capacity of 129 MWh (approx. 75 min full discharge). According to the AEMO (Australian Energy Market Operator Limited) the battery is connected to the same 275 kV network connection point as the 300 MW Hornsdale Wind Farm.

AEMO informs112 "*that under normal conditions, 30 MW of the battery's discharge capacity is made available to the wind farm operator for commercial operation in the National Electricity Market (NEM). Of the battery's total 129 MWh energy storage capacity, 119 MWh may be used for this mode of operation.*

The remaining 70 MW of battery discharge capacity is reserved for power system reliability purposes. This 70 MW reserve capacity has not been dispatched to date. Under arrangements with the South Australian government, this capacity is offered into the NEM at the Market Price Cap, ensuring this component of the battery will not be dispatched ahead of other generation in South Australia."

AEMO has found that the battery responds much better to the central Automatic Generation Control set-point than conventional steam turbines in terms of accuracy and speed of regulation. However, the higher quality of the regulation function is not remunerated in the present market structure. Still AEMO notes, that "*care would be required in establishing new markets, or modifying the assessment of frequency response capabilities in the NEM, to consider the current complex interactions between the dispatch of FCAS and energy in the NEM, the potential need to maintain technology neutrality, and the potential for limited competition in the delivery of any newly defined services".*

The battery has shown its potential to be profitable by earning an estimated 800,000 USD in a few days by responding to a crashed coal plant (loss of 560 MW nearly 1,000km away) in milliseconds[113]. In a wider perspective, the battery has contributed to the removal of the requirement for a 35 MW local Frequency Control Ancillary Service, saving nearly $40 million[114] per year in typical annual costs.

The application of the Tesla mega-battery described above gives an indication of how commercial applications of batteries may be most profitable, namely by delivering a mix of services. Some part of the battery´s potential and capacity can be reserved for grid ancillary services (maintaining frequency, voltage, short-circuit power, etc.) and another for stabilization of the output of a wind farm or balancing reactive or real power. Such mixed services also mean mixed profit sources and may provide considerably better business cases that just selling and buying electricity depending on price variations.

11.11 General technical and economic status of batteries

Lead-acid technology is still the most widely used electrochemical battery system[115], used in numerous applications from back up for uninterruptible power supplies and grid energy

---

[112] Initial operation of the Hornsdale Power Reserve Battery Energy Storage System, AEMO (Australian Energy Market Operator Limited), 2018

[113] https://electrek.co/2018/01/23/tesla-giant-battery-australia-1-million/ Accessed January 2019

[114] https://www.advancedbatteriesresearch.com/articles/16181/australian-battery-saves-40-million-in-its-first-year Accessed January 2019

[115] https://www.eurobat.org/batteries-contribution/battery-technologies/lead-based. Accessed January 2019

storage, to traction in battery electric vehicles and for starting, lighting and ignition (SLI) in conventional combustion engine vehicles. However, since Li-ion battery technology is rapidly penetrating the market for vehicle traction and grid stabilization and since EVs do not use dedicated start batteries, some of the dominating applications for lead-acid technology are vanishing in the years to come and in a few decades, lead-acid batteries may well have had their days in energy storage.

Since 2014, applications for Li-ion technology have almost exploded following a significant drop in prices and supported by excellent properties of the batteries, in particular including much longer lifetimes of batteries. Li-ion shows the highest energy density of all rechargeable battery systems operating at room temperature and furthermore they show relatively high power density, a high cell voltage and user-friendly features. A strong market pull and a widening of application areas have vigorously driven the present commercial status of different Li-ion batteries and part of the reason is found in Figure 47, where the energy densities of different battery chemistries are shown. Energy density is important in many battery applications.

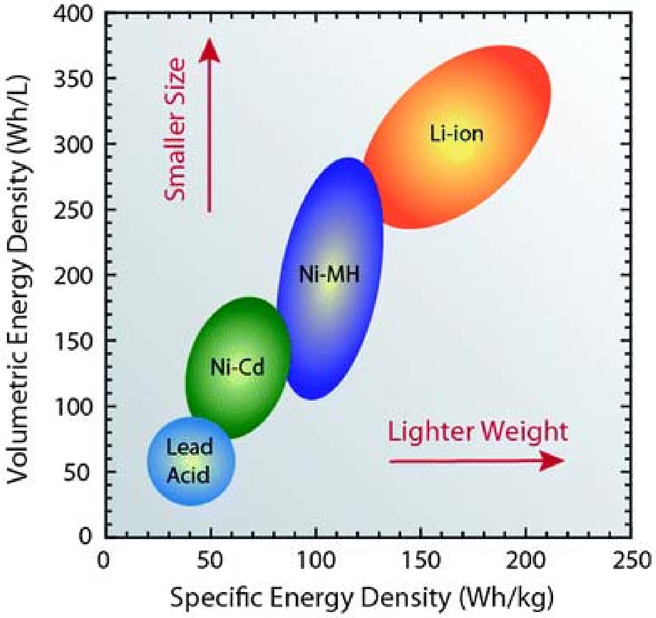


Figure 47[116]. Volumetric and gravimetric energy densities of well-known battery types

One important and exploding application of Li-ion technology is for traction in electric vehicles, EVs, and ships/ferries. In such e-mobility applications, however, improvements are still strongly needed for energy density, lifetime and safety. Perhaps the most important need for improvement is on energy density, where batteries hold 1-2 orders of magnitude lower energy density on weight basis, than chemical fuels similar to the fossil fuels used for more a century. However, the low-hanging fruits of pushing the energy density of Li-ion batteries have probably been harvested and it is likely difficult to increase the number substantially in the future. Higher energy densities in batteries must be found in completely new battery chemistries like metal-air or Li-sulphur batteries. By use of the best metal-air systems even aviation applications could be theoretically achievable.

In stationary applications, an explosion has happened too. While in 2014 stationary Li-ion batteries were installed by TSOs and DSOs on a test basis, such batteries are now installed

---

[116] https://www.epectec.com/batteries/cell-comparison.html Accessed January 2019

on commercial terms by balance responsible entities as well as by DSOs and TSOs. In addition, single consumers, who combine with roof top solar power installations in behind-the-meter applications, now buy stationary batteries. Examples of such batteries are multiple from European suppliers although the most well-known and hyped stationary battery for domestic use probably is the Tesla Powerwall systems.

For stationary batteries (e.g. UPS, residential PV/windmill storage, sub-grid ESS, power grid ESS and energy ESS) lifetime and cost are major issues. Lead-acid, NiMH, NaS, lithium-ion, zebra and flow battery technologies may all serve in large stationary energy storage systems but the need for long calendar lifetime, low cost per cycle, high round-trip efficiency, low self-discharge and O&M cost as well as high C-rates in auxiliary services point at lithium-ion already by now.

In energy storage system applications improvement on calendar and cycle life is needed. For both applications, the price is a major issue and an extended temperature range is desirable.

The large mobile energy consumers are transport devices (mopeds, cars, buses, trucks, off-road vehicles and ships/ferries) but also the market for portable devices - phones, laptops, GPS, electric hand tools, grass mowers and similar products - is not expected to drop in the years to come.

11.12 Status for batteries in industry and research in Denmark

Battery research has been peaking at Danish universities in recent years and a number of Danish companies are using, consider using or focusing on implementing batteries in commercial products. Four Universities and ten professional companies have formed Danish Battery Society[117] to share knowledge within research and applications of batteries. The primary purpose of DBS is to ensure knowledge sharing between Danish companies and research institutions active on RD&D within the battery area. Research within battery technology in Denmark is mainly led by university groups with thorough knowledge at international level within few and narrow niches. Danish Battery Society acts as a catalyst for joining national forces to improve international competitiveness.

Danish Universities perform battery research into energy materials (including cell chemistry) as well as materials processing. Studies are done in international collaboration via EU-funded projects and in projects supported by Danish funding authorities. Focus areas are primarily within new battery chemistries, but also within improving properties of existing technologies like Li-ion. Thus, new systems like Li-sulphur, Li-air and Zn-air batteries are studied to improve energy density, power density, durability and stability and solve problems about recharging, but also cheap flow batteries, based on cheap organic materials, are in focus. For more well-known systems research is done to identify better materials for Li-ion batteries, to model thermal properties of battery systems and develop better thermal management technologies for Li-ion batteries.

The research at Danish universities is done in close collaboration with companies and technological service organisations. Thus Lithum Balance, Danish Technological Institute and Vestas take substantial part in on-going research projects on development, modelling and use of batteries.
Vestas has experience from operation of grid-connected batteries over several years and has engaged in several R&D projects on better batteries for support to wind power.

---

[117] http://batteriselskab.dk/. Accessed January 2019.

Radius/Ørsted in 2017 inaugurated a large Li-ion battery facility in Copenhagen (Nordhavn) holding 460 kWh and providing max. 630 kW. The battery has been supplied by ABB.

Ørsted itself by January 2019 inaugurated their first project on commercial terms within battery storage[118] in the UK. It consists of three battery containers, all together 20 MW, as well as the associated power conversion system, all supplied by NEC.

Ørsted was also involved when publicly-owned power generation and grid utility SEV installed storage in conjunction with a 12MW Húsahagi[119] wind farm north of Tórshavn[120]. This was Europe's first commercial use of lithium-ion energy storage to support a wind farm. The system was supplied by Saft and is able to store 700kWh combined with a 2.3 MVA power-conversion system made by Enercon. The system was installed in spring 2016 and has been in operation since then, primarily to mask the effects of rapid changes in output on the local grid as the wind picks up or dips.

Topsoe A/S is looking into electrode production for battery manufacturing. Topsoe manufactures LNMO ($LiNi_{0.5}Mn_{1.5}O_4$) cathode material - a cobalt-free high-voltage (5 V) material for use in next-generation lithium-ion rechargeable batteries.

Lithium Balance is offering advanced battery management systems for automotive and stationary systems. Integrators of batteries can find assistance from Universities, Danish Technological Institute and the battery suppliers.

The products of the large Danish industry for hearing aids rely completely on efficient, energy-dense battery systems able to supply sufficient energy for the hearing device. Until now such batteries have not been rechargeable. GN ReSound is a member of the Danish Battery Society.

Since 2013 Scandlines has been operating hybrid diesel/battery ferries at the Rødby-Puttgarten connection between Denmark and Germany. The latest additions from 2016 – the ferries Berlin and Copenhagen - are two new-built hybrid 1500-passenger and 480-car ferries, each integrating a 1.5 MWh Corvus battery system into their hybrid electric propulsion systems[121]. The battery systems allow the diesel engines to operate at their most efficient power levels during harbor maneuvering and docking. Hybrid propulsion in the Puttgarden-Rødby ferries has reduced CO_2 emissions by up to 15% per crossing, or approximately 15,000 tons CO_2 annually.

Since November 2018, HH Ferries (now ForSea) has been operating the battery-driven ferries Tycho Brahe and Aurora between Helsingør (DK) and Helsingborg (S). Each ferry has a battery capacity of 8.32 GWh and charging in the harbour is done by a fully automated, laser-controlled robot arm, which connects the batteries to the grid. ABB has supplied the entire system[122].

---

[118] https://orsted.com/en/Media/Newsroom/News/2019/01/Orsteds-first-standalone-battery-storage-project-now-complete. Accessed January 2019.

[119] https://w3.sev.fo/framleidsla/ Accessed February 2019

[120] https://eandt.theiet.org/content/articles/2016/11/lithium-ion-batteries-can-help-to-safeguard-the-grid/. Accessed January 2019

[121] https://corvusenergy.com/scandlines-shares-experiences-with-hybrid-and-electric-ferry-technology/ Accessed February 2019

[122] https://csr.dk/f%C3%A6rger-p%C3%A5-batteri-mellem-helsing%C3%B8r-og-helsingborg Accessed February 2019

Thus, Danish R&D in batteries and battery-related topics is blooming these years, within existing battery chemistries as well as within new, promising battery chemistries of the future. Many Danish manufacturers of materials and equipment for batteries have joined the Danish Battery Association (Dansk Batteriselskab).

11.13 Status in other European countries

Battery manufacturing and to some extent battery research has taken place in East Asia and in the USA, where – not to forget - Tesla and GM build on Panasonic and LG technologies respectively. However, over the latest decade Europe has managed to re-establish a strong R&D environment supported by the European Commission as well as national R&D programmes in the member states. Currently, new giga-factories are underway in Sweden and Germany. Thus, in Germany the Daimler subsidiary Accumotive is building a $550 million plant designed to take annual lithium-ion battery production from its current level of 80,000 units up to around 320,000[123]. In north of Sweden, Northvolt is building another Li-ion battery factory. The first quarter will be completed in 2020 and the factory will at that point produce 8 GWh worth of battery capacity per year. The total target is 32 GWh/year. Several other factories – not all aiming for Li-ion technology – are planned123 within Europe as well as outside.

Presently, there are a few Li-ion manufacturers in Europe, the largest is SAFT Batteries in France, but the majority of large scale production is located in Asia (Japan, Korea Taiwan and China) and the USA as mentioned above.

FZ SoNick in Switzerland produces SoNick (sodium-nickel chloride) batteries for mobile, residential, industrial and community applications.

Austrian CellCube (former Gildemeister) produces VRBs scalable to the MW and MWh.

Materials, components and production equipment for battery cell production is a considerable business throughout Europe. Assembling of battery cells to battery packs including BMS is done in many European countries, partly because of safety risks during transport of assembled Li-ion batteries. R&D activities are intense in Germany and France.

Experience with grid-connected operation of large battery systems is now found in most Western European countries and the UK, France, Italy and Germany have been active in this topic for many years. A well-known example is the large installation by Terna (Italian TSO) on the Island of Sardinia, where approx. 9 MW storage capacity has been installed to test, compare and evaluate different suppliers (Li-ion, Zebra, Flow, others (Supercaps…))[124].

Most European battery manufacturers (many of which within lead-acid technology) and many battery users have joined in EUROBAT[125] – Association of European Automotive and Industrial Battery Manufacturers.

11.14 Development needs

Crucial focus points for improving batteries are:

---

[123] https://www.greentechmedia.com/articles/read/10-battery-gigafactories-are-now-in-progress-and-musk-may-add-4-more Accessed February 2019

[124] https://www.etip-snet.eu/wp-content/uploads/2017/06/2.-Storage-Lab-Project-Maura-Musio.pdf. Accessed January 2019.

[125] https://www.eurobat.org/. Accessed January 2019

- Higher energy density – volumetric as well as gravimetric
- Improved safety
- Higher charging rates
- Lower degradation rates
- Lower thermal losses – during charging and discharging
- Cheaper materials and manufacturing processes
- Improved control of battery operation (BMS)
- Decreasing environmental effects from use

Substantial R&D efforts have been devoted to improving the energy density of batteries. This is important for mobile applications – in particular in the transport sector, where the limitations of Li-ion technology set serious restrictions on driving range and/or charging times and charging frequency during touring. Efforts to understand and develop rechargeable Li-air technology have not yet resulted in systems suitable for practical applications within a near future and also other rechargeable metal-air batteries seem to be quite a distance from commercial, mobile use. Zn-air is probably the most developed system in that respect, but still needs considerable attention to understand and bypass problems on basic mechanisms during recharging.

Optimal operation is an important aspect of the use of batteries and novel monitoring and diagnostics methods that enable safe and reliable use of lithium batteries and protect against operation, that severely reduces lifetime need to be improved. Li-ion batteries may show serious thermal runaway – sometimes apparently unprovoked - resulting in fires and even explosions. The battery management system (BMS) must detect and be able to report problems in the battery system, to give notifications and to manage these problems safely. Such BMS systems are vital for safe operation of batteries and should be further developed and adapted to different battery chemistries and design.

Development of improved battery production processes could contribute to lower prices (energy-lean production), better safety, longer lifetime and more uniform product quality.
It is unlikely that only one type of battery will be superior in all battery applications and hence several battery types need to be developed in parallel in the years to come. Although the Li-ion sales have repeatedly reached all times high during the last decade, the sales of other types like NiMH and lead-acid are still notable in spite of the fact that lead is a highly unwanted material in most countries. In the period 2014-2017 sales by volume increased by 9% for NiMH and 23% for lead-acid[126]. For Li-ion the number is 38%.

In parallel with further development of core battery technologies and materials, characterization methods also need to be further developed to enable fast and consistent comparison of key performance properties to guide and support development at both cell and pack levels. Research into improved cell balancing technologies that maximize the effective capacity of battery pack is also required. Alongside this development, charging and discharging strategies and technologies also need to be developed to enable for example faster charging and possibly wireless charging of mobile battery packs. Synergies with other technologies such as fuel cells in hybrid systems should be explored as it may help bring both technologies to the market.

11.15 Players in Denmark

Actors with declared interest in battery relevant activities in Denmark:

<u>Universities and research organizations:</u>

---

[126] http://www.baj.or.jp/e/statistics/06.html. Accessed January 2019.

- Danish Technological Institute
  - Characterization of battery cells and battery packs
  - Batteries for niche vehicles
  - Battery systems for the electrical grid, solar and island operation
  - Batteries for electric vehicles
  - Research into nano-enhanced production processes.
  - Application support
  - Post mortem analysis

- Aarhus University
  - Research into different “classical” Li-ion technologies enhanced by nano processes.
  - Hand production of advanced prototype button battery-cells for characterization.
  - New types of high capacity batteries and nano-energy materials.
  - New types of flow batteries
  - Synthesis/characterisation of ion conducting polymer membranes
  - Solid state batteries

- Aalborg University
  - Research into different “classical” Li-ion technologies
  - Battery characterization, degradation and modelling at cell and package level.
  - Battery management systems, diagnostics and monitoring concepts
  - Thermal modelling and management
  - Battery diagnostic tools for lifetime assessment of EV batteries
  - Related power electronics and charging technologies

- Technical University of Denmark
  - Research into different “classical” Li-ion technologies enhanced by nano processes.
  - Battery characterization, degradation and modelling at cell and package level.
  - Research into new advanced battery chemistries
  - Zinc-air
  - Lithium-air
  - Li-sulphur
  - Organic flow

- University of Southern Denmark
  - Materials for rechargeable batteries
  - Material design and synthesis using various inorganic synthesis methods
  - Material characterization with focus on structure and topology
  - Battery fabrication and tests of battery performance.
  - Li-ion microbatteries manufactured on-location in circuits with methods of fabrications involving depositions of thin films (electrodes and electrolytes), contacting, and packaging.

Companies:

- Haldor Topsøe
  - Catalyst production; materials for electrode production

- Ørsted
  - Focus on wind power (off-shore and on-land) to end user. Knowledge on grid-connected battery storage

- IRD Fuel Cells

  - Fuel cell systems

- Lithium Balance
  - Battery Management Systems

- Nerve Smart Systems
  - Battery Management Systems

- GN ReSound, Widex, Oticon
  - Hearing aids

- AtoZ Electronic
  - Battery application support

- GMR Maskiner
  - Electric minitrucks

- Translift
  - Electric vehicles for internal transport

- AF trucks
  - Electric vehicles for internal transport

- IPU
  - Innovation services

- DFM
  - Fundamental research within metrology

Associations:

- Danish Battery Association
  - Ensure knowledge sharing between Danish companies and research within materials technology and research into batteries.

11.16 Specific recommendations for batteries in a Danish context

Batteries have become everyday devices of ordinary people and are used in numerous special applications as well. Therefore, relevant, continuous research and demonstration programs must be done on battery materials, processes, and systems to improve the specialists´ knowledge and keep it on the cutting edge.

Denmark is even likely to see increasing needs for electric energy storage, which could attract battery production, battery integrators, or even new – e.g. start-up companies - within new battery technologies. To support such development and future advanced battery applications, Danish R&D must develop and demonstrate State-of-the-Art knowledge and technology on all aspects of battery integration in international competition and cooperation. Research and demonstration programs addressing both energy efficient storage systems and specific relevant technologies will support keeping Danish development on the leading edge. Some of the specific technologies that have Danish relevance are:

- Development of new battery systems market better batteries in national and international collaboration

- Managing and balancing batteries to optimise life, capacity, safety, energy efficiency, reliable SoC (State of Charge) and SoH (State of Health), fast charge, self-test, multi chemistry support etc.

- Novel monitoring and diagnostics methods to help enhance battery life, give early warning, measure state of health, fast charging, assessment of remaining life etc.

- Energy efficient thermal management to prolong battery life and give optimal performance, enable fast charge etc.

- Mechanical and electrical battery package integration minimising energy losses and cost; optimising reliability, serviceability, safety, second life options, modularity, scalability etc

- Interface and function – mechanical and electric – to optimise integration into applications, scalability, design reuse, second life value improvement, production, fast charging, standards, application integration etc.

- Environmental concerns on resource availability, materials reuse, recycling, life cycle analysis, second life market support, hazard assessment etc.

- Manufacturing and test **-** battery pilot production for technology assessment, energy efficient production, quality enhancement, standards, battery performance verification, battery modelling, degradation prediction, post mortem analysis

12. Electrochemical Energy Storage

12.1 Technology description

Since a separate section of this document is devoted to batteries, the present section does not include batteries, even though batteries are indeed electrochemical energy storage devices. The reason for this distinction is that batteries are considered a special class of storage technologies among nonprofessionals and even among many technically educated people. Instead, the present section will treat the kind of electrochemical storage, where free chemicals are produced and can be removed from the producing devise and utilized independently e.g. as a fuel. This kind of technology (electrolysis) is often called “Power to something” or P2X, using a type of abbreviation, which has become notably popular over recent years.

In principle non-fuel chemicals can be manufactured based on electrolysis as well. Examples are polymers, e.g. for use in plastic materials and synthetic textile fibers, and eventually synthetic amino acids and proteins. However, these kinds of applications for electrolysis do not seem to hold an immediate application potential and besides this topic is beyond the scope of the present report.

Electrolysis is of high interest as a component in the future sustainable energy system. In this system, wind and solar power will be the prevailing generation technologies and it is well known that electricity (with a few minor exceptions) cannot be stored as such. Electricity must be converted to some other storable energy form if storage is needed or desired and electrolysis provides a number of such conversion technologies leading to the possibility for storage.

Electrochemical energy storage as discussed in this section can be illustrated by the chemical equation for splitting of water into its constituents (water electrolysis):

$2\ H_2O \rightarrow 2\ H_2 + O_2$

Input to this reaction in the form of heat and electricity is required.

Depending on the type of electrolyte used (which ions are conducted between the electrodes) the complete reaction above can be described by two separate electrode reactions as follows for the alkaline system:

$4\ H_2O + 4\ e^- \rightarrow 4\ OH^- + 2\ H_2$ Cathode (reduction of hydrogen from +1 to 0):

$4\ OH^- \rightarrow 2\ H_2O + O_2 + 4\ e^-$ Anode (oxidation of oxygen from -2 to 0)

Many other electrolysis reactions are applied industrially in a variety of processes within preparation of metals and chemical substances. Among the electrolysis reactions of interest in the present context are:

$2\ CO_2 \rightarrow 2\ CO + O_2$

and

$2\ N_2 + 6\ H_2O \rightarrow 4\ NH_3 + 3\ O_2$

The first reaction is highly useful for the manufacturing of *synthetic carbon-based fuels* and the second is important because ammonia can play a role as a *suitable fuel for fuel cells* and besides ammonia is an important chemical and used for fertilization in agriculture.

Water electrolysis has been known since approx. 1800 and has been utilized industrially for more than one century.

The overall reaction of water electrolysis (water dissociation) has been described above. The basic thermodynamics of the reaction is shown in Figure 48 in dependence of temperature (V is the corresponding voltage). It is seen that the total energy input of the dissociation reaction increases weakly at temperatures above 100 C whereas the required electricity input (as represented by ΔG) decreases in the same range, which leaves the heat demand ($T\Delta S$) to increase.

Below 100 ˚C the required energy input is high and includes evaporation of water. The need for electricity input is higher for any temperature below 100 C than for above.

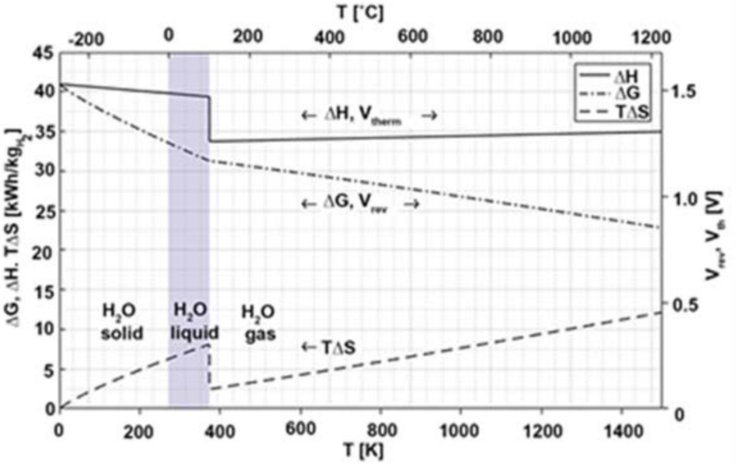


Figure 48 Thermodynamics of water dissociation[127]. Thermodynamic values are shown in dependence of temperature and V is the corresponding voltage

Three electrolysis technologies have been dominating the technological development the last decade – each based on different electrolytes and addressing different temperature ranges in Figure 48.

12.1.1 Alkaline electrolysis cells (AECs)

AECs are the most mature water electrolyser technology. They generally operate at ambient or moderated pressure of ca. 30 bar and approx. 60-80 C and the migrating ions are OH^- ions. For more details cf. [128].

To obtain an improved hydrogen production rate per cell volume, AECs are usually operated at rather high cell voltages (1.7−1.9 V as compared to the equilibrium potential of 1.23 V at 25 ˚C). Although the electrolysis process is endothermic, the ohmic losses in the alkaline

---

[127] N. Gallandat, K. Romanowicz and A. Züttel, An Analytical Model for the Electrolyser Performance Derived from Materials Parameters, Journal of Power and Energy Engineering, Vol.5 No.10, October 2017

[128] M. Schalenbach, A.R. Zeradjanin, O. Kasian, S. Cherevko and K.J.J. Mayrhofer, Perspective on Low-Temperature Water Electrolysis – Challenges in Alkaline and Acidic Technology, *Int. J. Electrochem. Sci.,* 13 (2018) 1173 – 1226, doi: 10.20964/2018.02.26

cells exceed the amount of heat required for the reaction and cause heat to be produced as a waste or by-product.

The principles of alkaline electrolyzer is shown in

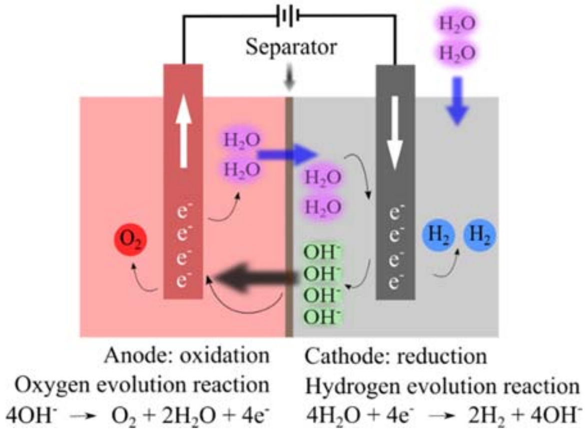


Figure 49[129]. Drawing showing the principles in alkaline electrolysis

The efficiency of alkaline electrolysis is around 70% when calculated as the higher heating value for the produced hydrogen over the electrical energy input required for the production. Hydrogenics in an industrial brochure quotes[130] 4.9 kWh/Nm^3, which can be recalculated to 72.5% conversion efficiency (based on HHV 286 kJ/mol H_2). Higher heating value (HHV) includes the heat of condensation of the water produced by the reaction between oxygen and hydrogen

In recent years, alkaline water electrolysers have been developed to produce hydrogen at higher pressure than 1 bar and higher temperatures than mentioned above. Increasing the operating temperature of an electrolyser leads to faster electrode reactions as well as better ion-conductivity in the electrolyte, which in turn means higher production rates for the electrolyser and reduced overall system costs. This has intensified research in high-temperature (up to about 250ºC) alkaline electrolysis. The liquid state of water is maintained by the high operation pressure (water vapor pressure at 250 ˚C is 40 bar) and the final product is also delivered at high pressure[131].

Commercial alkaline electrolysers are available for direct production of hydrogen at 10, 25 and even 35 bar (e.g. GreenHydrogen [132]). The higher pressure eases the final compression of hydrogen as is required for pressurized storage of hydrogen or use of hydrogen for further synthesis processing.

12.1.2 Polymer Electrolyte Membrane (PEM) electrolysers

PEM (sometimes called Proton Exchange Membrane) electrolysers are solid state technology using a hydrogen ion conductive polymer electrolyte membrane as electrolyte.

---

[129] https://lepa.epfl.ch/page-129875-en-html/page-130174-en-html/page-139282-en-html/ Accessed February 2019

[130] https://www.hydrogenics.com/technology-resources/ Accessed November 2018

[131] Alkaline electrolysis cell at high temperature and pressure of 250 °C and 42 bar. F. Allebrod, C. Chatzichristodoulou, M.B. Mogensen, Journal of Power Sources, Vol. 229, 2013, p. 22-31.

[132] http://greenhydrogen.dk/technology/hyprovide-250tm/ Accessed November 2018

The membranes are based on material (Nafion) developed by DuPont in the 1960s and the principles in PEM electrolysis are shown in Figure 50

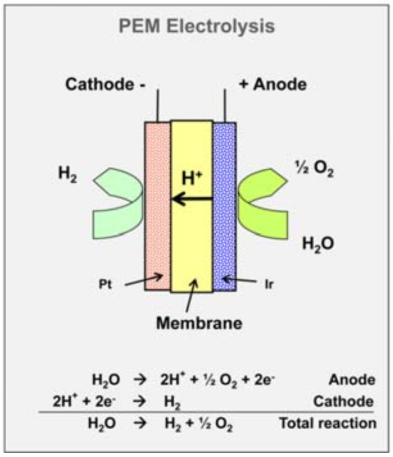


Figure 50[133]. Principles of PEM-based water electrolysis

The major advantage of PEM electrolysis is the ability to operate at high current densities, to achieve a low gas crossover rate leading to high gas purity, due to its solid structure which also facilitates high-pressure operation. The high current density available in PEM means that investment costs are not very much higher than for alkaline technology. However, the materials costs of PEMs are still high for the electrolyte as well as for the electrodes used. The electrodes still contain precious materials such as Pt and Ru and an important research task is to reduce or replace the amount of these expensive materials in PEM.

Initially PEM technology was operating at 60-80 ˚C, but the discovery of PBI (polybenzimidazole) membranes made the temperature range up to several hundred ˚C available for PEM membranes and since then a distinction between LT- and HT-PEM (low and high temperature) technology has been made, although HT-PEM electrolysis is still causing problems with durability of the membrane.

12.1.3 Solid oxide electrolysis

Solid Oxide Electrolysis Cells (SOECs) operate at quite high temperatures, typically in the range of 600-1000ºC. The electrolyte is a solid oxygen ion conducting ceramic component and the electrodes are based on ceramic materials as well, sometimes, though, with for example Ni metal in one electrode. The electrolyte allows transfer of oxide ions from one electrode to the other. Figure 51 shows the principle of an electrolysis cell.

---

[133] http://www.fz-juelich.de/SharedDocs/Downloads/IEK/IEK-3/Flyer/Flyer_PEM-EL(E).pdf?__blob=publicationFile Accessed February 2019.

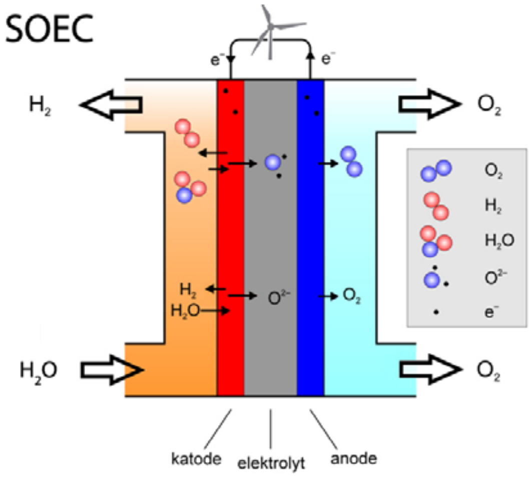


Figure 51: Principle of electrolysis shown for an oxide-conducting electrolyte (O-SOEC)

The high operational temperature of an SOEC means fast physical and chemical reactions and at the same time, all elements used in SOECs are non-precious. Consequently, SOEC technology holds a promising potential to become a cheap and affordable electrolysis technology. In addition, utilization of the electrical energy in an SOEC can be very high, close to 100%[134] . The reason is a high utilization of Ohmic heat in the dissociation of water.

SOEC is furthermore able to electrolyze CO_2 into CO and O_2, as well as perform co-electrolysis of both H_2O and CO_2 to produce mixtures of CO and H_2, called syngas, a very well-known industrial basis for production of higher carbon containing compounds such as hydrocarbons, methanol and dimethyl ether (DME) etc. Today syngas is produced industrially from fossil fuels, but in future, it may be produced via electrolysis, utilizing CO_2 from point sources such as the cement industry, biogas production, power stations and steel industry etc.

Some of these critical issues may now also be resolved through high temperature AEC and PEM.

The SOEC described above is the traditional SOEC with an oxide ion-conducting electrolyte (O-SOEC). However, also electrolysis based on a proton-conducting electrolyte is of interest and called P-SOEC. Similarly to PEM, the hydrogen produced in a P-SOEC is of high purity and the device may also be pressurized. In contrast to PEM, the electrodes can be free of Pt and Ru, making them much cheaper than PEM. P-SOFC must work at high temperatures, presently 500-1000ºC, and are still at a relatively low TRL.

O-SOEC is already commercial (HTAS) in the market for CO production. However, the cost of hydrogen production from O-SOEC must be reduced. Issues like long-term durability, robustness to electrical load variations, the manufacturing of cells and stacks with a larger cell area and the general optimization of a series of manufacturing steps need attention.

For P-SOEC (still at low TRL) a substantial R&D effort is highly needed to improve production of materials, cells and stacks, improvements to durability and demonstrating stacks and systems.

---

[134] Ebbesen, S.D., and Jensen, S.H., Hauch, A., Mogensen, M., "High Temperature Electrolysis in Alkaline Cells, Solid Proton Conducting Cells, and Solid Oxide Cells," Chemical Reviews, vol. 114, no. 21, p. 10697–10734, 2014.

12.3.4 Hydrogen storage

Hydrogen produced by electrolysis can be stored in several ways and many of these are very mature techniques that have been used widely in industry for decades.

- The most well-known technique is **storage of hydrogen at high pressure** in metal cylinders or in underground caverns. Cylinders have long been used for commercial distribution of hydrogen. Subsurface cavern storage - as also used for natural gas storage - has been used in some places over the world and has been proven to be feasible. Compressing hydrogen is not straight forward and consumes energy, which must be considered when hydrogen is used for storing energy. The higher pressure, the more energy is used. Compressing to 700 bar takes[135] approx. 11-16 % (depending on compression technology) of the energy in the hydrogen, whereas for 350 bar it is 8-12 %
- **Storage of liquid hydrogen** is also used for commercial distribution of hydrogen in larger quantities and is well known for use in space programs. Liquefaction of hydrogen consumes quite some energy, which must be considered, when hydrogen is used for storing energy. The energy loss amounts to 35-40 % of the energy contained in the liquefied hydrogen[136] and furthermore there is an inherent loss of hydrogen from its liquid state because of boil-off coming from heat developed during ortho-para (parallel and anti-parallel nuclear spins) conversion in the hydrogen. This boil-off must be vented.
- **Storage of hydrogen in solids,** e.g. metal hydrides and complex hydrides, has been studied with varying intensity since the 1980s and is indeed doable. However, heat of reaction is sometimes considerable. For MgH_2 the heat of reaction is approx. one third of the energy contained in the stored hydrogen, which means, that very much heat must be removed when hydrogen is stored in Mg and besides the released heat should preferably be utilized. Even if magnesium hydride is one of the worst hydride systems concerning heat of reaction, storing hydrogen in solids has not yet found any wider practical energy-related application.

12.2 Applications of electrolysis

As mentioned above alkaline electrolysis has been applied industrially for production of hydrogen for more than a century. Hydrogen has been and still is an important raw material in chemical industry, where a significant part is consumed for production of ammonia and methanol, reducing agent in metallurgical industry, hardening (saturation) of vegetable oils and many other crucial applications. In a sustainable energy system, such demands must be met by non-fossil hydrogen and electrolysis is an obvious supply possibility, although not directly a storage application of electrolyzers.

Hydrogen is the most common, the most obvious and the most simple synthetic fuel to be produced from renewables using electrolysis. Disregarding nuclear fuels, hydrogen furthermore has the highest energy density on weight basis among known fuels. However, at ambient temperatures elemental hydrogen can only be stored in the gaseous state and at

---

[135] Energy and the hydrogen economy, U. Bossel and B. Eliasson, US DOE, EERE, 2016 http://www.afdc.energy.gov/pdfs/hyd_economy_bossel_eliasson.pdf

[136] Efficiency of Hydrogen Liquefaction Plants, T.Fukano, U. Fitzi, K. Löhlein, I. Vinage, Linde Kryotechnik AG, CH-8422 Pfungen, Switzerland, and Nippon Sanso Corporation, JP-210-0861 Kawasaki-City, Japan

high pressure. Thus, fuel cell vehicles usually store compressed hydrogen in composite gas cylinders at a pressure up to 700 bar and efforts are devoted to driving this limit further

However, the future production of synthetic fuels – similar to those we know from fossil sources – is a way to store electrical energy as chemical energy. The production of synthetic hydrogen- and carbon-containing fuels requires vast amounts of hydrogen, and this hydrogen can be produced sustainably via electrolysis. See also "Synthetic fuels besides hydrogen" below.

Many grid-connected demonstration plants for testing production of hydrogen in a real environment have been constructed. Since alkaline technology has been the most widely used industrial electrolysis technology for production of hydrogen (P2H), the majority of early demonstration plants since 2000 in terms of accumulated MW have been based on this technology. However, as can be seen in Figure 52, this picture is likely to change now and PEM technology is projected to gain market a dominating share in a growing market. Thus, Figure 52 anticipates a stop for new installations of alkaline P2H demonstration plants after 2018. This development is naturally associated with uncertainty, but the figure expresses expectations of specialists working in the field. It is also interesting to note that Europe is far ahead of other continents as measured by number of installed demoplants. Europe has 153 installations, whereas 18 are found in North America and 13 in Asia[137].

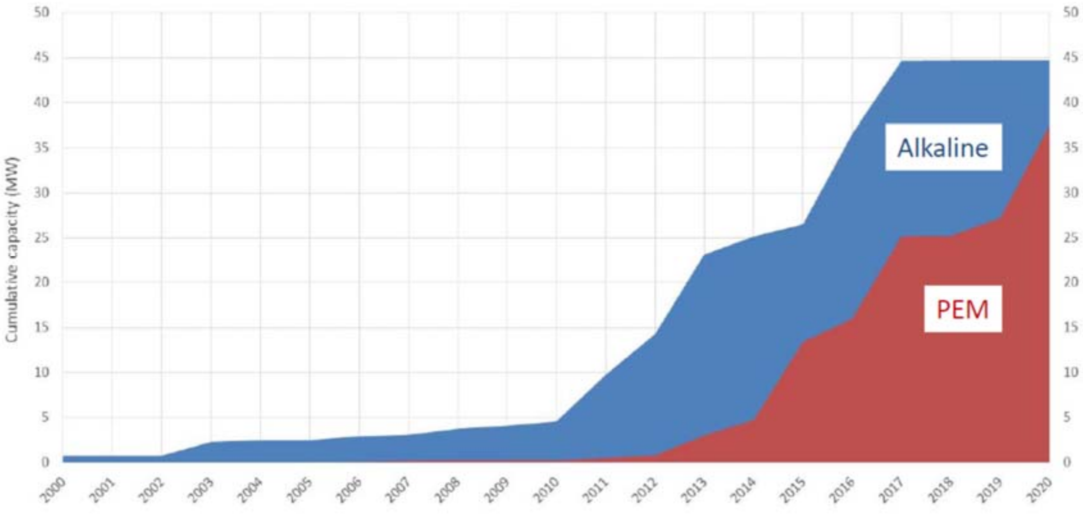


Figure 52. Cumulative capacity in MW of running P2H demo-projects within the framework of IEA/HIA (Hydrogen Implementing Agreement)[137].

A map showing the geographical distribution of power to gas demonstration projects in Europe is seen in Figure 53. The figure shows that Germany, even taking population into account, is the leading European country for installation of demonstration projects.

---

[137] Critical assessment of running P2H demo-projects within the framework of IEA/HIA. Presented by J.Proost, Power to Gas Conference, Copenhagen, 17-18 October 2018

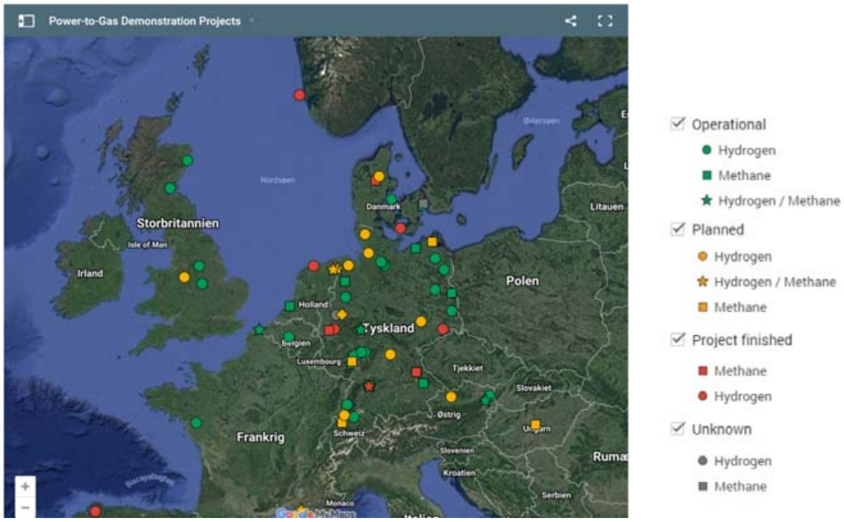


Figure 53. Power-to-gas demonstration projects in Europe[138]

12.3 Synthetic fuels besides hydrogen

Hydrogen may form compounds with carbon to make hydrocarbons and oxygenated hydrocarbons (e.g. methane, DME, methanol, gasoline etc.) or with nitrogen to make ammonia (NH_3). Hydrocarbons and ammonia have the advantages over hydrogen that they are easier and cheaper to store and transport, and that a widespread infrastructure for distribution and use is already available in many cases.

Several ways are viable for production of synthetic carbon-containing fuels based on hydrogen and CO_2 and the most important routes are mentioned below.

12.3.1 Sabatier reaction for methane production

The direct combination of hydrogen with CO_2 is well known, and the Sabatier process is a commercial technology based on the reaction:

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$$

The reaction is exothermic ($\Delta H = -164$ kJ/mol) and requires optimally 300–400 °C as well as high pressure[139]. The processes in the production of synthetic methane is shown in Figure 54.

---

[138] http://europeanpowertogas.com/projects-in-europe/. Accessed December 2018.

[139] Review on methanation – From fundamentals to current projects, S. Rönsch, J. Schneider, S. Matthischke, M. Schlüter, M. Götz, J. Lefebvre, P. Prabhakaran and S. Bajohrc, Fuel, Vol. 166, Pp 276-296, 15 February 2016.

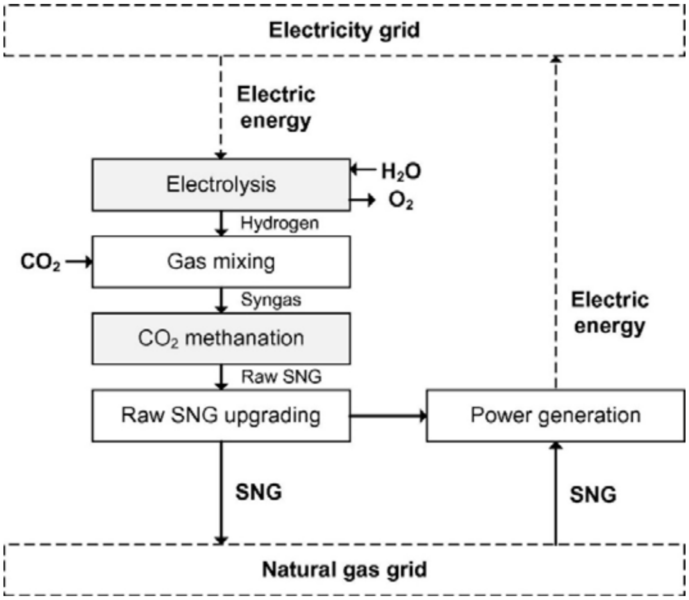


Figure 54[139]. The steps in producing CH_4 from electricity, CO_2 and H_2. The gas flow is shown as utilized for re-electrification.

12.3.2 Biogas upgrading to form methane

Biogas is strongly gaining importance in many countries, where natural or agricultural resources allow utilization. Biogas is a mixture of approx. 40% CO_2 and about 60% of biomethane and is produced by fermentation or digestion processes based on organic material like plants or animal waste from food production. The fraction of biomethane in the natural gas grid is increasing and in Denmark it (temporarily) reached 26% by summer 2018 as shown in Figure 55. The figure furthermore shows that the share of bio-natural gas is increasing steadily although fluctuating on a seasonal basis.

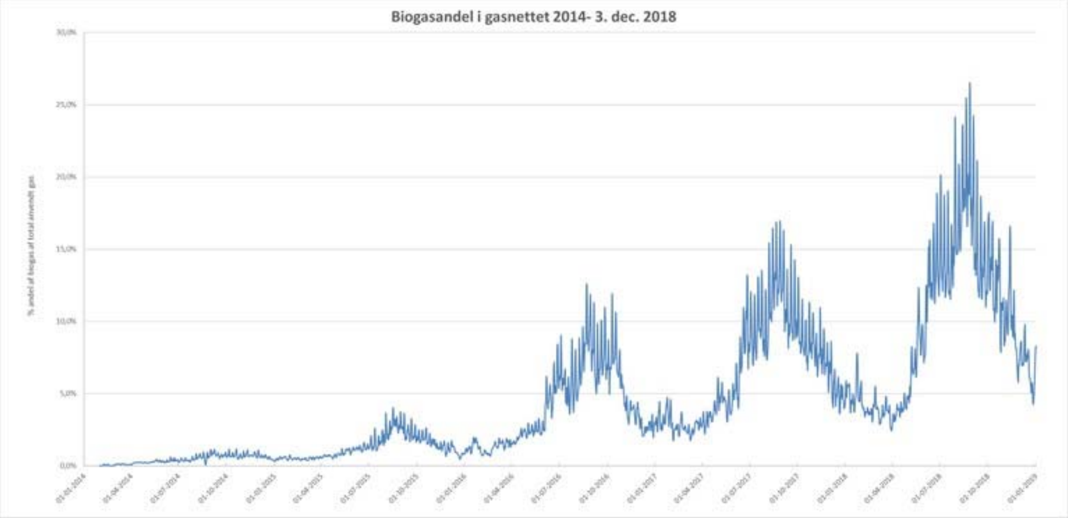


Figure 55[140]. Share of bio-natural gas in the Danish gas grid 2014 – 2018.

---

[140] Energinet- energidataservice: Bionaturgasandel i gasnettet. Obtained from Naturgasfakta, http://www.naturgasfakta.dk/copy_of_miljoekrav-til-energianlaeg/biogas. Accessed December 2018

As mentioned, biogas contains a considerable amount of CO_2, which is currently separated from the raw gas to obtain methane of grid quality which can be injected into the gas grid. However, this obvious and potentially sustainable - which it is not necessarily today - carbon source can be utilized for storing hydrogen in the form of methane.

The Danish company Haldor Topsøe A/S, who is specializing in catalysts for chemical industrial processes, is working to streamline an upgrading process for biogas, which utilizes the inherent CO_2 and produces methane.

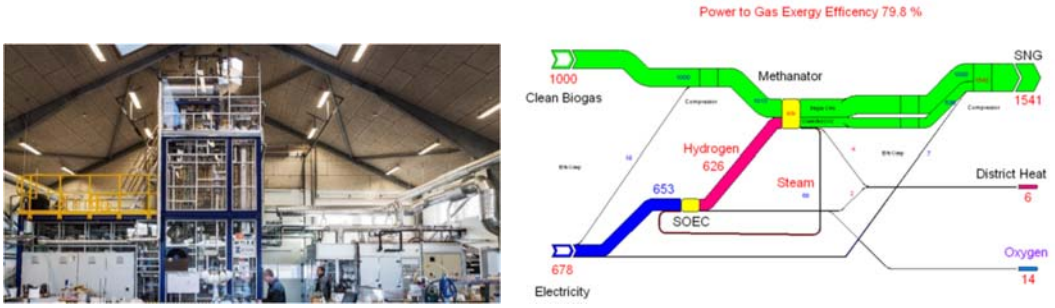


Figure 56[141]. Left: Haldor Topsøe biogas upgrading plant in Foulum, Denmark. The plant includes a 50 kW hydrogen-producing SOEC unit for steam electrolysis and catalytic methanisation, where CO_2 in the biogas is upgraded to pure methane of pipeline quality. Right: Exergy efficiency in the process is calculated to be approx. 80%.

12.3.3 Microbiological technology for production of methane

In recent years, microbiological techniques have been applied for production of methane from hydrogen and CO_2. An example is seen at the Avedøre wastewater treatment plant at Avedøre at Copenhagen. Here the solid organic content in the wastewater from a large city is separated as a part of the treatment processes and is fermented/digested to form biogas,. Currently such biogas is upgraded by separation and isolation of the methane and CO_2 is subsequently led to atmosphere. However, at Avedøre the CO_2 is converted into methane by certain bacteria, whose metabolism is based on this process. Electrochea is the company, who installed the bio-reactor and the energy flow in the process is shown in Figure 58.

Figure 57. Energy flow in the Electrochea process[142] installed at Avedøre, Denmark. The heat is released at approx. 60˚C.

---

[141] Solid Oxide Cell Enabled Ammonia Synthesis and Ammonia based Power Production, J. B. Hansen, Haldor Topsøe A/S, 2017

[142] Industrial Scale Biological Methanation - Learnings and Insights. Presented by D. Hafenbradl, Electrochaea, presented at Power to Gas Conference, Copenhagen, 17-18 October 2018

12.3.4 Co-electrolysis of steam and CO_2

Production of syngas (mixture of H_2 and CO) by co-electrolysis of water and CO_2 is another route that might reduce the overall costs, especially when the electrolysis process runs at elevated pressures.

From syngas, a variety of options for producing hydrocarbons is available following the Fischer-Tropsch types of reaction:

$$(2n + 1)\ H_2 + n\ CO \rightarrow C_nH_{2n+2} + n\ H_2O$$

where n is usually in the range up to 20 and the reaction is exothermic and depends on efficient removal of heat.

The Fischer-Tropsch[143] reaction scheme has been utilized extensively and commercially since it was developed in the middle of the 1920s. By controlling catalyst, temperature and pressure the resulting n (in the reaction equation) can be selected to some extent, and also alcohols can be available from the process.

From a storage point of view, the interesting aspects of Fischer-Tropsch synthesis and the above-mentioned Sabatier process are that hydrogen and carbon monoxide - sustainably produced from electrical energy - can lead to formation of a spectrum of liquid and gaseous fuels, that are very well established via past fossil use. Thus, an extended infrastructure is available in most countries for natural gas grids and for distribution and use of liquid fuels for transport whether by sea, air or road. Furthermore, carbon-containing fuels generally hold very high energy densities, which is an attractive and even decisive property for fueling the transport sector. Some relevant energy densities of different propellants, which may play a role in the future transport system. The advantages of synthetic fuels – and in particular the carbon-containing ones - are clearly seen. A comparison with the data for batteries shows some of the main problems about using batteries in transport: the poor energy density of batteries on volume and weight. It takes a lot of space and weight (!) to carry sufficient energy in a car battery to achieve driving distances similar to what we now from fossil fuel and which green synthetic fuels can meet.

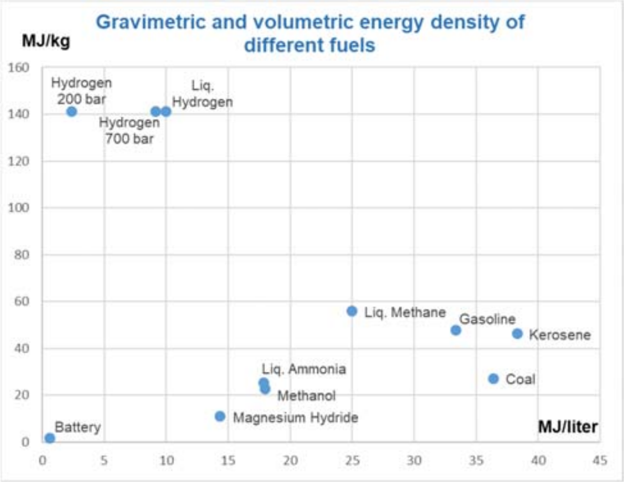


Figure 58. Energy densities of different fuels. The numbers do not take containment etc. into account

---

[143] "Fischer–Tropsch Process", Arno de Klerk. Kirk‐Othmer Encyclopedia of Chemical Technology. Weinheim: Wiley-VCH, 2013

Solid oxide cells (SOCs) are interesting in this context since they can be operated both as electrolyzers (SOEC), and as fuel cells (SOFC) to convert fuels into electricity. Both productivity and conversion efficiency are improved if the SOC operating pressure is increased from ambient to 10–30 bar [144],[145].

12.3.5 Carbon sources

CO_2 is a viable carbon source for the described P2X technologies. Even though the concentration of CO_2 in atmosphere is too high from a climate point of view, it is still quite low from a collection point of view. Green plants are collecting CO_2 very well from atmosphere and principles for artificial extraction of CO_2 from atmosphere are indeed being studied and developed – se e.g. [146]. However, on short terms, point sources of CO_2 may have a more obvious potential since CO_2 is more easily accessible from such located sources.

Point sources releasing CO_2 can be found in industry, where fermentation processes, chemical reactions during the production of chemicals, iron and steel, and cement emit considerable amounts of CO_2.

12.3.6 Ammonia

Ammonia, NH_3, is an important raw material in chemical industry and crucial for the productivity of today’s farming. Ammonia can be considered a condition for feeding the billions of inhabitants on the Earth. The production, storage and distribution of ammonia is therefore well established.

Ammonia is traditionally produced from N_2 and H_2 by reactions at an iron catalyst at high temperature and pressure, the so-called Haber-Bosch process. Most of the hydrogen used is produced from fossil sources, but the use of sustainable hydrogen is also found and anticipated to become more common in the future. There is a well-known example at the Aswan Dam in Egypt, where hydrogen is produced using hydropower through alkaline electrolysis and connected to a large ammonia reaction plant. Such units are on a very large scale for reasons of cost. There are interests and research activities in producing NH_3 directly through electrolytic and electro-catalytic processes, leading to the ability to produce and store energy sustainably in the form of ammonia locally, and at low energy costs.

---

[144] Characterization of a Planar Solid Oxide Cell Stack Operated at Elevated Pressure, Jensen, S.,Graves, C., Chen, M., Hansen, J. and Sun, X., J. of The Electrochemical Society, 163 (14) pp F1596-F1604, vol. 14, no. 163, 2016

[145]] PRESSURIZED REVERSIBLE OPERATION OF A 30-CELL SOLID OXIDE CELL STACK USING CARBONACEOUS GASES, Jensen, S., Langnickel, H., Hintzen, N., Chen, M., Sun, X., Hauch A. and Bute, G., in European Fuel Cell Technology & Applications Conference - Piero Lunghi Conference, Naples, 2017.

[146] A Process for Capturing CO2 from the Atmosphere, D.W. Keith, G. Holmes, D. St. Angelo, K. Heidel, Joule, Volume 2, Issue 8, 15 August 2018, Pages 1573-1594

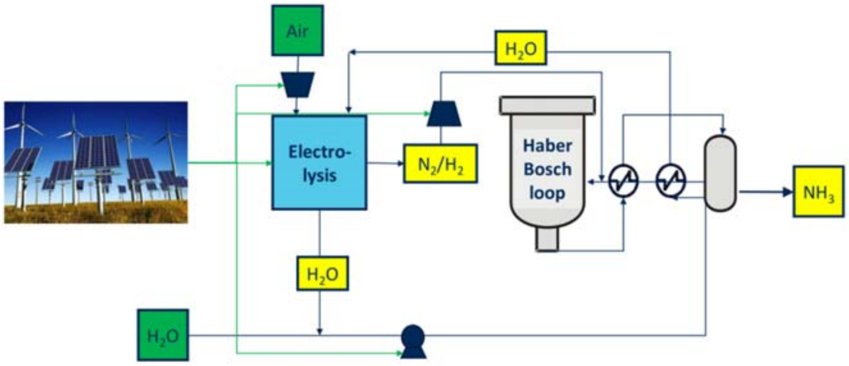


Figure 59. Future vision of ammonia production by Haldor Topsøe A/S[147].

Research, development and demonstration requirements. Electrochemical methods to produce NH_3 are recommended. Probably high-temperature, high-pressure electrolysis systems are preferable, e.g. P-SOEC. The development of catalysts in the “NH_3 electrode” that are highly selective to H_2+N_2 to NH_3 conversion, rather than solely H_2 production, should be one important attempt. The assembly of working cells and stacks should be realized.

12.4 Case stories power to gas

Power to gas projects in an energy context have not yet reached sufficient maturity to allow fully commercial activities, at least if some old electrolysis projects – typically associated with hydropower - are disregarded

In general, projects within power-to-gas are still characterized by development of the involved technologies, particularly the electrolysis technology, but also methane formation from hydrogen and carbon dioxide.

The two cases below thus rather illustrates the status and development of P2G technology, than business profits.

In **Falkenhagen**, Northern Germany, Uniper Energy Storage constructed what was claimed to be the world’s first demonstration plant for storing wind energy in the natural gas grid[148]. The plant stores electricity from wind power. Around 360 Nm³/h of hydrogen has been generated by means of 2 MW alkaline electrolysis and fed via a pipeline into the gas grid. Thus, the stored energy has been available as a combustible gas to the electricity, heating, mobility and industrial market, similar to natural gas. In the first year of operation, more than 2 million kWh of hydrogen were fed into the grid up to July 2014.

In May 2018 the expansion of the power-to-gas plant to a methanation plant was completed. Hydrogen from renewable energy is converted into methane, using CO_2 from a bio-ethanol plant. Methane in contrast to hydrogen can be used in more established ways. It can be made available to a variety of markets, including the manufacturing sector, the electricity, and heating market as well as the mobility sector. Moreover, it relies directly on the existing natural gas infrastructure, including transport and storage. The stored energy is then available as backup whenever there is an insufficient supply of solar and wind power.

---

[147] Power-to-X activities at HTAS: perspectives on electrification of the chemical industry. P. Blennow, presented at Power to Gas Conference, Copenhagen, 17-18 October 2018

[148] https://www.uniper.energy/storage/what-we-do/power-to-gas Accessed January 2019.

Figure 60[149]. Left: photo of the Falkenhagen P2G plant. Right: X-ray illustration of one container showing the electrolyzer stacks inside

In **Berlevåg** – almost on the northern-most tip of Norway - a 2.5 MW PEM-based power-to-gas project[150] (called Haeolus) is underway supported by the EU. The electrolyzer will be supplied with electricity by wind power from a 45 MW wind farm nearby. The project will demonstrate a 2.5 MW PEM electrolyser with a single-cell stack of up to 420 cells from Hydrogenics.

The plant will be operated in three main modes recommended by the International Energy Agency:

- Electricity storage
- Mini-grid
- Fuel production

For each mode, new operating strategies will be developed, optimizing operation concerning uncertain weather and power-price forecasts, but also constraints of the specific operating mode.

Haeolus aims to demonstrate how wind-hydrogen integration can reduce the unpredictability of power produced by a wind farm, and thereby enabling much higher rates of renewable energy penetration in the European grid.

The following project characteristic numbers are expected:

- Energy consumption is 52 kWh/kg
- CAPEX, 2 M€/(t/d)
- Yearly degradation, 1.5%
- Hot-start time, 2 s
- Cold-start time, 30 s

---

[149] https://www.windpowerengineering.com Accessed January 2019.
[150] http://www.haeolus.eu/ Accessed January 2019.

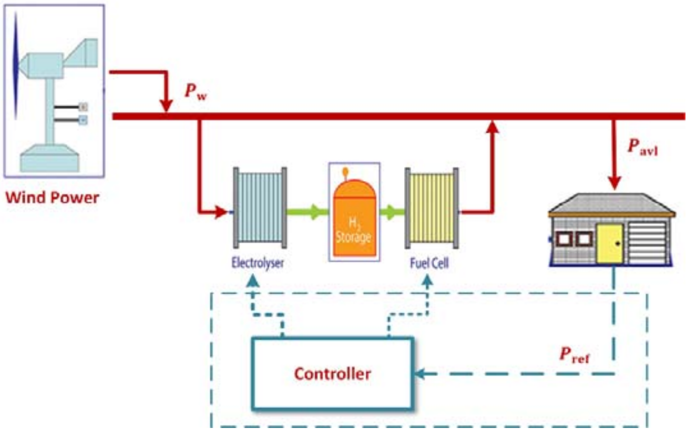


Figure 61[150]. Principles of the Haeolus project.

12.5 Technology status in Danish industry and research community

Since 2014 some commercial producers of electrolysers have emerged in Denmark and the research community in Denmark still has a leading position within electrolysis research on the following three electrolysis technologies:

- Alkaline electrolysis is primarily developed by **GreenHydrogen.dk** and **DTU Energy**. GreenHydrogen.dk markets alkaline electrolysers and has been a commercial actor over recent years with the HyProvide series in the power range up to 270 kW per module. GreenHydrogen provides electrolysers for hydrogen fueling stations (automotive applications), power-to-gas applications, power-to-power/back-up & storage as well as on-site industrial applications. Additionally, GreenHydrogen has experience with producing methane (SNG) and methanol based on electrolytic hydrogen. Former **H2 Logic in Herning, since 2015 a part of Norwegian Nel Hydrogen**, manufactures hydrogen-fueling stations for fast 70 MPa fueling of Fuel Cell Electric Vehicles. The production and development takes place in Herning.
- PEM electrolysis is in Denmark primarily developed at **DTU Energy**, where efforts are focused within LT-PEM technologies. **Danish Power Systems** and **IRD Fuel** Cells develop and provides components for electrolysis and consulting assistance within electrolysis based on long experience with PEM technology and materials.
- SOEC electrolysis: SOEC electrolysis is developed and marketed by **Haldor Topsoe A/S** and **DTU Energy**. DTU Energy has been a pioneer within SOEC research and is world leader within co-electrolysis and pressurization of SOEC stacks. Haldor Topsoe A/S provides SOEC technology, called eSOs, allowing production of carbon monoxide directly at the site of facilities where the gas is needed. Commercial offering produces 96 Nm3 CO/h (up to 99.999% pure) and approximately 300 kW SOEC unit. More units may be combined for larger demand. Furthermore, Haldor Topsoe is participating in several RD&D projects aiming at developing SOEC technology for commercial production of hydrogen and mixtures of hydrogen and carbon monoxide (syngas) aiming at carbon-containing fuels. Finally, Hador Topsoe has activities aiming at electrolytic production of ammonia. Haldor Topsoe A/S is the only company worldwide, which has both Solid Oxide Cells, catalysts and technology for synthesis gas conversion within the same company. Haldor Topsøe A/S is

currently operating a 50 kW SOEC system for biogas upgrading in a project sponsored by EUDP..

Danish universities and consultancy companies have established a solid foundation for simulation and optimization of sustainable energy systems. Recently, funding has been provided for “Faststofoxid Celle baseret Produktion og Anvendelse af Ammoniak” (solid oxide cell for production and use of ammonia - main applicant Haldor Topsoe) and for “HyTon - verdens største brint compressor” (World´s largest hydrogen compressor - main applicant NEL Hydrogen) as well as Power2Met (main applicant GreenHydrogen.dk). In addition, public funding has been given to several other projects related to electrochemical storage, e.g. “Teknologimodning af keramiske elektrolysesystemer” (maturing ceramic technology for electrolysis systems towards present markets), “HyBoost-2 »Mere brintoptankning for mindre«” (improving hydrogen refuelling stations) “H2Cost-2” (reducing costs for hydrogen production and fast hydrogen refueling). Danish actors are furthermore active in International Energy Agency in IEA Hydrogen TCP 2019 – 2020, IEA_HIA Task 39 and IEA Task 39 Hydrogen in the maritime. Furthermore, DTU is involved in the IEA TCP on Advanced Fuel Cells, Annex 30, where electrolysis is included.

However, still lacking in the complete value chain in a Danish context is dedicated power electronics, cost efficient water purification and large-scale system integrators (including manufacturing of high pressure equipment). The important coupling to biomass gasification has received considerable attention lately but still needs a stronger Danish commitment.

12.6 Status in other European countries

In connection with the German “Energiewende” a substantial amount of work has been initiated partly sponsored by public German funds. Germany seems to be the leading state in the EU concerning number of power-to-gas projects. As a very recent example, the gas and electricity net companies Gasunie Deutchland, TenneT and Thyssengas aim to convert wind power into green hydrogen[151]. The plan is to build a 100-MW power-to-gas plant in Lower Saxony. Starting in 2022, the pilot plant will be connected to the grid gradually. The new facilities will be the largest of its kind in Germany and are intended to connect the energy, transport and industrial sectors and stabilize the electricity grid, limit the curtailment of wind energy and reduce the future need for grid expansion. However, many other

However, many other projects on electrochemical storage are being planned or under development in Germany as also reflected in Figure 53. Most of the plants use alkaline technology, but still more plants are based on PEM technology (in MW) and one company, Sunfire, in 2015 announced their production of synthetic diesel from air, water and green electrical energy[152].

In the UK, substantial interest also exists for Power-to-gas technologies, so far mainly for hydrogen production including injection into the natural gas grid. A major player is here ITM Power using PEM technology. ITM Power is currently together with INOVYN, Storengy, Cadent and Element Energy wishing to explore the feasibility of siting a 100 MW Proton Exchange Membrane (PEM) electrolyzer at the INOVYN Runcorn Site, which already produces hydrogen (used mainly on-site) as a co-product of the chlorine-alkali process.

---

[151] https://www.tennet.eu/news/detail/gasunie-tennet-and-thyssengas-reveal-detailed-green-sector-coupling-plans-using-power-to-gas-tec/

[152] https://www.sunfire.de/en/company/press?file=files/sunfire/images/content/company/press/archive/2015_Apr_Sunfire%20now%20produces%20synthetic%20fuel%20from%20air.pdf

In France, the efforts have mainly been led by CEA so far, but the GRHYD project inaugurate France's first Power-to-Gas demonstrator in 2018 including several industrial partners. The project runs 5 years and has a budget of 15 MEUR. The relatively weak position of France in the area is also indicated in Figure 53.

In Italy, SOFC Power has participated in one EU project together with Spanish and German partner as well as (by then) TOFC. Italian partners are active in the Power-to-Gas projects in Italy: INGRID and STORE&GO projects, which were described as "A first-of-this-kind experience" [153].

12.7 Applications

Applications are numerous. Chemical energy storage can be integrated in many ways in the future energy system. Intermittent electricity production can be levelled and converted to transport fuels like hydrogen, methane, methanol, DME, gasoline or diesel. Such fuels can also be used for central or decentralized CHP production and for high temperature process heat in industry.

In the CEESA project the preferred, realistic 2050 scenario calls for 8 TWh used for steam electrolysis combined with 10 TWh synthesis gas producing 17 TWh transport fuel and 21 TWh used for co-electrolysis of CO_2 and steam producing 13 TWh. This can be compared with the 8 TWh used directly for electrical vehicles.

Conversion of electricity into methane would integrate the electricity and gas grid.

Electrolysers at hydrogen refueling stations could be used for decentralized storage and balancing of the electricity grid.

Although the conversion processes involved in chemical storage are rather efficient there are also opportunities to use the waste heat for district heating purposes, which would increase the overall conversion efficiency even further.

12.8 Development needs for electrolysis to become mature for markets

AEC electrolyzers have been used commercially for a long time but still development needs for AEC are essentially persisting:

- Still too expensive as the hydrogen can only be produced at (too) high cost
- Increase the energy conversion efficiency
- Make load following performance more efficient and cost-effective
- Corrosion and materials durability issues when increasing the operating temperature are important
- For low-temperature (about 80ºC) electrolysers, the hydrogen output rate per volume of electrolyser could be increased by developing zero-gap membranes
- Going to higher temperatures and high pressures will improve efficiency.
- Materials research is needed to achieve long-term stability.
- Further RD&D in general on high-temperature, high-pressure AEC is highly needed.

---

[153] http://93.62.162.196:8080/opencms/export/sites/Anigas/Galleria_Documenti/RelazioniInterventi/28052018-Bertoncini-PtG-INGRID-StoreGo.pdf

- Demonstration of suitability for 0-100 % dynamic load operation within seconds and cold start and overload capabilities will be important.

For **<u>PEM systems:</u>**

- A major issue is (still) the reduction or elimination of the use of noble metals, both for catalysts and for internal protective coatings.
- Cost reduction in general.
- Demonstration of suitability for 0-100 % dynamic load operation within seconds – especially when operated pressurized.
- Co-electrolysis of carbon dioxide and water seems within reach, but needs more attention.
- R&D focus is also needed on
    - cost reduction
    - improving performance (efficiency)
    - increasing robustness
    - achieving stable high pressure operation.

For **<u>SOEC</u>** the main development focus is on:

- Degradation rates and robustness
- Demonstration of high ramping rates (up and down) for providing ancillary servives to the electricity grid
- Pressurized operation has already been demonstrated and promises improvements on efficiency and cost if further developed
- It will also be essential if reversible operation (operating the same system both in electrolysis and fuel cell mode) is further developed for re-electrification
- An important feature of electrolysis technology is the ability to expand the potential of biomass energy considerably. This is because biomass (roughly CH_2O) is deficient in hydrogen compared to desired high-density fuels like methane or methanol. The coupling between electrolysis and biomass conversion, whether biogas upgrading or biomass gasification, should receive attention and could provide for use of oxygen generated in water electrolysis too.
- If carbon-based fuels and the related existing infrastructure is to be enjoyed in the future the scarce resource could in fact be CO_2. The use of closed cycles with SOEC/SOFC/Gas Turbines with oxygen combustion plants could provide a solution and should be studied.
- Simulations of the total energy system providing background for varying load tests on developed equipment are essential.
- Technology for large-scale storage of hydrogen, oxygen and/or CO_2 is also important enabling elements.
- Efficient power electronics development still needs priority.
- Further development of hydrogen refueling stations for energy storage and balancing and further demonstration and analysis efforts will be needed, in particular focusing on economical optimization of production and storage sizes.

12.9 Danish competition position

The topic of electrochemical energy storage is highly important for the energy transition, because it connects the large sectors of electricity, gas (storage) and transport. Besides the thermal losses in the chemical process and in the compression can be utilized in the district heating systems possibly via heat pumps. In general, Denmark holds a very strong position within electrochemical energy storage and two Danish companies offer commercial electrolysers: Haldor Topsoe and GreenHydrogen.

The world leading position of Haldor Topsøe A/S within the field of heterogeneous catalysis and synthesis gas conversion creates a unique Danish opportunity to optimize possible synergies in coupling electrolysis and synthesis gas conversion.

GrrenHydrogen is taking part in advanced RD&D projects and recently received an important order for a HyProvide™ A60 electrolyzer for on-site hydrogen generation in a NEL hydrogen fueling station in Mariestad, Sweden.

Denmark's front position within wind turbine technology and deployment, district heating, sustainable energy system optimization and biogas production forms a strong home base for further demonstration and later international roll out and exports.

12.10 Specific recommendations

It is necessary to maintain and even expand the RD&D activities within the electrolysis field if this key enabling technology is to play the foreseen role in the politically desired future energy scenarios.

Presently, Danish technology status is at the leading edge, but competition in Europe and further abroad must be foreseen to grow considerably.

There is a need for continued research ranging from fundamental materials research, identifying degradation mechanisms, next generation electrodes, electrolytes and stacking solutions to demonstration units in a sufficient scale to bridge the gap from laboratory to commercial deployment in as few steps as possible. Such demonstrations should be carefully timed and sized as they by nature are quite expensive but unavoidable in order to make the solutions a reality. The funding of such demonstration units may require a concerted effort on behalf of the different actors and funding mechanisms in play today. The demonstration should take place within different applications e.g. synthetic fuel production, methanization and hydrogen fuel.

Denmark has a unique opportunity to deploy and commercialize the chemical storage technology due to the ambitious energy policy with respect to renewable electricity generation, district heating and natural gas infrastructure, its biogas potential and synergies with other untapped biomass resources. The production of synthetic fuel is vital for meeting the energy policy objectives of being independent of fossil fuels and luckily electrolysis processes are rapidly catching up as commercial components in the energy system. Alkaline technology has been available many decades, PEM electrolysis is gaining market access these years (cf. case story above) and SOEC is still one or two decades from now to be fully commercially applicable and competitive.

12.11 Players in Denmark

Universities and research organisations

AAU

AU

DTI

DTU Energy

DTU CASE

DTU Chemistry

DTU Physics

DTU Mechanical

KU Chemistry

SDU

Industries

Greenhydrogen.dk - Alkaline electrolyzer technology

Haldor Topsøe A/S - SOEC technology, chemical conversion

IRD Fuel Cells A/S - PEM fuel cells

Blue World Technologies - methanol fuel cell systems for automotive and mobile applications.

Serenergy - High Temperature PEM-based Fuel Cells

Oticon – fuel cells in hearing aids

Widex - fuel cells in hearing aids

GreenLab Skive

Hydrogen Valley

Air Liquide - Gas handling and supply

Danish Power Systems – High Temperature Fuel Cell technology (Membrane Electrode Assemblies)

Ballard Power Systems Europe A/S (former Dantherm Power) - Fuel Cell power back-up systems

Former H2 Logic A/S (now NEL Hydrogen) - hydrogen technology, hydrogen filling stations

Strandmøllen Industrigas, - Gas Handling and Supply

Utility companies e.g. Ørsted, TREFOR, SEAS-NVE, SE – users of electrolysis technology

13. Thermal Energy Storage

On world basis, almost half[154] of final energy demand is demanded as heat but until recently thermal energy storage (TES) has only attracted limited R&D efforts (although hot water storage tanks have been developed and designed in combination with other components of the energy system, in particular in combination with CHP). However, this has changed over the last decade and now more focus is on a wide range of TES from many sides. This is reflected in EU R&D programs as well as in national Danish programs and seems well justified by the fact that thermal energy storage has actually been playing a significant role for many decades as illustrated by the hot water containers in almost all buildings and in many district heating and cooling systems in developed countries. For such storage tanks in the range from less than 1 m^3 in homes to 75,000 m^3 in a district heating system, the thermal energy (heat) can be stored from a variety of cheap heat sources, e.g. low price electricity, solar or various district heating production plants aiming at securing supply capacity for hot water in peak demand periods like morning shower time. The summed power and storage capacity of such hot water containers is enormous and the technology is likely one of the earliest storage technologies applied after industrialization.

The rationale for TES in modern and future energy systems are the same as reported in "Status and recommendations for RD&D on energy storage technologies in a Danish context" from February 2014. Heating plays a dominant role in the Danish energy system and the demand will be almost constant as heat savings will be compensated by increasing building stock. (With the still higher share of electricity from fluctuating renewable energy sources in the Danish energy system, highly efficient energy conversion technologies from electricity to heating and cooling is needed. Thermal energy storage has already been an important element in almost all Scandinavian district heating systems counting more than 400 in the range from a few hundred to 200,000 m3 up to 90 ˚C and a few up to 120 ˚C, but such storage facilities will become an even more important factor for efficient generation, supply and distribution of heat and cooling where the cost-effective heat supply and demand do not match in time or space. The energy should be stored at high or low temperatures to obtain extensive utilisation (high exergy content) of the stored energy, which also calls for efficient conversion technologies, new efficient insulation, new heat exchangers, new materials etc., and for effective thermal management within heating/cooling, process heat, power generation as well as optimised utilisation of renewable energy supply investments. Attractive features of TES systems are a broad spectrum of available temperatures and power levels as well as a multitude of technologies to transfer energy from one reservoir to another. Every individual application of energy in the form of heat or cold requires specific levels for temperature, power and energy capacity and therefore availability of a diverse spectrum of storage technologies, energy conversion technologies and system designs is needed in the future Danish energy system.

Thermal energy storage and corresponding conversion technologies comprises a number of specific technologies able to store and convert energy in different ways. The following types of thermal energy storage and conversion technologies exist:

- Sensible heat storage (SHS). Sensible heat storage is by far the dominating heat storage technology including domestic hot-water tanks, large hot-water tanks in district heating

---

[154] http://www.iea.org/topics/heat/

systems and large-scale storage in underground reservoirs or surface pits. Each of these methods requires application of specific, advanced technologies and hold an attractive potential for large-scale heat storage.
- Latent Heat Storage based on Phase change materials (PCM) and latent heat storage
- Thermochemical heat storage (TCS)

13.1 Sensible Thermal Energy Storage

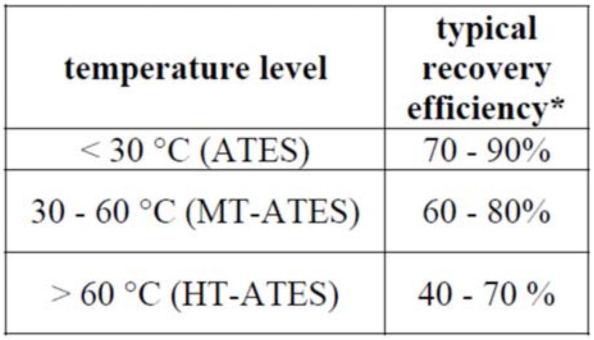
By storing heat using **sensible heat storage,** the temperature of a material – most often water - is increased by addition of heat. In this way heat is stored in the material and the storage properties depend on the heat capacity of the material as well as the thermal insulation of the system.

In the present work special emphasis is put on the following techniques within sensible heat storage:

- Aquifer thermal energy storage (ATES) - a low-temperature underground thermal energy storage (UTES) technology which functions as a seasonal storage of cold and heat. The aquifer is accessed by two wells or multiples of two wells (typically) and screened in the same groundwater aquifer. In the winter, cooled water from a heat exchanger (or a heat pump) is pumped into the cold well at a temperature below normal ground water temperature, e.g. 6 ˚C, while heated water from the aquifer is abstracted from the other well and provides a heat source for the heat exchanger (or the heat pump). In summer the cold well supply cooling directly to the cooling network in the building or to district cooling network, in the first stage directly, but supplemented by a heat pump or a chiller once the temperature increases the demand. Thus, the cold well mainly a storage for useful cold energy, whereas the warm well only stores ambient heat, which has to be upgraded by a heat pump
- High-temperature underground thermal energy storage (HT-UTES) in hot geothermal reservoirs, where energy is stored in the underground as heat by injection of heated formation water of 75–200 °C, i.e. water that is somewhat warmer than the *in situ* water of the deep geothermal aquifers. The technology is in principle similar to shallow aquifer thermal energy storage (ATES), but HT-UTES in hot geothermal reservoirs utilises that the geological formation is already heated to some extend and under pressure. Thus, the storage can - unlike the ATES - supply heat at the required temperature.
- Borehole thermal energy storage (BTES) where the principle of the storage is to heat soil and cool it down again. This is done in a closed system with vertical boreholes (30-100 m deep) filled with one or two plastic pipes and grouting.
- Pit thermal energy storage (PTES) based on sensible heat and cold storage in water pits. The water should be thermally insulated in order to minimise energy losses, by an insulated cover and by several meters of dry soil surrounding the pit.
- High Temperature Thermal Energy Storage in rock-based or steel-based materials. In this technology rocks (or steel) are heated to 600-800˚C, a temperature range which is applicable in steam turbines.

Underground Thermal Energy Storage

Underground thermal energy storage is based on storing thermal energy (heat as well as cold) by heating or cooling of porous subsurfaces layers e.g sand, sandstone or limestone. In several technologies for underground storage porous sand or lime stone is used with water as the transferring medium for thermal energy. Water of different temperatures is then injected into the underground and stored until the energy is required for use. Heat loss during the storage operation is shown for different types of aquifers in Table 5.



temperature level	typical recovery efficiency*
< 30 °C (ATES)	70 - 90%
30 - 60 °C (MT-ATES)	60 - 80%
> 60 °C (HT-ATES)	40 - 70 %

Table 5[155]. Recovery efficiencies for different types of aquifers. The efficiency* is calculated as energy out divided by energy in.

A recent review article[156] (dated 2018) has studied interesting data for use and occurrence of ATES installations and the following citation is given here: "*ATES systems achieve energy savings between 40% and 70% and CO_2 savings of up to several thousand tons per year. Capital costs decline with increasing installed capacity, averaging 0.2 Mio. € for small systems and 2 Mio. € for large applications. The typical payback time is 2–10 years. Worldwide, there are currently more than 2800 ATES systems in operation, abstracting more than 2.5 TWh of heating and cooling per year. 99% are low-temperature systems (LT-ATES) with storage temperatures of < 25 °C. 85% of all systems are located in the Netherlands, and a further 10% are found in Sweden, Denmark, and Belgium. However, there is an increasing interest in ATES technology in several countries such as Great Britain, Germany, Japan, Turkey, and China*". It can be noted here, that in particular for Denmark several new ATES installations have emerged recently – two examples are the ATES system at Copenhagen Airport, Kastrup, Bjerringbro district heating, Widex office building and another at Bispebjerg Hospital in Copenhagen, and furthermore many others are in the pipeline

Drilling a well in the underground to a depth of several km or even just 100 m is expensive and the risk for not reaching exploitable subsurface formations is high. This constitutes a serious barrier for introducing the technique in many locations. On the contrary, the underground offers large storage volumes in porous layers, and the benefit of a vertical geothermal gradient of 25-30 ºC/km in Denmark, potentially reducing the loss of heat from stored water or brine.

---

[155] High-temperature aquifer thermal energy storage (HT-ATES): sustainable and multi-usable B. Drijver, M. v. Aarssen, B. de Zwart, Innostock 2012, The 12th International Conference on Energy Storage, Lleida, Spain, May 16th - 18th 2012

[156] Worldwide application of aquifer thermal energy storage – A review, P. Fleuchaus, B. Godschalk, I. Stober and P. Blum, Renewable and Sustainable Energy Reviews, **94**, July 2018, DOI: 10.1016/j.rser.2018.06.057}

For all underground storage technologies caution must be taken not to conflict with drinking water resources. In Denmark potable water guidelines[157] require temperatures below 12 °C to secure taste of the water but also to minimize risks for microbiological pollution.

Normally a precondition for approval is that there is energy balance during a year, so that the injected heat is compensated by the same amount of extracted heat.

There can however also be an important symbiosis between ATES and ground water. The ground water below many old industrial sites are contaminated and the contaminated water may flow towards drinking water wells. In that case it is necessary to pump up the contaminated water to redirect the flow. Therefore, carefully planned, ATES can help to solve this problem by cleaning the all water or by pumping the water back to a recipient.

13.1.1. Low Temperature ATES

LT-ATES technology description
Different techniques are applied in underground thermal energy storage. The most widespread technique is – as mentioned above – low temperature Aquifer Thermal Energy Storage, LT-ATES, where temperatures are below approx. 25 °C. The depth of the storage volume is typically in the range 100-200 m and a smart way to utilize ATES is a combination of seasonal and sequential storage of heat and cold (summer and winter respectively) as illustrated in Figure 62.

ATES is quite common in the Netherlands, partly because the subsurface conditions are attractive for utilization of the technology, which lowers the investment risk of drilling wells, but also because of a very dedicated Dutch policy on the technology. Since 1995, the implementation of ATES systems in the Netherlands has grown substantially. In 2015 there were 2,500+ systems in place[158],[159] (compare 1990:10, 2000: 200, 2010: 1500[160] with a total capacity superior to 1,000 MW. Projections of installed systems for the year 2020 surpass the number 20,000, contributing to a 10% national reduction of GHG emissions.

ATES systems hold a large potential for reducing CO_2 emissions related to heating and cooling for buildings by district heating and cooling as well as process cooling in industries, because the technology can deliver free cooling, combined heating and cooling via electric heat pumps in combination with seasonal storage of the heat production. In district heating and cooling systems with thermal storage and a combination of production plants, the electricity to be used in combination with ATES can to some extend respond to fluctuating electricity prices and thus contribute to integration of fluctuating energy generation.

---

[157] http://www.klimatilpasning.dk/sektorer/vand/grundvand-og-vandforsyning/drikkevand. Accessed November 2018.

[158] The Netherlands Country Update on Geothermal Energy, V.v. Heekeren and G. Bakema, G, World Geothermal Congress 2015, Melbourne.

[159] Dutch Policy on ATES Systems, Dutch ATES, 2016

[160] Status and recommendations for RD&D on energy storage technologies in a Danish context, p 96, EUDP and Energinet.dk, February 2014

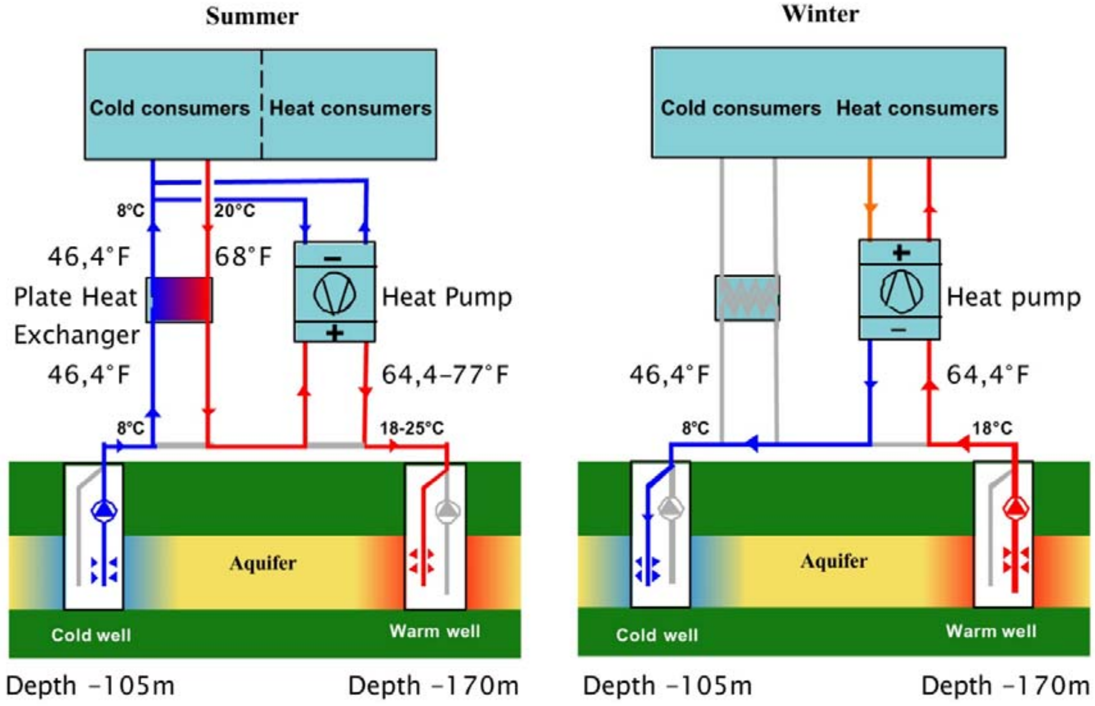


Figure 62. Principles for seasonal use of ATES[161].

The principle of ATES as shown in Figure 62 is as follows: At summer, cold water 8 ˚C is retrieved from a cold well in the underground and used for cooling purposes. After use the cold water has been heated and is returned to the warm well at 18-25 ˚C. The effects are boosted by a heat pump as illustrated in the “Summer” figure to the left. At winter – oppositely - warm water at 18 ˚C is retrieved from the warm well and used for heating where after cold water at 8 ˚C is returned to the cold well. Also in this mode of use a heat pump is applied to boost the temperature obtained from the warm well. The pair of cold and warm well is called a dipole.

LT-ATES status in industry and research

LT-ATES is a mature technology and in Denmark the total number of installed plants is about 25-30. Several private companies and consulting engineers offer components and services aimed at constructing LT-ATES plants (see section on players below). Furthermore, LT-ATES owners – like Bispebjerg Hospital and Copenhagen Airport – may assist with user information and experience.

Undoubtedly, the status in the Netherlands and a few other countries is higher than the in Denmark due to the higher number of plants in those countries.

LT-ATES applications

Danish ATES plants are still predominantly established as individual, mainly privately owned plants with a capacity of around 0,5 to 5 MW with a cooling COP of 50 to 60 and a heating COP of 4-5. Whereas the early plants were mainly serving a need for cooling in the industry, the later plants are typically constructed to supply both cooling and heating in large buildings and in district heating and cooling. Denmark is among relatively few countries until now to employ ATES technology in heating and cooling. Around 25-30 plants have been installed

---

[161] http://www.climatetechwiki.org/technology/jiqweb-utes. Retrieved October 2018.

and more are likely to come, The latest is underway at Bispebjerg Hospital, where currently an ATES system is being finished[162] (planned operation January 2019) to supply a new part of the hospital with cold and heat.

LT-ATES geological considerations

Generally boreholes for LT-ATES plant must pump from and reinject to the same aquifer. To obtain this, knowledge of aquifer extension and groundwater flow is required. Furthermore, it must be ensured that the boreholes can provide and reinject the amount of water needed. Supplementary investigations required by law is specified in the act[163] regulating heat extraction and groundwater cooling plants.

A preliminary screening and datamining of areas potentially suited for LT-ATES have recently been performed by GEUS[164].

LT-ATES Development needs

LT-ATES is a well-known technology based on well developed, existing components. Major challenges and risks associated with the technology are related to

- costly exploration phase is needed to verify the aquifer storage resource
- high costs associated with drilling the wells
- geological uncertainties since high yielding aquifers are needed but not always present. This leads to risk that the drilled wells will not be useful and applicable because of insufficient properties of the subsurface
- a time-consuming approval process must be completed. An approval to use an aquifer for heat and cold storage cannot be taken for granted, and an application must include detailed information from geological investigations and numerical modelling, documenting that the ATES plant will not be a threat to current or future utilization of groundwater for drinking water purposes.
- Seismic risks must be assessed
- Mapping on a national scale of the potential for heat and cold storage in shallow aquifers taking district heating and cooling infrastructure and geological conditions into consideration
- National guidelines and municipal planning of the environmentally safe usage of ATES with respect to groundwater resources for drinking water
- Further validation of model predictions of flow velocity of cold and heat plumes downstream ATES plants using data from existing Danish ATES facilities
- Studies of combining environmental protection against contaminated ground water with ATES

Specific recommendations for LT-ATES

The required R&D activities and regulatory initiatives to support ATES are:

ATES seems to gain a more prominent position in the mind of authorities, energy planners, consultants and building architects. However, municipalities should be more keen to include ATES in their municipal energy planning and water supply planning and municipalities with

---

[162] https://www.bispebjerghospital.dk/nythospital/nyt-og-presse/nyheder/2017/Sider/Danmarks-st%C3%B8rste-grundvandsk%C3%B8leanl%C3%A6g-er-p%C3%A5-skinner.aspx Accessed January 2019

[163] Bekendtgørelse om varmeindvindingsanlæg og grundvandskøleanlæg, BEK nr 1716 af 15/12/2015

[164] Ditlefsen et al. 2019 (in preparation). A web application is available on http://data.geus.dk/geusmap/?mapname=varmelagring Accessed February 2019

an ATES potential should be obliged to plan for the efficient use of the potential e.g. by avoiding the many ATES installations on building level to eliminate the risk of interfering with each other. Installations should be kept centralized and operated by the district heating companies. In particular, it should be an obligation to plan for efficient use of ATES in district cooling compared with building level ATES. Furthermore, cooperation and coordination between water and district heating utility companies will be of paramount importance and should be facilitated in the legislation.

If ATES could in advance be considered an option in the energy planning (e.g. the integration of ATES in new buildings, or as part of the total energy supply of district heating and cooling concepts in new areal development projects), it would be possible to plan for a longer permit, test and construction period than for conventional dry cooling, and its successful integration would be more likely.

In Denmark ATES plants are established on a first-come, first-served basis as in most other countries. The disadvantage is that the individual ATES plants are not necessarily integrated in the energy supply structure in the most coherent, energy efficient and socio-economic favourable way. Also this first-come, first-served principle makes it impossible to plan for the most efficient use of the potential energy storage capacity of a given aquifer.

It is recommended that water and district heating utility companies should be given the possibility of investing in ATES and in independent district cooling companies. This would demand new legislation. According to current legislation district cooling companies can only be founded by commercial companies and without access to municipal financial support or guaranties. This restriction is justified by the perception that district cooling (contrary to district heating) isn’t a public benefit to all citizens. However, for ATES plants both the heating and cooling are to some extent of equal standing. Therefore it can be justified that municipalities are given legal access to invest in district cooling and hence ATES.

As wind power becomes dominant in Danish power supply (50% from 2020), heat pumps and energy storage will play an important role in the main energy supply system. As a cooling technology, ATES reduces the summer peak electricity loads hence reduces risk of power system instability. As a source of heating, ATES offers the opportunity to substitute fossil fuels for heating by wind generated electricity via heat pumps. After the reduction in electricity taxes for heating, ATES for heat production has become considerably more viable from a financial point of view. In order to tap these potential benefits, the ATES potential should (as previously mentioned) be integrated into the municipal heat planning following the principles of maximizing the socio-economic and environmental benefits laid out in the current heat planning legislation. This would encourage the use of ATES in ways best possibly suited to the local conditions, including local demands for cooling and heating, annual load distribution of cooling and heating etc. The optimum use of ATES would often involve both heating and cooling. In order to secure an efficient integration of these two types of energy supply, district heating utilities should be given access to also supply cooling at least to the extent that this would increase the total economic and environmental benefits.

The potential for CO2 emission reduction by ATES is estimated in [165] to be 220.000 tons. If ATES is fully integrated in collective energy supply in the best possible way, it is our evaluation (supported by the Dutch experiences), that a much larger figure can be achieved. Individual ATES plants should be prohibited in areas where there is collective district heating and where district cooling is planned.

---

[165] Grundvandsvarmepumper og –køling med grundvandsmagasiner som sæsonlager. Enopsol ApS, DONG Energy A/S, Hundsbæk & Henriksen A/S, Cenergia ApS, SBI, 2007. Elforsk PSO-F&U.

The potential for CO2 emission reduction by ATES is in the same reference estimated to be 220.000 tons. If ATES is wise fully integrated in collective energy supply it is our evaluation (supported by the Dutch experiences), that a much larger figure can be achieved.

LT-ATES players in Denmark

- Multi Køl & Energi A/S, Enopsol A/S, GEO A/S as consultants and contractors
- Brøker A/S as drilling contractor
- GEUS as research institution has a strong knowledge about thr Danish supsurface
- Grontmij A/S, COWI A/S, Moe A/S, Niras A/S, PlanEnergi, Rambøll Danmark A/S, HUNDSBÆK & HENRIKSEN as consultants
- Heat Pumps, Heat exchangers, Pumps, Control Systems: Several

13.1.2 HT-ATES

HT-ATES technology description

High-temperature underground thermal energy storage (HT-UTES) is applied in hot geothermal reservoirs, where energy is stored as heat by injection of heated formation water of 75–200 ˚C, i.e. water that is somewhat warmer than the water already found in the deep geothermal aquifers that are utilized. Principally, the technology is similar to the aquifer thermal energy storage (ATES) described above, but HT-UTES in hot geothermal reservoirs utilizes that the geological formation is already heated to some extend and under pressure.

A Danish project on HT-UTES was carried out on the period 2011-2017.The aim of the project – the HeHo project[166] - was to investigate the feasibility of storage of hot water in warm geothermal reservoirs in Denmark. The idea was that the relative high aquifer temperature will minimize heat loss due to convection. The hot water to be injected could be generated by surplus heat from renewable but intermittent energy sources like sun, wind and waste incineration. The hot aquifer storage should be directly integrated with geothermal energy extraction and district heating. The project found, that sandstones of the Gassum Formation (north Jutland) at a depth of 1700 m are well suited for the purpose. More than half of the injected energy can be retrieved and that the sandstone will only suffer minor loss of permeability and strength as a consequence of hot water injection. The results would have had much more societal impact if political decisions had supported the use of geothermal energy in Denmark.

HT-ATES applications

HT-ATES technology is not yet established in Denmark, but the technology can be implemented in combination with existing or new geothermal plants, thereby enabling minimal heat loss, large storage capacity and reasonable additional costs. Furthermore, the geothermal plant capacity will be increased and waste heat from warm summer periods can substitute fossil fuel-based heat production in peak-load winter periods.

The excess heat needed to heat exchange the hot formation water to the even higher injection temperature is currently believed to be available from waste incineration plants, industrial processes, solar energy sources, or combined heat and power plants. In such facilities, excess heat is typically produced during summer when the geothermal plant is available for storage purposes.

---

[166] https://energiforskning.dk/en/project/heho-heat-storage-hot-aquifers. Accessed December 2018.

HT-ATES development needs
Major issues requiring attention further research are:

- recovery efficiency (cf Table 5)
- impact on formation water composition (unwanted mobilization of chemical species in the underground)
- scaling of material in the underground
- seismic risks must assessed
- impact on formation water geochemistry and microbiology which is not fully known
- changes in the reservoir due to dissolution and precipitation of minerals because of changes in temperature, formation water composition and flow rates
- alternative water treatment methods
- optimization options to improve the recovery efficiency.

HT-ATES specific recommendations
Despite a growing interest in the technology and promising research results there is still a need for a proof-of-concept in order to kick-start the deployment of the technology, because the investment in a geothermal plant with HT-UTES facilities is rather large compared to the budget of a typical Danish district heating company. Thus, the main catalyst to initiate deployment of HT-UTES will be to establish a successful demonstration plant. Establishment of such a plant would include a variety of tasks such as exploration drilling and coring, pumping-tests, laboratory experiments, and numerical simulation of formation pressure, heat flow, etc. Such a demonstration plant could very well be established in combination with a possible large future geothermal plant in Copenhagen.

In short it is recommended that:

- Full attention is paid to the results and recommendations, which can be derived from earlier and on-going research projects.
- Advanced computer models within topics related to the technology are applied and developed to save as much effort (costs) as possible and optimise plant design before initiating demonstration projects.
- Based on results obtained already, establishment of a demonstration plant with HT-UTES in deep geothermal reservoirs should be considered.
- Further R&D related to the technology and the heterogeneity of the potential reservoirs (not covered already) should be supported.

HT-ATES Players in Denmark

- DFG – Danish Geothermal District Heating (in Danish: Dansk Fjernvarmes Geotermiselskab) is a geothermal consultant and participant in the two Danish DSF research projects.
- DTU BYG – Technical University of Denmark, DTU Civil Engineering is Project Lead in the “HeHo – Heat Storage in Hot Aquifers” DSF research project.
- GEUS – Geological Survey of Denmark and Greenland is actively taking part in several project related to HT-ATES, and is furthermore geological-geophysical consultant for all geothermal projects in Denmark.
- HOFOR (Greater Copenhagen Utility), CTR (Metropolitan Copenhagen Heating Transmission Company), and VEKS (The Heat and Power Company of Western

Copenhagen) are all district heating suppliers that consider HT-UTES in combination with a possible future geothermal plant in Copenhagen.
- Sønderborg Fjernvarme and Thisted Varmeforsyning are district heating companies utilizing geothermal energy.

Thermal Energy Storage in Solids

13.1.3 High Temperature storage in rocks

Technology description

In this technique a heat-resistant material is heated by electricity (from wind or solar) to high temperatures (usually above 400 ˚C). Materials used are often cheap natural rock materials like basalt or similar, but also fabricated materials like cement-based have been used.

Many natural rock materials have a heat capacity of approx. 0.7 J/g·K rising to more than 1 at 500 ˚C[167]. Increasing temperature of 1 m^3 of rock bed with a filling degree of 75% and a density of 3 g/cm^3 by 600 ˚C leads to a storage capacity of approx. 300 kWh/m^3 or about half of the capacity of an advanced battery. Losses by storage over time can be minimized by use of very thick but cheap layers of insulation material.

The heat stored at high temperature can be reused to drive a steam turbine and regenerate electricity with efficiency about 30-35% (depending on the operation conditions) and the waste heat can be utilized in district heating systems as is well known from combined heat and power plants.

The technology is still under development in several laboratories[168] and the development meets significant challenges for reaching optimal operation. As examples:

- the applied storage materials must be durable and resistant to repeated thermo-cycling
- forces in the rock bed from repeated expansion and contraction in consequence of the thermal cycling must also be handled
- the temperature distribution in the rock bed should be kept as close to two levels (one part at maximum temperature and the other part at minimum temperature – a steep temperature cline) as possible to maximize the exergy of the stored energy. This should be done during charging as well as discharging.

Applications

The technology is suitable for electricity generation and preliminary calculations[168] show that economy of such plants appear favorable in the regime of future fluctuating electricity prices – in particular if the waste heat resulting from driving a turbine can be utilized for heating purposes. The anticipated storage period is weeks down to days. Even if the storage plant can be designed (insulted) to maintain the stored energy for longer periods - up to seasonal – with acceptable loss, the plant must be used frequently to keep Levelized Cost of Storage low (this argument is indeed valid for all storage technologies).

---

[167] E. C. Robertson, "Thermal properties of rocks," United States Department of the Interior Geological Survey, Reston, Virginia, USA, 1988.

[168] High-Temperature Thermal Energy Storage for electrification and district heating, A.S. Pedersen et al., Proceedings of the 1st Latin-American SDEWES conference, Rio de Janeiro, Brazil, 2018

Siemens[169], [170] together with Hamburg Energie and TUHH are currently establishing a complete thermal store in Hamburg. The full-size facility will be able to store around 36 megawatt hours (MWh) of energy in a container with around 2,000 cubic meters of rock. Via a boiler, the heat it contains will generate so much steam that a Siemens compact steam turbine can generate output of up to 1.5 megawatts of electricity for up to 24 hours a day. Siemens expects to generate effectiveness of around 25% even in this early development phase. In the future the concept has the potential for an effectiveness of around 50%. Partner Hamburg Energie will investigate appropriate marketing options for the stored energy.

Proof of system is expected to start operation in 2019.

Development needs
As indicated above the HT-TES technology is still under development. Main challenges to be met to allow the technology to become industrially applicable within the coming 5-7 years are:

- identification of sufficiently durable and stable storage materials in terms of chemical and mechanical stability. This will require accelerated thermal cycling experiments with promising rock materials
- identification of optimal balance between rock size and size distribution as well as rock shape and airflow through the bed (hot or cold)
- optimal geometrical design of rock bed to support and maintain optimal temperature cline between the hot and cold parts of the rock bed

Specific recommendations
The technology is still immature and further experimental investigations must go on before a larger scale demo-plant can be recommended in Denmark. However, if the results of an ongoing EUDP project, led by SEAS-NVE, are positive, the technology seems ready for upscaling.

Players in Denmark

- SEAS-NVE
- DTU
- Aalborg CSP

Thermal Energy Storage in Liquids

13.1.4 Thermal Energy Storage in molten salt

Molten salt is another option for storing thermal energy sensibly at high temperature. Molten salt is heated sensibly, similar to water but at much higher temperature. The heated molten salt is then stored in large insulated tanks for later reuse (also similar to water).

The materials used for the purpose are inorganic salts operated at typically 500-600˚C allowing production of superheated steam via a heat exchanger to power a conventional

---

[169] https://www.siemensgamesa.com/en-int/products-and-services/hybrid-and-storage/thermal-energy-storage-with-etes. Accessed December 2018.
[170] https://www.siemens.com/press/en/pressrelease/?press=/en/pressrelease/2016/windpower-renewables/pr2016090419wpen.htm&content[]=WP Accessed January 2019

steam turbine and generate electricity. The technology is often used in Concentrated Solar Power (CSP) plants to store solar energy from daylight time for use at nighttime, when solar power is not available. The principles of molten salt storage and CSP is shown in Figure 63.

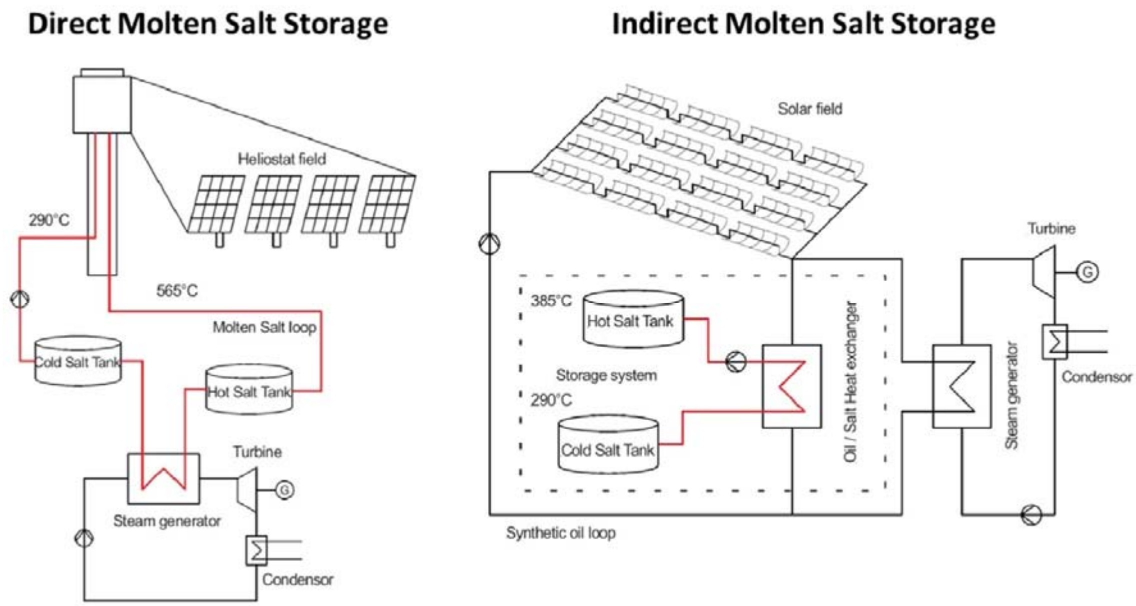


Figure 63[171]. Principles of salt storage in combination with Concentrated Solar Power

As for water, it is important to secure that the salt does not solidify in the system, since that may lead to damage (due to contraction and expansion) and/or costly re-liquefaction of the salt. However, the melting point of the salt or salt mixture used can be chosen sufficiently low and the storage temperature sufficiently high to secure that solidification does not occur. Salts commonly used in molten salt storage technology are nitrates or nitrides but also carbonates. One material option, sometimes called "solar salt", is a eutectic mixture[172] of 40% KNO_3 and 60% $NaNO_3$ by weight. It has a fusion point around 222°C. Table 6[173] shows some key properties of carbonate salt mixtures developed for CSP.

Molten nitrate Solar Salt (binary mixture of $NaNO_3$ and KNO_3) is not aggressive with regard to corrosion of a variety of metals and alloys, including stainless steels and other ferrous alloys[174].

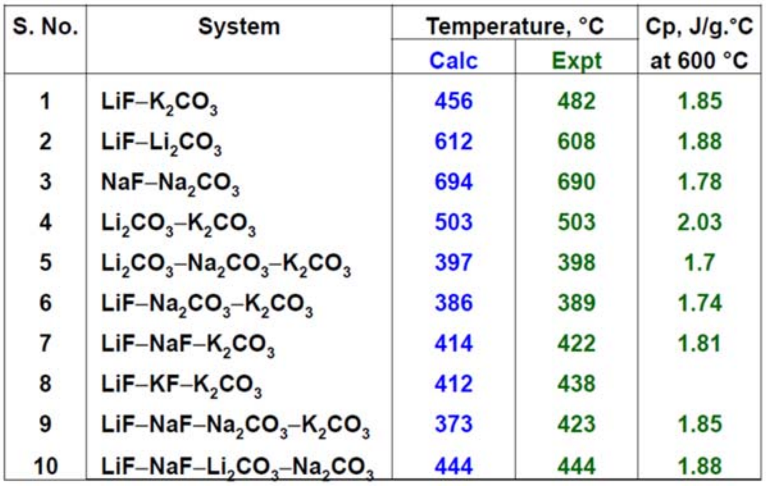
---

[171] Advanced heat transfer fluids for direct molten salt line-focusing CSP plants, A. Bonka, S. Saub, N. Urangac, M.Hernaizc and T. Bauerd, Progress in Energy and Combustion Science, Volume 67, July 2018, Pages 69-87.

[172] Linear Fresnel reflector (LFR) plants using superheated steam, molten salts, and other heat transfer fluids, M.Collares-Pereira, D.Canavarro and L.L.Guerreiro, in Advances in Concentrating Solar Thermal Research and Technology, Woodhead Publishing Series in Energy, 2017, pp 339-352

[173] Novel Molten Salts Thermal Energy Storage for Concentrating Solar Power Generation, R. G. Reddy, University of Alabama.

[174], "Corrosion of Alloys and Metals by Molten Nitrates", R. W. Bradshaw and S. H. Goods in High Temperature Corrosion in Molten Salts, C. A. C. Sequiera, Editor, TransTech Publications, Zurich, Switzerland, 2003, ISBN 0-87849-917-2.



S. No.	System	Temperature, °C		Cp, J/g.°C
		Calc	Expt	at 600 °C
1	$LiF–K_2CO_3$	456	482	1.85
2	$LiF–Li_2CO_3$	612	608	1.88
3	$NaF–Na_2CO_3$	694	690	1.78
4	$Li_2CO_3–K_2CO_3$	503	503	2.03
5	$Li_2CO_3–Na_2CO_3–K_2CO_3$	397	398	1.7
6	$LiF–Na_2CO_3–K_2CO_3$	386	389	1.74
7	$LiF–NaF–K_2CO_3$	414	422	1.81
8	$LiF–KF–K_2CO_3$	412	438	
9	$LiF–NaF–Na_2CO_3–K_2CO_3$	373	423	1.85
10	$LiF–NaF–Li_2CO_3–Na_2CO_3$	444	444	1.88

Table 6. Melting point and Heat Capacities of Carbonate Salt Mixtures

Applications

As mentioned liquid salts for thermal energy storage is applied in several concentrating solar power energy storage.

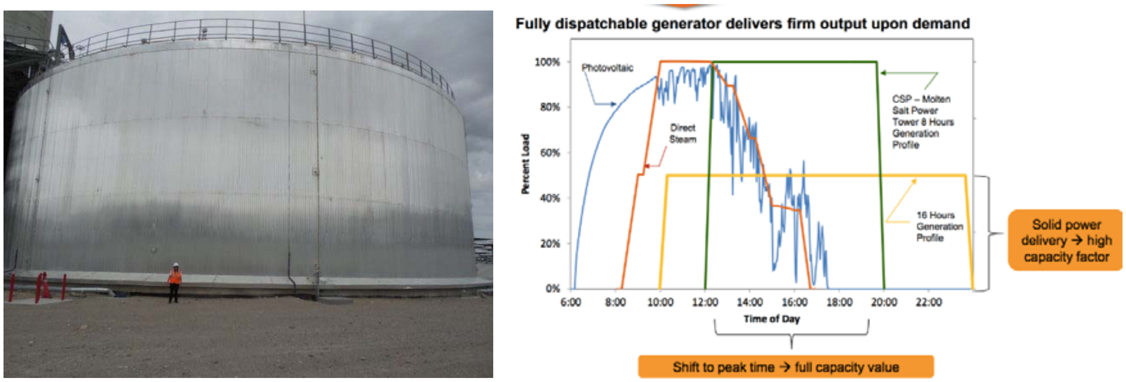


Figure 64. Left[175]: A hot storage tank at the 110 MW Crescent Dunes CSP power tower plant in Nevada holds molten salt at 565°C and can deliver 10 hours (1100 MWh) of stored solar energy at any time day or night. Right[176]: The principles of combining molten salt storage with solar power (same plant in Nevada).

Development needs

- Since the technology depends on insulation to keep temperature above the melting point of the used salt, improved insulation techniques and materials are required. Furthermore, the high temperature in combination with salts may set tough requirements on materials used in pipes, valves, fittings and containments in general.
- Storage systems for solar power could be developed on thermo-chemical reaction systems (see also section on this technology)

---

[175] http://www.solarpaces.org/how-csp-thermal-energy-storage-works/ Accessed February 2019

[176] http://reneweconomy.com.au/wp-content/uploads/2013/07/Screen-Shot-2013-07-04-at-8.54.01-AM.png Accessed February 2019

Specific recommendations

Until now, the technology has mainly found practical use in areas with more stable and intensive PV conditions than in Denmark (e.g. South Europe, North Africa, southern parts of the USA etc.). Therefore no specific recommendations (apart from the mentioned development needs) should be given here.

Players in Denmark

Aalborg CSP (has recently signed a 600 MWe order with Shanghai Electric for no-leaks steam generation systems to a Dubai CSP project, based on 700MW CSP+250 MW PV)

13.1.5 Hot water storage in tanks

Technology description

Most applied Low Temperature Sensible Thermal Energy Storage (LT-TES) techniques utilize TES in water up to approx. 90 ˚C and are found in most district heating systems as well as at building level as hot water containers installed in extremely many residences as well as commercial and industrial buildings, where occasional demand for warm or hot drinking or sanitary water occurs. The volume of such water tanks vary greatly – between 0.01 in small cottages and 75.000 m^3 up to 95 ˚C and 24,000 m^3 up to 120 ˚C in district heating systems[177] (in Central Europe there are storage tanks, which can store up to 160 ˚C water from waste incineration, but this is expensive due to larger pressure).The total summed number of such installed containers constitutes an enormous storage capacity in terms of energy and power. In Denmark and other countries, where district heating plays a significant role in space heating, most hot water containers are supplied by heat from the system hot forward water. However, in other countries, the containers are heated by electricity and coupled directly to the electricity grid. This offers excellent opportunities to serve as quite fast upregulating as well as downregulating reserves in the electricity and the potential is already utilized in some countries (e.g. France and Germany), where the reserve capacity is traded commercially between suppliers and customers. The trading is usually found in connection with nuclear power installations, which are optimally operated at constant power, but the trade of capacity and availability can equally well be utilized in energy systems based on variable, renewable sources, where production does not match demand.

In recent decades, solar thermal power – often in combination with other power sources - has become of widespread use in buildings and in district heating systems. However, because of the inherent daily peak production of solar technologies storage of the thermal energy is often required and here hot water storage tanks can be used appropriately.

Very large hot water storage tanks (see Figure 65) are used in district heating systems to even out differences between heat demand and production

---

[177] https://stateofgreen.com/en/partners/ramboll/solutions/district-heating-in-the-copenhagen-region/. Accessed November 2018

Figure 65. District heating water storage tanks (to the left) in connection with a power plant[177].

Efficiency of hot water storage in insulated tanks depends on

- Conversion efficiency from applied energy source to heated water (usually high for electricity, but lower if heat exchanges are needed as in district heating systems)
- tank design (in particular surface to volume ratio – for a cube and a sphere this is inversely proportional to cube length/sphere radius)
- efficiency (thickness) of insulation
- applied storage periods
- temperature of the stored water (thermal diffusion is proportional to temperature difference)
- temperature stratification in the tank during charging and storage

Status in Danish industry

Because of a strong and wide-spread district heating sector in Denmark, developed over very many years, and because of the importance of thermal energy supply in general (as mentioned earlier about 50% of energy demand is demanded as heat) thermal energy storage in containers has a strong status in Denmark compared to many other countries. The Danish position is seen clearly in huge hot water containers within the district heating system and in the domestic hot water containers found in almost all households.

Surprisingly Denmark lacks behind concerning similar cold water storage tanks, probably because of the lack of planning for district cooling. However the first steel tank, (2,000 m^3 for district cooling), is being established in 2019 by Taarnby Forsyning

Applications

Applications are widespread in Denmark and abroad in securing hot water supply and curtailing need for peak production. Many Danish companies have been operating for many decades on commercial markets for the technology

Development needs

Even if the technology has been optimized for very many years development efforts are still required. Stratification within containers and more effective insulation are issues to be addressed.

Specific recommendations

Much development effort can be left to industry. Only in few and special cases collaboration between industry, technological service organisations and universities.

Players in Denmark

- Vølund Varmeteknik, www.volundvt.dk/
- Metro Therm, www.metrotherm.dk
- Danfoss
- Grundfos
- Many district heating companies
- Rambøll Denmark

13.1.6 Borehole Thermal Energy Storage

Technology description

In Borehole Thermal Energy Storage (BTES) the storage principle is to heat soil and subsequently retrieve the energy by cooling down the soil again. This is done in a closed system with vertical boreholes (usually 30-100 m deep) filled with grouting. Tubes are mounted in the grouting and some liquid serves as energy transfer agent. The optimal distance between the boreholes is usually about 3 m, but this distance as well as geometrical placement of the holes should be determined/optimized by thermal modelling based on the local thermal properties of the underground formations to be utilized. BTES basically uses soil as a thermal battery by heating it during summer and retrieving heat during winter. The principle of borehole storage is shown in Figure 66.

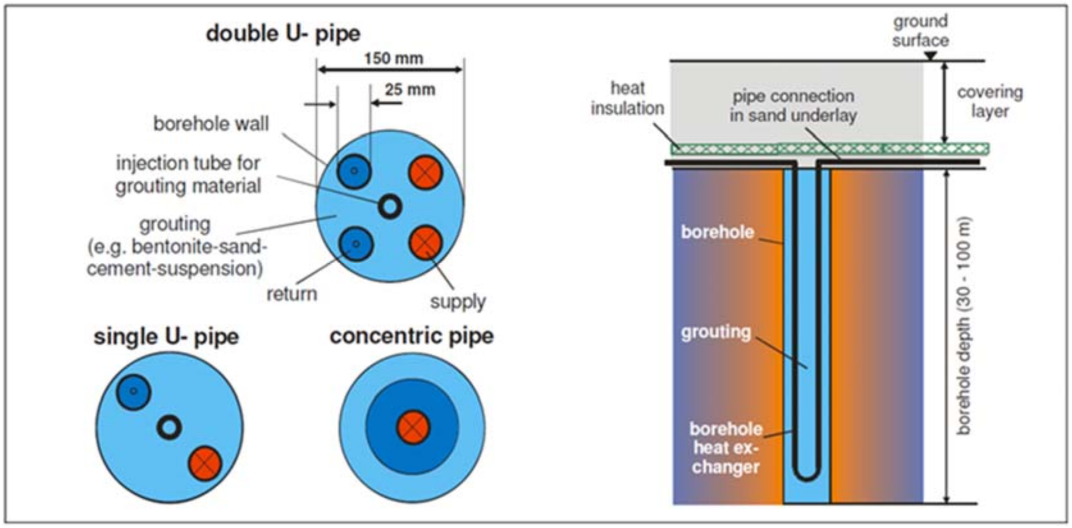


Figure 66. Principle of construction of borehole heat exchangers and part of a borehole energy store[178].

---

[178] Integrated Cost-effective Large-scale Thermal Energy Storage for Smart District Heating and CoolingDesign. Aspects for Large-Scale Aquifer and Pit Thermal Energy Storage for District Heating and Cooling, T. Pauschinger (Editor), T. Schmidt Steinbeis Research Institute Solites, Germany, P.A. Soerensen, PlanEnergi, Denmark, A. Snijders, IFTech International, The Netherlands, R. Djebbar, Raymond Boulter, NRCan, Canada, J. Thornton, TESS, USA, IEA, Technology Collaboration Programme on District Heating and Cooling including Combined Heat and Power, September 2018.

Applications

The first BTES projects carried out in Sweden[179] in the 1980s used BTES for storing solar or waste heat from summer to winter for space heating. However, today BTES is used also for cooling purposes. BTES installations are found in several other countries like the US, Canada and Germany.

Until now only one BTES facility has been established in Denmark. In 2012, a BTES facility was established in connection with Brædstrup District Heating in Denmark. The plant was a test plant and the construction was coordinated by PlanEnergi and reported in [180] in 2013. Since then experimental experience has been achieved, but not yet reported. The plant is very stable and secure, but subjected – like all BTES facilities - to somewhat slow exchange rates due to the need for heat transport in the soil, which sets limits to the maximum thermal power (J/s) that can be exchanged in the ground.

According to the reference in footnote 180 the main data for the Brædstrup boreholes are:

Data for the storage in Brædstrup:

- Built 2011-12
- Size: 19.000 m^3 earth
- Price 270.000 € excl. Transmission pipe and buffer tank or 0.43 €/kWh
- Temperatures 10-70^o C
- Charge and discharge capacity 300 – 600 kW

The performace of the facility over the period 2014-2017 can be found in Figure 67[181]. The storage efficiency of 65% is lower than the design value of 74% calculated for long-term operation. According to the authors, the difference can mainly be explained by the fact that the Brædstrup BTES plant in the considered period was still in its start-up phase which, according to simulations, normally takes between 3 to 5 years.

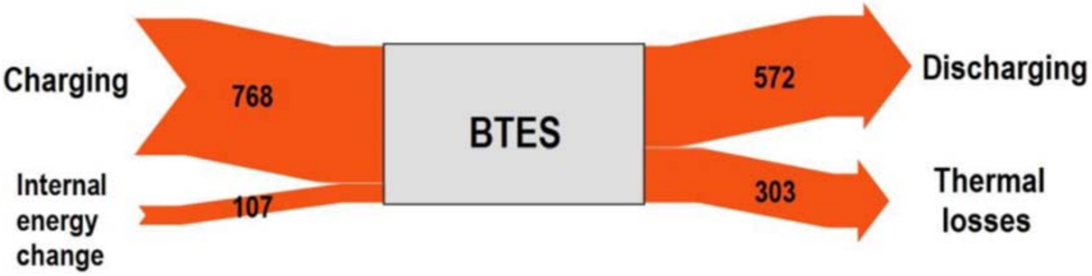


Figure 67[181]. Heat balance for the BTES in Brædstrup for the period 2014-2017, numbers in MWh.

BTES geological considerations

In order not to lose, the stored heat to the surroundings groundwater flow around a BTES plant is unwanted. Therefore, locations with limited groundwater are preferred. In a Danish context these will typically be found in:

---

[179] The use of borehole thermal energy storage (BTES) systems, M. Reuss, Advances in Thermal Energy Storage Systems, Methods and Applications, Woodhead Publishing Series in Energy 2015, Pages 117-147.

[180] Boreholes in Brædstrup, Final report, June 2013, EUDP, project no. 64012-0007-1

[181] Follow up on large scale heat storages in Denmark, P.A. Sørensen, J. Larsen, L. Kjærgaard, J. Frey, T. Schmidt, H. Bjørn and S. Furbo, Final Report, EUDP Project No. 64014-0121, Dec. 2018

- Areas with a thick unsaturated zone
- Areas with homogeneous clay of low permeability
- Areas with limestone of low permeability
- Areas with hard bedrock of low permeability

A preliminary screening of areas suited for BTES has recently been performed by GEUS[164].

BTES development needs

BTES is an established technology based on documented and well-known techniques, but still wider experience and development is lacking concerning:

- cheaper borehole drilling costs (common for underground technologies)
- improved heat exchange rate in the subsurface
- exhaustive learning from existing plants
- Continued monitoring of the pilot plant in Brædstrup.
- Attention on existing boreholes for ground source heating – some of them have installed facilities for BTES
- Experiences with cheaper drilling of boreholes.
- Full-scale demonstration plant.
- Demonstration plant in water filled clay.

BTES specific recommendations

For BTES, the next steps are recommended to be

- demonstration of the integration into smart energy systems as for PTES and
- demonstration in centralised CHP systems.

Players in Denmark

- Geotechnical investigations: GEO
- Drilling: Several
- Import of probes / production of probes: ROTEX
- Pipes in boreholes: Wawin
- Cover building: several
- Control system: several
- Consultancy: PlanEnergi
- Education: VIA University College, Horsens

12.1.7 Pit Thermal Energy Storage

Technology description

PTES is done by heating water in a surface pit. The technology has been developed over many years in Denmark, where the first larger project started in 1995 and in 2014 the world´s largest pit storage facility was established in connection with Vojens Fjernvarme.

Characteristic numbers for this plant is[182]:

- Surface area: 23500 m^2
- Volume: 203000 m^3
- Depth: 14 m
- Solar thermal power from 70000 m^2 solar collectors

---

[182] Her er verdens største varmelager og solfanger, S.Wittrup, Ingeniøren, 26th September 2014

- Maximum temperature: 80-90 ˚C at top and 40-60 ˚C at bottom (due to stratification)
- Charging season: April - September
- Minimum temperature; 40-45 ˚C
- Discharging: October - January
- 2000 consumers connected
- Expected annual savings on heating bill: 10-15 %
- Expected annual CO^2 saving: 6000 t

The warm or hot water must be covered by a lid to insulate and prevent evaporation of water, which would lead to a significant heat loss. At Vojens Fjernvarme a 0.7 m thick lid[183] of LECA contained in 2 mm HDPE plastic material able to adapt to shape and volume changes of the water. Unfortunately, this lid construction appears to be vulnerable to ravage.

During operation, warm water is injected into different layers of the pit depending on its temperature and the current stratification, whereas warm water is always taken from the top layer.

Figure 68 shows measured performance of the PTES in Dronninglund during 2016[184]. A very high efficiency (discharged energy over charged energy) of the plant is clearly seen.

Figure 68. Energy flow diagram of the Dronninglund PTES plant in 2016 after monitoring data for the year. Numbers in MWh.

Figure 69. Left: Pit Thermal Energy Storage at Dronninglund in Denmark. The storage volume is being filled with water and the heavy plastic liner separating water from the soil is

---

[183] Verdens største damvarmelager kører nu i Vojens, S.Wittrup, Ingeniøren, 22nd May 2015

[184] Monitoring results from large scale heat storages for district heating in Denmark, T. Schmidt and P.A. Sørensen, 14th Int. Conf. on Energy Storage, 25-28 April 2018, Adana, Turkey.

visible. Photo: PlanEnergi[185]. Right: Lid of PTES at Vojens District Heating being finalized. Photo by S. Wittrup183.

PTES applications

Pit Thermal Energy Storage is used in connection with district heating systems.

Part of the district heating thermal energy storage capacity in Denmark is found as PIT storage facilities, which have been established over the country in recent years. All together 5 PIT and one BTES systems are found in Denmark (Marstal, 75000 m^3, 2012; Dronninglund 62000 m^3, 2014; Vojens, 203000 m^3, 2015; Gram, 122000 m^3, 2015; 2015; Toftlund, 2017, 85000 m^3), but the experience is mixed[186]. In general, the energy storage efficiency is about 60-82% over one charging cycle, when the plants are operating as planned, but unexpected problems have occurred, in particular to the liners and the lid. The liners have considerably lower lifetime than expected and a few lids show holes, where water is absorbed by the insulation material and thereby heat is led to the surroundings. The resulting malfunction has had implications for the economy of the storage facilities. The experience must be seen as a part of a learning process and the latest Danish plant in Toftlund is constructed without this vulnerability.

PTES Development needs

Most development needs for PTES are related to long-term testing and capacity up-scaling. The major issues are:

- Development of better and more durable liners
- Cheaper stores, e.g. by using existing infrastructure (gravel pits, dry docks from closed shipyards)
- Storage technologies for new purposes (surplus heat from industrial processes, incineration plants)
- Reliable monitoring results for demonstration plants.
- Demonstration of cheap stores for low temperature purposes (below 50 °C)
- Demonstration of larger units.
- Implementation in larger systems in combination with solar, CHP, electric boilers and heat pumps, which allow increased number of annual load cycles from typically 2 for solar heating only to around 25. This will significantly reduce the heat losses in pct. and the capital costs per MWh stored heat.

PTES specific recommendations

For PTES, the next step is demonstration of how to integrate large heat stores in smart energy systems, and show

- how and where the heat storage can provide flexibility to the heat and electricity systems
- how to move surplus heat from summer to autumn and winter and offer heat storage for 'power to heat' from heat pumps and electric boilers.
- heat storage integrated into the Danish central CHP systems is of importance.

PTES Players in Denmark

- Import of liners: John Hunderup

---

[185] PlanEnergi, http://planenergi.dk/arbejdsomraader/fjernvarme/saesonvarmelagre/. Accessed November 2018

[186] https://ing.dk/artikel/solvarmen-siver-ud-nye-fjernvarmelagre-212978 Accessed January 2019.

- Excavation: Several
- Welding of liner: PBJ Miljø
- Implementation of lid: PBJ Miljø
- In- and outlet: Several
- Connection pipes, heat exchangers: Alfa Laval, SONDEX
- Pumps: Grundfos, Desmi
- Valves: Broen
- Control system: Several
- Consultancy: Rambøll, PlanEnergi, Niras, GEO (geotechnical consultancy)

13.2 Latent Heat Storage (LTES)

LTES technology description

Latent heat storage is based on Phase Change Materials (PCM) and relies on the fact that heat is involved in phase changes of matter. Aluminum heated through the application of constant (thermal) power starting from room temperature thus follows a temperature curve, as shown in Figure 70 below.

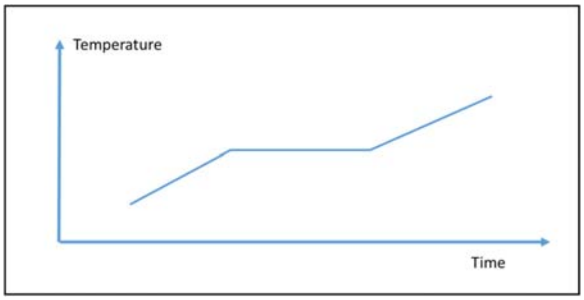


Figure 70. Development of temperature of aluminum upon heating with constant power input

The aluminum is initially heated sensibly to melting point and then kept constant until all the matter has been melted. Additional power simply increases the temperature of the molten aluminum. The interesting aspect of latent heat storage is the constant temperature at which heat is added or extracted (the horizontal part of the heating curve) during the phase transformation. This contrasts with the varying temperature of sensible heat storage. Another attractive aspect of phase change materials is the possibility to utilize sub-cooling effects and controlled release of the latent heat.

Experimental research and development on latent energy storage is taking place at the Danish Technological Institute, where aluminum is switched between the liquid and solid phases. The melting point of aluminum is approx. 660˚C and the heat involved in the phase transition is 321 J/g[187]. The numbers mean that 1 m^3 of pure aluminum releases/absorbs close to 900 MJ during the phase transition. This is an attractive property from an application point of view and in addition aluminum has excellent thermal conduction and the melting temperature fits well with use in conjunction with a steam turbine. Furthermore there is much practical experience with aluminum, it is cheap and melts congruently without sub cooling. One serious drawback of the system is that aluminum is highly chemical aggressive – in

---

[187] https://www.engineeringtoolbox.com/latent-heat-melting-solids-d_96.html. Accessed December 2018

particular in the liquid phase and requires use of resistant materials for containment as well as in heat exchangers.

LTES status in industry and research

Firstly, one Danish company (Suntherm) has started marketing small LTES systems for private households in Denmark. This market introduction can be expanded to larger energy consumers and systems and eventually lead to export of the technology.

Furthermore, several technological service organizations and universities are currently working with testing and identification of new tailored LTES systems.

LTES applications

Latent heat storage (traditionally known in the form of small pocket heaters) has attracted interest over recent years for its use in connection with thermal power whether from solar installations or heat pumps. Thus, by October 2018 the Danish company Suntherm[188] had sold 23[189] salt-based latent heat (solid-liquid phase transition) storage devices in connection with local heat pumps and local heat supply for households.

Suntherm has been collaborating with DTU on studies of the salt sodium acetate trihydrate[190] with a melting temperature of approximately 58˚C. This effort has been directed to applications like the one now applied by Suntherm.

A crucial point in latent heat storage is insulation. Once heated and molten the temperature must be maintained by efficient insulation. This means that the insulation must be sufficiently thick and efficient to secure acceptable loss of heat from the store over the applied storage periods.

LTES development needs

- Further studies of chemically and physically stable phase change materials and materials with appropriate transition temperatures
- Studies for control of solid nucleation by cooling are required.
- Studies and development of improved heat transfer materials and technologies are required for applying these LHS techniques.
- Develop and test materials and systems for different types of applications and temperature levels
- Develop metals and alloys for LHS
- Develop and test heat exchangers and insulation materials for LHS
- Develop LHS storage tanks and components for pumping of two phase slurry ice, vacuum ice and PCM slurries

  Perform basic research to identify and develop new advanced heat transfer fluids optimally combining heat conduction and heat storage properties in same material.
- Improve integration of heat storage properties in building elements and construction materials, eg by including phase change materials in wall constructions.
- Perform studies (theoretical and experimental) of using PCM in building envelopes to increase comfort and allow demand side management.

---

[188] https://www.suntherm.dk/ Accessed January 2019

[189] https://www.energy-supply.dk/article/view/628571/suntherm_har_langet_23_saltbatterier_og_varmepumper_over_disken Accessed January 2019

[190] Dannemand, M., Kong, W., Johansen, J.B. and Furbo, S., "Laboratory test of a cylindrical heat storage module with water and sodium acetate trihydrate," Energy Procedia 91 (2016) 122 – 127, vol. 91, pp. 122-127, 2016.a

- Perform R&D of multi-functional thermal management materials like encapsulated PCM

Specific recommendations

The emerging marketing by Suntherm of smaller systems should be supported by appropriate collaboration schemes between the the industry and R&D organizations engaged in the technology.

Players in Denmark

- Suntherm
- DTI
- DTU
- Aalborg CSP
- Verdo
- Støtek
- Johnson Controls
- Grundfos
- Danfoss

13.3 Thermochemical energy storage

Technology description

Chemical reactions are connected with the uptake or release of heat, as illustrated in the following reaction equation:

$Mg + H_2 \leftrightarrow MgH_2 + Q$

where Q is the amount of heat released by the formation of magnesium hydride from the elements. The reaction is one of many that can be used for TES following the principles illustrated in Figure 71 below.

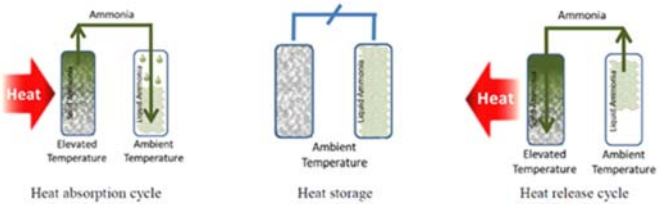


Figure 71. Principle of Thermo-Chemical Energy Storage illustrated by a system involving ab- and desorption of ammonia. Starting from the left, heat is added to the ammonia-containing compound, and ammonia is liberated. In the middle, a valve is closed to isolate the ammonia. To the right, the valve has been opened and the ammonia is allowed to react, release heat again and close the cycle. Figure by courtesy of D. Blanchard.

The heat involved in chemical reactions can be considerable.

Table 7 shows selected examples of reaction systems and the reaction heats involved, as well as the applicable temperatures.

Chemical system	**Heat involved kJ/mol**	**Practical temperature ˚C**
$Ca(OH)_2 \leftrightarrow CaO + H_2O$	100	500
$MgH_2 \leftrightarrow Mg + H_2$	35	400
$MgCl_2{\cdot}6NH_3 \leftrightarrow MgCl_2 + 6NH_3$	218[191]	Ambient to 200

Table 7. Examples of reaction systems and corresponding molar heats involved

One significant advantage of TCS is that once the dissociative reaction has taken place (cf. Figure 71) and the separating valve has been close, the thermal energy is stored without loss for as long as the system is gas tight. However, in some cases it may be necessary to preheat the reactants to facilitate reaction but the energy released from the system is still the same. For example the Mg-H_2 reaction in Table 7 will not happen if the system is allowed to reach room temperature (see also Figure 72), but requires preheating of the system.

Status in industry and research

Few industries market commercial products based on thermo-chemical energy storage. However, several universities and service organizations are collaborating with private companies in studies of materials and systems and in relatively few years more commercial products can be expected.

Applications

Not many thermo-chemical systems are yet in practical use today because they are still at the research stage and need further development. Materials stability and appropriate reaction rates, including rates for thermal power in and out of the systems, are important research topics.

An interesting application of TCS systems is the proposed use of metal hydrides for energy storage in combination with Concentrated Solar Power (CSP). Metal hydrides offer the possibility to store energy with an order of magnitude less raw material than molten salts due to their impressive energy densities – see Figure 72.

---

[191] Lespinasse, E. and Spinner, B., "Cold production through coupling of solid-gas reactors I: Performance analysis," Int. J. Refrig., vol. 17, no. 5, pp. 309-322, 1994.

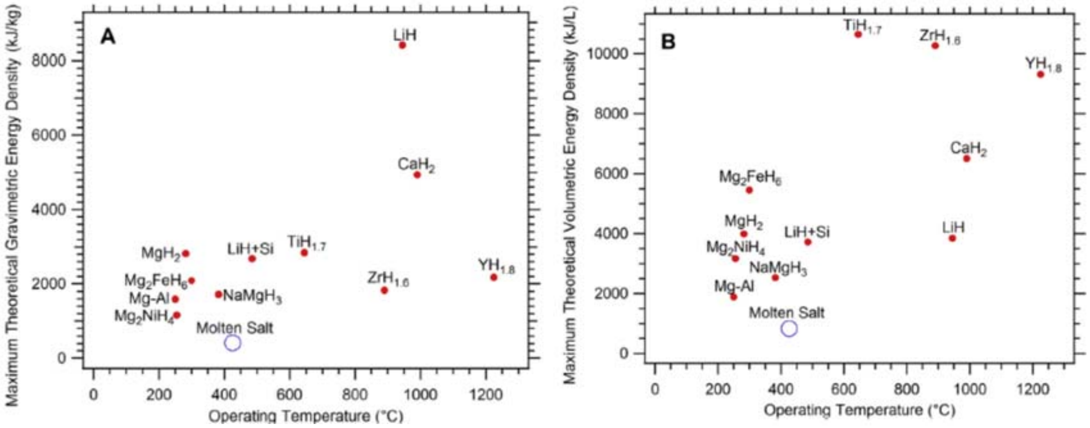


Figure 72 [192]. Maximum theoretical A) gravimetric and B) volumetric energy storage densities of select metal hydrides compared to existing molten salt technology. Operating temperatures are given as the 1 bar hydrogen equilibrium pressure temperature. The molten salt energy densities are based on the specific heat of a eutectic nitrate salt mixture over the entire operating temperature range, 288-565 ˚C.

Development needs

- Tailoring TCS systems for different applications – in particular concerning temperature
- Develop complete, compact heat storage systems by use of thermo-chemical reactions utilising the high energy density of such systems
- Identify suitability of TCS systems based on all solid or liquid materials to bypass problems about handling gases (e.g. ammonia)
- Study use of open water-based TCS systems exchanging water with the atmosphere

Specific recommendations

Because of the attractive high energy storage densities found in TCS systems it is recommended to initiate R&D projects aiming to bring the systems to a higher TRL.

Players in Denmark

- DTU
- Amminex (experience with ammonia systems)

13.4 Cold storage

Technology description

Cold storage is in principle equivalent to heat storage: two systems are brought out of thermal equilibrium. Thus where low temperatures are desired, for instance in food industry, cold storage can be used the same way as heat storage and provide the same kind of services to the overall energy system.

---

[192] Metal hydride thermal heat storage prototype for concentrating solar thermal power, M.Paskevicius, D.A. Sheppard, K. Williamson and C.E. Buckley, Energy 88, 2015, 469-477

Cold storage has been utilized for centuries in the form of ice storage in simple temperature-protected caverns in manors and castles, where access to ice – e.g. from lakes nearby - was available during winter. Actually, ice is still used for cold storage applications, but now based on modern and efficient insulation materials. An example of commercial application of ice storage is found in [193].

The ice production must be efficient to minimize energy losses. Traditional ice production includes rather large temperature differences (cooling system temperatures of -10 °C or lower for freezing of water at 0 °C are common practice). The combination of water as refrigerant and ice as cold store medium can result in very efficient systems for ice production and storage, especially when utilizing direct contact heat exchanger can be developed. Research and development is needed in the field of ice generation based on pure water, charging and discharging the ice storage and measurement of the stored amount of ice.

However, cold storage is also done based on cold water only and this technology plays a role in the rapidly emerging district cooling systems in larger cities in almost all climate zones. An example is a recently established district cooling system in the municipality of Frederiksberg, in connection with development of a new city area. The cooling system is supported by horizontal cooling water storage tank[194] of 4.000 m^3 installed in the ground below a road and the tank can deliver 4 MW cooling power for 5-6 hours. The main application is to supply peak cooling power during daytime. The system´s cooling water forward temperature is 9°C and return temperature 17°C.

Figure 73[194]. Left: Construction of the cold storage facility. Left: Covering road after finishing.

Taarnby Forsyning is in 2019 establishing a district cooling system including a 2,000 m^3 chilled water tank, which will be the fist of its kind in Denmark and many more are in the pipeline (Ramboll).

Applications

- District cooling systems
- Datacenters

---

[193] https://www.ice-energy.com/technology/ Accessed January 2019

[194] Horizontal Cooling Water Tank in Frederiksberg, Denmark, J. P. Truelsen, Frederiksberg Forsyning

- Domestic cooling
- Cooling in industries

Development needs

Cold storage based on water/ice is a mature and commercial technology

Specific recommendations

Cold storage should be considered for peak-shaving demand for cooling when new cooling applications are planned. Even in existing cooling supply systems cold storage could be considered.

Cold storage – like heat storage – is suitable for and should be considered for integration into smart energy systems.

Players in Denmark

- Rambøll
- Frederiksberg Forsyning

14. Mechanical and Thermo-Mechanical Energy Storage

14.1 Hydro Power Dams

Hydro power plants, which utilize the natural water flow in a river combined with a dam and an upper reservoir can act as a storage similar to the pumped hydro storage (cf. below). As the water flows in the river it may be accumulated in a lake behind the dam and the same storage function as provided by pumped hydro storage, can be achieved.

14.2 Pumped Hydro Storage

By far the dominating energy storage technology in terms of worldwide installed storage capacity is Pumped Hydro Storage (PHS). In 2016, pumped hydro storage accounted for well over 95% of global installed energy storage capacity[195]. In PHS different levels of two water reservoirs are utilized to

- absorb electricity during pumping water from low level to high level
- generate electricity via a turbine when passing water from high level to lower level

Pumped Hydro is efficient and flexible and allows large-scale storing of energy. Pumped hydro storage spans from very short-duration (frequency response services for grid operators) to very to long (seasonal storage in hydro reservoirs). PHS is well-proven technology utilized by utilities to balance the grid and to support increased renewable energy input. A graphic illustration of the principles of PHS is seen in Figure 74.

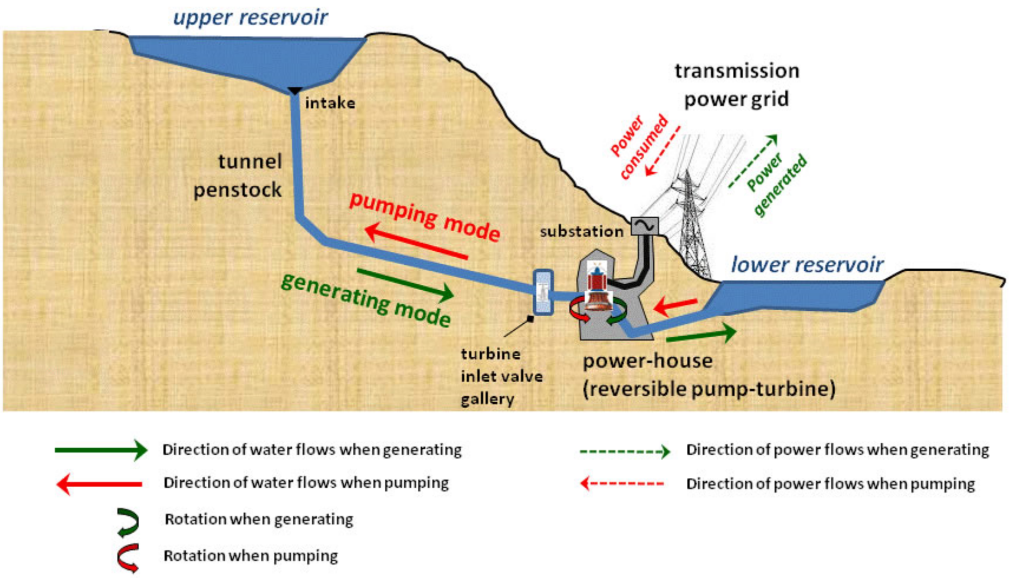


Figure 74. Principles of Pumped Hydro Storage[196]

---

[195] World Energy Resources. E-Storage | 2016. World Energy Council, 2016

[196] https://www.ourworldofenergy.com/images/other-renewables-energy/vignette_image_10_1.jpg Accessed January 2019

Denmark is characterized by geographic and topological conditions, which do not immediately point to the use of PES technology. Nevertheless, Denmark relies heavily on Norwegian hydropower even though the Norwegian electricity system does not include pumped storage to any significant extent, but simply reservoir storage, where water is accumulated in lakes/reservoirs behind the hydropower plant. Norway has a very large natural storage capacity working this way and in addition, Norway has a large potential for installing pumped hydro storage as well giving rise to interest in expanding interconnector capacity among neighbor countries to Norway.

A special variant of pumped hydro energy storage technology does appear to be applicable in Danish locations, the so-called 'membrane technology'. A small start-up company has been developing the technology and has brought the concept (called energy membrane – underground pumped hydroelectric storage (EM-UPHS) to a state where it appears to be interesting for application.

The EM-UPHS system is an idea for a PHS system which is based on a storage reservoir, where water is enclosed in a plastic membrane placed underground with soil on top as shown schematically in Figure 75. The overlaying soil gives the necessary pressure to run a pump/turbine and store large amount of electrical energy. A 50x50 m EM-UPHS test facility was built and tested at Nybøl Nor, a location 12 km outside the Danish city Sønderborg. Experimental results showed that the system efficiency of the EM – UPHS technology was very close to that of the traditional and existing PHS technology (75-85%).

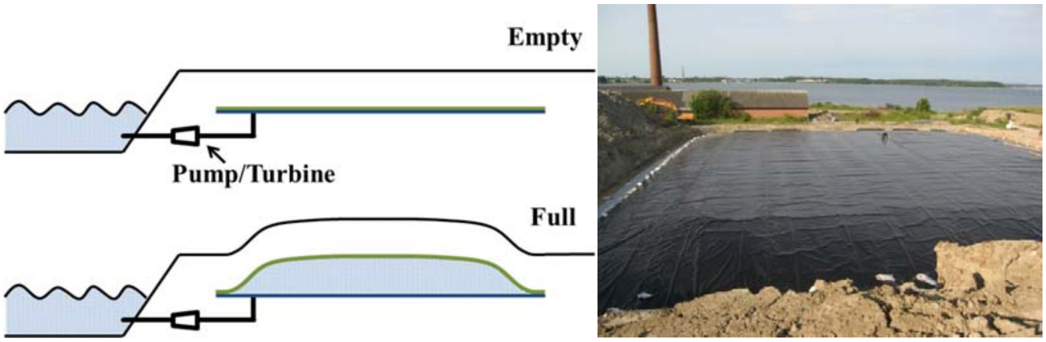


Figure 75. Left: Sketch of the EM-UPHS concept. Water is pumped into a cavity bonded by two impermeable membranes (blue and green for top and bottom membrane respectively) and soil on top is lifted during charging. Right; The test facility at Nybøl Nor. The plastic membrane is being covered by soil.

Unfortunately, until now lack of funding has prevented further development of the system, but the results from the experiments have been reported in the reference given in footnote [197].

---

[197] A new principle for underground pumped hydroelectric storage, J. Olsen, K. Paasch, B. Lassen and C. T. Veje, Journal of Energy Storage 2 (2015) 54–63

14.3 Flywheels

Technology Description

Flywheels store energy mechanically as kinetic energy by bringing a mass into rotation around an axis. According to classical, mechanical physics the kinetic energy of a rotating mass m in distance r from the point of rotation can be expressed as:

$$E_{kin} = ½ \cdot I \cdot \omega^2,$$

where I is the moment of inertia – equal to $m \cdot r^2$ – and ω is the angular velocity (radians per second).

It is seen from this expression that the kinetic energy of a rotating flywheel increases proportionally to the mass and to the distance from the rotation point squared. The energy also increases proportionally to the angular velocity squared.

To maximize the stored energy for a given mass and rotation speed, the mass should be separated from the rotation point as much as possible. On the other hand the centrifugal force acting on the mass is defined as:

$$F_c = m \cdot r \cdot \omega^2$$

and thus the requirements to the materials binding the mass to the rotation center - increases proportionally to the separation distance. This fact sets limits to the maximal available distance because of the properties (tensile strengths) of known, available construction materials.

Whereas flywheels were formerly mainly constructed of metallic materials, modern flywheels are usually constructed – at least partially - by polymer/fiber composite materials. Flywheels are appropriate for fast dynamic energy storage for applications like peak shaving or long energy storage times. Large flywheels should preferably be designed from composite materials due to the high rotational speeds and the bigger strength to weight offered by these materials. Metallic rotors are mainly used for simple seconds to minutes energy storage systems like UPS (uninterruptable power supplies). Thus, Amber Kinetics believes in steel as a suitable rotor material as seen on the photo to the right in Figure 76.

Figure 76. Photo of WattsUp Power´s and Amber Kinetics´ flywheels. The latter allowing for a look into the internal steel rotor whereas the first utilizes composite materials for the rotor[198].

Modern flywheels are operated in high vacuum to eliminate (or strongly reduce) aerodynamic drag. Likewise, the bearings are usually contact-less magnetic bearings, which means that the mechanical energy losses during a full storage cycle are negligible from a practical perspective. Flywheel technology in itself does not imply any significant energy loss even over prolonged periods. However, the power electronics taking care of converting primary power to the power format suitable for the flywheel and vice versa (the power electronics include rectifier, bus, inverter and converter) gives rise to loss of energy during the use of flywheels. These losses are naturally associated with charging and discharging the wheels and depends somewhat on the mode of operation. In 2018 WattsUp Power stated that stand-by losses of today's flywheel technology is about 5% per day whereas round trip efficiency is 98 % for the wheel.

Status in industry

Flywheels are produced by several companies worldwide and in Denmark the company WattsUp Power produces two unit sizes[199]:

- A 30 kWh consumer device focused on integrating solar power into the power distribution grid.
- A 100 kWh industrial device focused on industrial application.

<u>30 kWh</u> – Specifications.

- Designed for outdoor use
- System fully charged: 30kWh
- Power Loss < 1%
- Charge time less than 1 hour
- Max. power output: 100kW
- Life time: +20 years¨

- <u>100 kWh</u> – Specifications.
- System fully charged –100kWh
- Power Loss < 1%
- Charge time less than 1 min
- Max. power output: 1 MW
- Life time: +20 years

---

[198] http://www.elp.com/articles/2016/01/amber-kinetics-signs-flywheel-energy-storage-contract-with-pg-e.html. Accessed November 2018.
[199] https://wattsuppower.com/products/ Accessed February 2019

WattsUp Power is currently delivering units for onshore and off shore industrial application.

Applications

Flywheels have been known and used for centuries in steam and combustion engines, whereas development of the independent energy storage potential has only been underway since the 1960s[200]. According to the reference given in footnote [201] the world´s largest flywheel has been in operation since 1985. It consists of 6 discs each with a diameter of 6.6 m and thickness 0.4 m, weighing 107 t. The system can supply 160 MW over a 30 sec period and has shown excellent reliability, particular concerning the mechanical construction. Another system developed by Okinawa Electric Company and Toshiba ROTES (ROTary Energy Storage) has been operated since 1996. The two examples indicate that flywheels represent highly reliable technology.

Due to its mechanical design and working principle, flywheels have zero degradation in energy storage capacity over time. This is independent of how the system is operated and in particular independent of depth of charge and discharge, which is in noteworthy contrast to the properties of most electrochemical battery systems.

Flywheels can absorb and release electro-mechanical energy extremely fast. The response time is up to 10 times faster than the response times of batteries, meaning that flywheels can react on demand and supply signals almost instantaneously. This property is attractive for providing ancillary services in the power grid and makes flywheels highly suitable for frequency regulation.

Due to the fast response time flywheels can provide ultrafast ancillary services to the grid, with reaction times down to 3 ms. In particular primary reserves – and even synthetic inertia - for maintaining grid frequency can easily be provided and managed by use of flywheels. The reason for flywheels sometimes outshining batteries for certain applications is their high ramping rate.

An example illustrating the response time of a flywheel system can be seen in Figure 77.

---

[200] "Grid Energy Storage" I. Gyuk et al., US Department of Energy, 2013

[201] S.-i. Inage, "Prospects of Electricity Storage in Decarbonised Power Grids, IEA Working Paper Series," OECD/IEA, 2009.

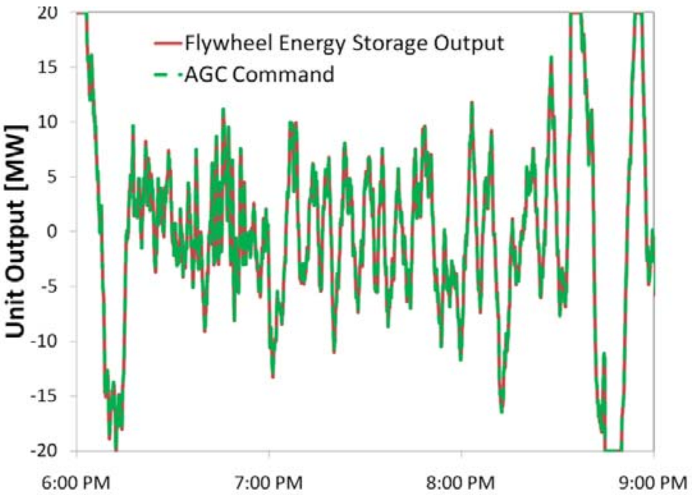


Figure 77. The reaction of a flywheel (MW input/output) in response to signals from the Automatic Generation Control. It can be seen that within the accuracy of the graph (please note the axis scaling) the flywheel follows signals completely. Source: Beacon Power.

The energy storage density – whether on volume or weight basis – for flywheels (about 0.05 Wh/kg) is comparable to advanced batteries and in the range of 1-2 orders of magnitude lower than for chemical methods for storing energy (in ways similar to the natural energy storage media oil and gas). This is, however, not important for static applications. On the other hand flywheels have high <u>power</u> densities of about 1 kW/kg[202] also confirmed by WatssUp Power in February 2018.

Flywheels for energy storage can be produced and deployed in numerous sizes ranging from multi MW utility applications to small systems (few kW and kWh) intended for use in cars and buses. Until recently Beacon Power seems to be the dominating producer of large scale flywheels. Their systems are based on a modular flywheel size (a single flywheel) of 100 kW and 25 kWh, with the standard unit size consisting of an assembly of 10 modules which can be combined in any multiple of 10. Such modules sum up to 1 MW and 250 kWh. Figure 78 shows a photo of an example of their systems that currently provides 20 MW of frequency regulation service.

Figure 78. Photo of Beacon Power flywheel installation in commercial operation in PJM, Hazle, Pensylvania. The plant includes 200 flywheel modules lowered into the ground (5 on

---

[202] Electrical Energy Storage Systems: A comparative life cycle cost analysis, B. Zakeri and S. Syri, Renewable and Sustainable Energy Reviews, vol. 42, pp. 569-596, 2015.

each side of a container. The plant currently provides 20 MW of frequency regulation service to PJM and reached full commercial operation in July 2014[203].

Flywheels can be constructed to store energy from seconds to years. Flywheels have relatively small standby losses, and the user or producer will design a flywheel for each specific application. Now a typical 10 second storage application could be a UPS (uninterruptable power supply) for hospitals or server centers. In applications like power peak shaving the flywheel will be designed to store the power for days and in the most extreme conditions in space applications NASA's flywheel designs store the power for up to 3 years.

Figure 79 is an excerpt from test data for a flywheel run in the New York ISO grid in the US. The extremely fast reaction time of flywheels is indicated (often superior to reaction times for batteries). There is no reason to anticipate improvement (or need for improvement) of this performance.

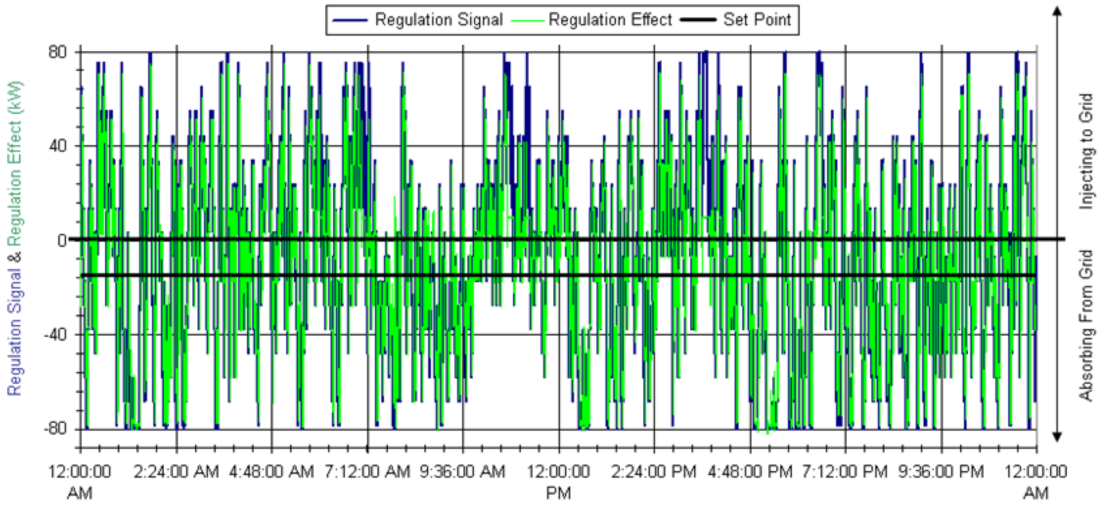


Figure 79. Test data run in the New York ISO grid in the US. The data shows regulation during one day and night after 8 months following fast changing frequency regulation signal. Availability to respond 97.2% of the time it was online. Source: Beacon Power.

The expected lifetime for a flywheel system in 2017 is in the range of 20-25 years for the wheel or more than 1,000,000 cycles.

Losses from flywheels are low and can be down to the range of 1%/year when the wheel is left in a spinning state[204].

A significant decrease of material prices for manufacturing the flywheel rotors has been seen over recent years and this development is believed to continue in years to come. Since the cost of the rotor in 2017 is about 40% of system costs a decrease in materials prices has a significant impact on the full system cost. This is the explanation why flywheel system prices

---

[203] http://beaconpower.com , Beacon Power. Accessed November 2018.

[204] W. Torell, "Lifecycle Carbon Footprint Analysis of Batteries vs. Flywheels, White Paper 209," Schneider Electric, 2015.

have recently decreased up to 30%/year and is expected to continue decreasing significantly over the next decades.

Flywheels are generally considered to be a little less mature technology than many batteries and in addition the cost is perhaps still too high to make them competitive on the commercial market somewhat depending on the specific application, though[205]. However, flywheels also seem to be catching up rapidly and gain market shares although batteries are still dominating in many energy storage applications. In some applications – like grid stabilization for railways and large battery charging – flywheels are often a preferred solution.

Development Needs

The European Association for Energy Storage (EASE) stated the following R&D needs for flywheels[206]:

- Flywheel disc: research on better materials for carbon and glass fibre composite flywheels (high density) should be carried out to reduce the total cost and increase energy density.
- Electrical machines: high performance machines are required to be used in these devices and although permanent magnet machines seemed to be the best option, the high cost of the magnets has redirected the research towards new machine concepts with fewer magnets.
- Bearings: faster control systems are being developed to improve the bearings response and more efficient actuators are being used to increase the performance of the complete system. Magnetic and superconducting bearings need to be studied as a solution for high speed flywheels. The lower complexity and energy losses of the superconducting bearings allow a time decay of the stored energy in the range of a 20% in 200 hours. Improvements in the reliability of the cryogenics will lead to a more competitive system.
- Digital control and communications/power electronics: digital control and fast communication improvements allow operating the system with guarantees of robustness, being able to analyze a lot of variables, maintaining a complete diagnosis of the application from anywhere, and facilitating integration with other subsystems. Another important point is to increase the added value of the power electronics in the energy storage system, ensuring robustness and reliability and leading to a higher roundtrip efficiency.
- Efficiency of the flywheels: reduction of losses in idle state.

Specific recommendations

Flywheel energy/power storage technology is highly relevant in renewable electricity grids and systems. Noting the significant price drop for flywheels, that has occurred over recent years, and that flywheels can indeed be exported to many other countries, it seems highly relevant to care about an emerging, yet still small, industry in Denmark, which has already been quite successful. The industry may need continued financial back up for upscaling unit size and to expand the range of applications for flywheels.

It is recommended that:

---

[205] N. K. Kohli, "Short-Term backup power through flywheel energy storage system, 2012. Available on https://www.slideshare.net/Drnavinkumarkohli/ppt-fly-wheel-navin-kohli. Accessed November 2018.

[206] Joint EASE/EERA recommendations for a European Energy Storage Technology Development Roadmap. Update 2017", EASE and EERA, Brussels, 2017.

- The flywheel industry seeks collaboration with manufacturers of other storage technology providers (even batteries and battery management systems) to market hybrid storage solutions with synergetic added value
- The industry is encouraged – perhaps by economic incentives - to work closely together with universities and technological service organizations
- National R&D programmes in Denmark are phrased in a way to allow for qualified applications supporting the development flywheels and flywheel manufacturing technology.
- Schemes for (part-)funding for large scale demo-projects within flywheel storage are made available

Players in Denmark
Supplier of flywheels: WattsUp Power. Users: Maersk Drilling, Banedanmark, Suppliers of power electronics: several (Danfoss, others)

14.4 Compressed Air Energy Storage

Technology Description
Compressed Air Energy Storage (CAES) stores electrical energy mechanically and the input is electricity to drive an air compressor. Compressed air can subsequently be stored in pressure tanks or in huge amounts in underground cavities, where such suitable formations are available. When release of the stored energy is required, the compressed air is used to drive a turbine able to generate electricity. The expansion of air is associated with a temperature droop.

When air is compressed, heat is released and constitutes a loss of energy during the storage operation because it dissipates to the external environment. However, if the heat may be stored intermediately (e.g. sensibly in ceramic material), the heat may be reinjected during the expansion process and thus it is not lost. Obviously this has an impact on the overall efficiency (electricity to electricity). This form of CAES is called Adiabatic CAES, A-CAES (or sometimes Advanced Adiabatic CAES, AA-CAES) because of the lack of exchange of heat between the storage system and the external environment.

Presently CAES technology is used in combination with gas turbine combustion, which can be said to compensate for the temperature droop. Traditional CAES releases CO_2. Figure 80 illustrates a plant diagram of two different CAES plants.

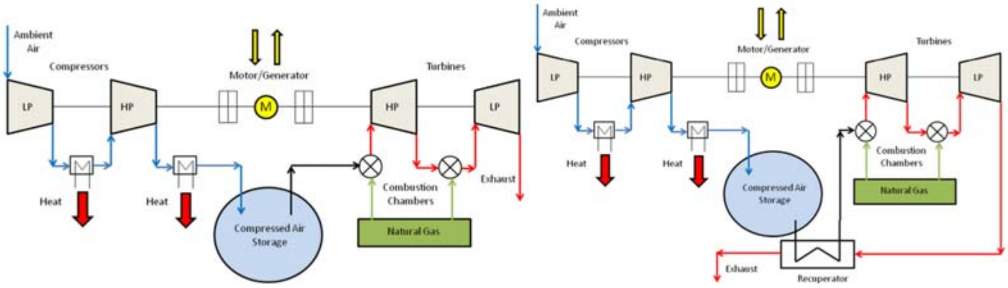


Figure 80 Operating principle of the CAES plant Huntorf (left) and the McIntosh (right)[207].

---

[207] S. Karellas and N. Tzouganatos, "Comparison of the performance of compressed-air and hydrogen," vol. 29, 2014.

Air storage volumes

CAES depends completely on connection to suitable storage volumes. Small units may utilize high pressure gas cylinders (surface level), but to allow for large amounts of energy (hundreds of MWh) CAES must be established in connection with large underground formations able to hold significant amounts of compressed air. Such formations could be depleted oil or gas fields, aquifers, salt caverns, lined rock caverns and abandoned mines.

The two existing CAES plants are connected to solution-mined caverns in salt domes. Such caverns can be relatively cheaply and easily developed and suitable salt deposits are found in many places all over the world.

Related technologies

In addition to CAES and ACAES, the following types of thermo-mechanical energy storage technologies should be mentioned:

- Isothermal compressed air energy storage. The technology holds resemblance with ACAES and is being developed by a few companies like SustainX[208]
- Adiabatic liquid piston compressed air energy storage, ALP-CAES[209]
- Liquid air thermo-mechanical storage. Liquid air energy storage (LAES) uses the thermal potential stored in a tank of cryogenic fluid. The research and development of the technology began in 1977[210] with theoretical work at Newcastle University, was further developed by Hitachi in the 1990s and the first pilot demonstration plant was built by Highview Power Storage in 2010. A larger demonstration plant is being established in the UK[211],[212] also by Highview Power[213], but operational experience has not yet been reported. In a press release from 2018[214] the plant is mentioned as "world's first grid-scale liquid air energy storage plant will be officially launched today". The 5MW/15MWh LAES plant, located at Bury, near Manchester will become the first operational demonstration of LAES technology at grid-scale. By December 2018 the plant was not yet reported finished[215]
- Transcritical carbon dioxide thermo-mechanical storage

Basically – and not the least from a practical point of view - none of these technologies have been developed to a significantly better status than described in the report "Status and

---

[208] https://www.smartgrid.gov/project/sustainx_inc_isothermal_compressed_air_energy_storage.html. Accessed November 2018

[209] Adiabatic Liquid Piston Compressed Air Energy Storage, Petersen, T.; Elmegaard, B.; Pedersen, A. Schrøder,Tecnological Institute of Denmark and Technical University of Denmark, 2013

[210] Liquid air energy storage – from theory to demonstration, R.E. Morgan, International Journal of Environmental Studies, 2016, Vol. 73, No. 3, 469–480

[211] https://arstechnica.com/science/2018/06/liquid-air-energy-storage-the-latest-new-battery-on-the-uk-grid/. Accessed November 2018.

[212] Cryogenic Storage Offers Hope for Renewable Energy, Yasmin Ali, BBC News, 2016. http://www.bbc.com/news/science-environment-37902773 Accessed January 2019

[213] https://www.highviewpower.com/ Accessed January 2019

[214] https://www.highviewpower.com/news_announcement/world-first-liquid-air-energy-storage-plant/ Accessed January 2019

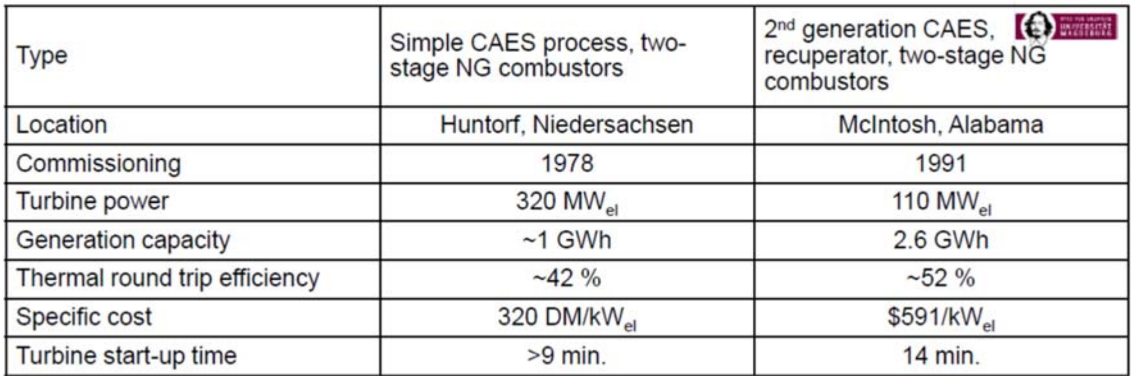
[215] https://www.highviewpower.com/news_announcement/highview-power-builds-energy-dream-team-to-drive-global-development-of-its-liquid-air-energy-storage-solution/ Accessed January 2019

recommendations for RD&D on energy storage technologies in a Danish context" from February 2014[216]. Thus, no commercial plants have been installed and operated until now.

Applications

Although the concept of CAES has been considered favorable for energy storage for many years for storing variable, renewable energy only two plants have been realized until now, the first in Huntorf, Germany, in 1978 and the second in McIntosh, Alabama, USA, in 1991. Interestingly, the Huntorf storage facility was constructed to balance nuclear power so that the nuclear generation could be run in an optimal way and the CAES facility could handle the differences between production and demand for electricity. None of the realized facilities are based on A-CAES, but only on CAES, meaning that the round trip efficiencies are relatively low. Both plants have been operated with use of natural gas turbines to compensate for the lost heat (cf above).

Table 8 gives key data for the same two plants. The Huntorf plant uses 0.8 kWh of electricity and 1.6 kWh of gas to produce 1 kWh of electricity and was the world's first CAES plant when it was commissioned in 1978[217]. The newer McIntosh plant includes a recuperator which recycles waste heat from the exhaust stream and uses 0.69 kWh of electricity and 1.17 kWh of gas to produce 1kWh of electricity217.



Type	Simple CAES process, two-stage NG combustors	2nd generation CAES, recuperator, two-stage NG combustors
Location	Huntorf, Niedersachsen	McIntosh, Alabama
Commissioning	1978	1991
Turbine power	320 MW_{el}	110 MW_{el}
Generation capacity	~1 GWh	2.6 GWh
Thermal round trip efficiency	~42 %	~52 %
Specific cost	320 DM/kW_{el}	$\$591/kW_{el}$
Turbine start-up time	>9 min.	14 min.

Table 8 . Data for the Huntorf and the McIntosh traditional CAES plants[218].

For A-CAES (a technology, which has not yet been realized) storage of heat has been proposed in ceramic materials like rocks or brigs at elevated temperatures (say 600 °C).

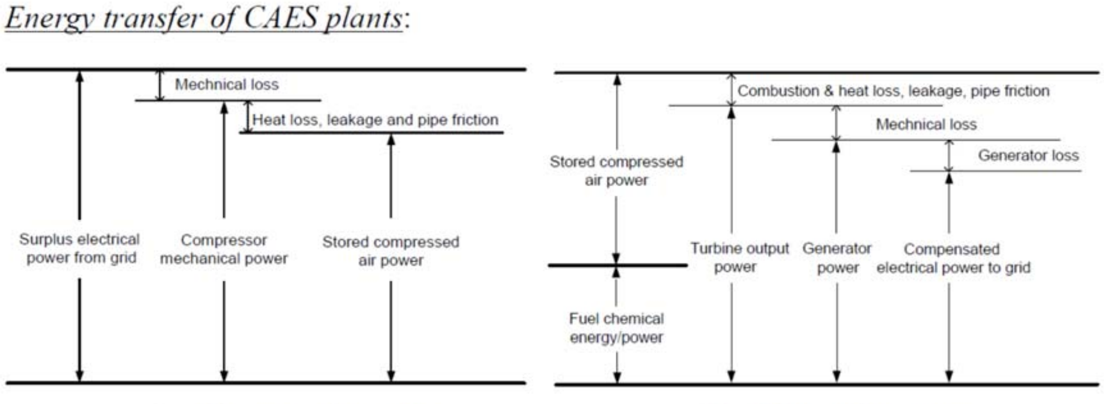
Figure 81 illustrates details of the energy lost by using CAES in the compression stage and in the expansion stage. The numbers which can be derived are a charging efficiency of about 80 % and a discharge efficiency of about 70 % leading to a round cycle efficiency of approx. 55 % (electricity to electricity). However, input of chemical fuel in this calculation complicates the calculation since the electricity that could have been produced from the fuel should be subtracted. Setting the electrical efficiency of chemical fuel to 35 % the output efficiency in Figure 81 would be 44 % leading to a round cycle efficiency of 44 %.

---

[216] Status and recommendations for RD&D on energy storage technologies in a Danish context. A.S. Pedersen et al. EUDP, Energinet et al., February 2014

[217] E. Barbour, http://energystoragesense.com/compressed-air-energy-storage/ Accessed November 2018

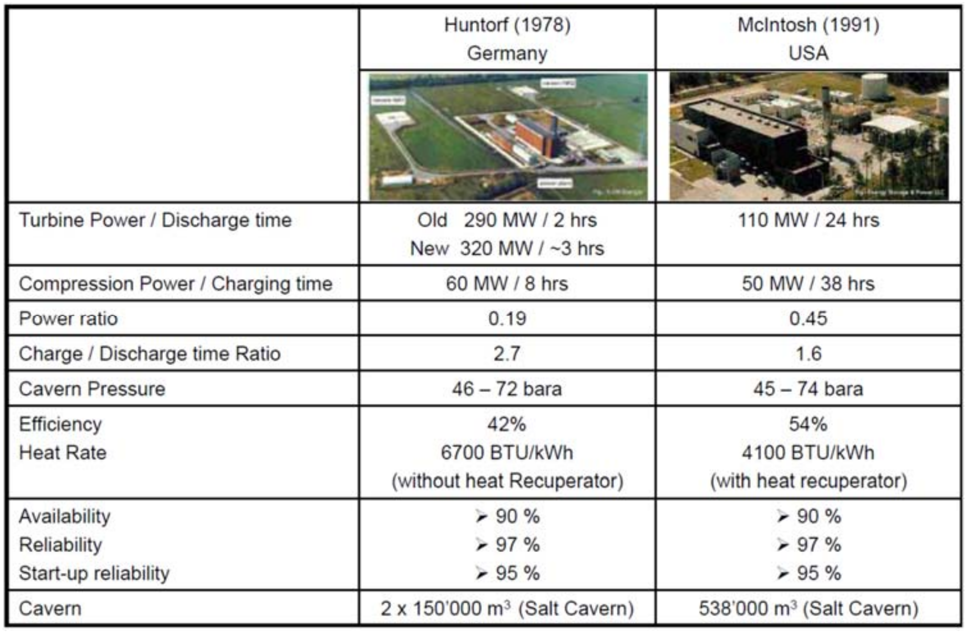
[218] S. Zunft, S. Freund and E. M. Schlichtenmayer, "Large Scale Electricity Storage with Adiabatic CAES," Paris, November 2014.



a) Compression stage b) Expansion stage

Figure 81. Energy transfer of a conventional CAES plant[219]. The source does not quote numbers but only graphics.

Startup times of about 10 minutes are described in the literature for CAES[220]. This allows several ancillary services and thus both black starts, secondary reserves and reactive power system services are possible. Furthermore, CAES technology is well suited for load shifting (the original purpose of the Huntorf plant) within the limits of available storage and power capacity.



	Huntorf (1978) Germany	McIntosh (1991) USA
Turbine Power / Discharge time	Old 290 MW / 2 hrs New 320 MW / ~3 hrs	110 MW / 24 hrs
Compression Power / Charging time	60 MW / 8 hrs	50 MW / 38 hrs
Power ratio	0.19	0.45
Charge / Discharge time Ratio	2.7	1.6
Cavern Pressure	46 – 72 bara	45 – 74 bara
Efficiency Heat Rate	42% 6700 BTU/kWh (without heat Recuperator)	54% 4100 BTU/kWh (with heat recuperator)
Availability Reliability Start-up reliability	➢ 90 % ➢ 97 % ➢ 95 %	➢ 90 % ➢ 97 % ➢ 95 %
Cavern	2 x 150'000 m³ (Salt Cavern)	538'000 m³ (Salt Cavern)

Table 9. Supplementary descriptive data[221] for the Huntorf and McIntosh facilities. The indicated heat rates (thermal energy in over electrical energy out) can be recalculated to 1.96 kWh/kWh for Huntorf and 1.20 kWh/kWh for McIntosh.

---

[219] J. W. X. Luo, "Overview on current development on Compressed Air Energy Storage, EERA Technical Report – CAES.," School of engineering, University of Warwick, December 2018.

[220] I. Gyuk and S. Eckroad, "EPRI-DOE Hanbook of Energy Storage for Transmission and Distribution Applications,1001834, Final Report," EPRI and DOE, December 2003.

[221] Nakhamkin and Brotel, "Second generation compressed air storage," in *Energy Storage Forum Europe*, Rome, 2012.

Based on the numbers shown in Table 9 the energy storage capacities of the plants are 480 MWh for Huntorf and 1,900 MWh for McIntosh. Clearly CAES is a bulk storage technology in the same class as power to gas and pumped hydro.

The practical span of storage period for CAES can be estimated from the reference in footnote [222] . The annual number of starts vary in the range 50-200 with extremes up to 400 and down to about 25. This shows that practical storage periods range between hours and days. However, these storage periods reflect the facility´s actual use pattern rather than the capability. Since air is stored in underground caverns in salt domes, which are very tight (cf. use of salt caverns for natural gas) the air can be stored for much longer time if so desired. Naturally, the levelized cost of energy storage will increase if longer time periods are applied, but it can easily be done.

Recorded performance – in terms of electricity to electricity efficiency – for the Huntorf and McIntosh plants are 42 % and 54 % respectively[223]. The main reason for the difference is that the McIntosh plant utilizes recuperation of waste heat from the expansion turbine. Conventional CAES uses additional fuel in the discharge phase and thus has a not ignorable CO_2 emission.

It may be expected that future CAES plants 10-15 years from now will be based on adiabatic CAES, which has a much better efficiency, estimated to be around 70 %. We are therefore likely to see a stepwise increase in efficiency of CAES at some point in the future, when appropriate thermal energy storage technology has been developed. Considering present activities within high-temperature energy storage technologies this point is estimated to be about 2030. Naturally the use of A-CAES will also lead to increased costs, because of the addition of the thermal energy storage. For an indication of the price difference see Table 10.

It may be questioned how many traditional CAES plants will actually be built in the future. Many optimistic studies have been performed - particularly in the US - during the past 25 years, however it remains a fact that none have been built. Since 2013 the Irish utility company Gaelectric has been working to establish a traditional CAES plant in Larne, Northern Ireland. The company reports that plans are underway to establish CAES plants in the United Kingdom and in the Netherlands. Gaelectric states the total investment cost to be £300 million in the Larne CAES project, according to independent analysis by PMCA Economic Consulting[224]. The facility will generate up to 330 MW of power for periods of up to 6 hours. It will create demand of up to 200 MW during the compression cycle.

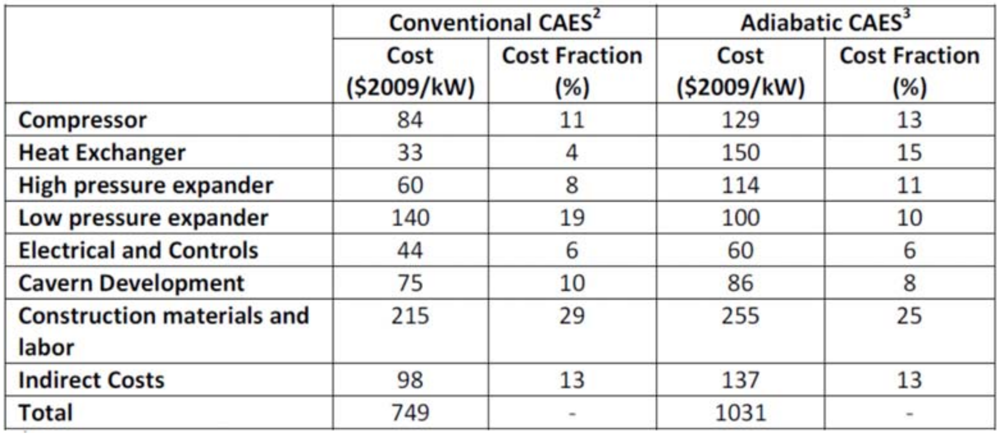
Table 10 gives cost breakdown for CAES and A-CAES plants illustrating the cost differences between the two types. The total cost for A-CAES is seen to be stated as 43 % higher than for conventional CAES.

---

[222] F. Crotogino, K.-U. Mohmeyer and R. Scharf, "Huntorf CAES / More than 20 yeasr of successful operation," Orlando, April 2001.

[223] Energy Storage Technology Roadmap, Technology Annex, p. 5, International Energy Agency, March 2014.

[224] Gaelectric energy storage: The missing link. Brochure by Gaelectric. Availble on http://www.gaelectric.ie/wpx/wp-content/uploads/2015/09/Gaelectric-Supplement-June-2015.pdf . Accessed November 2018.



	Conventional CAES[2]		Adiabatic CAES[3]	
	Cost ($2009/kW)	Cost Fraction (%)	Cost ($2009/kW)	Cost Fraction (%)
Compressor	84	11	129	13
Heat Exchanger	33	4	150	15
High pressure expander	60	8	114	11
Low pressure expander	140	19	100	10
Electrical and Controls	44	6	60	6
Cavern Development	75	10	86	8
Construction materials and labor	215	29	255	25
Indirect Costs	98	13	137	13
Total	749	-	1031	-

Table 10. Cost breakdown for a conventional and adiabatic CAES system deployed with a salt cavern[225]. These costs represent a conventional system with 10 hours of storage and an oversized expander (110 MW) relative to the compressor (81 MW). Capital costs are expressed in terms of expander capacity. [3]These costs represent an adiabatic CAES system with 10 hours of storage and oversized compressor (96 MW) relative to the expander (72 MW). Capital costs are expressed in terms of expander capacity.

The perspectives for significantly improving performance of conventional CAES are not very positive. The technology relies on quite well known technology (i.e. compressors, expanders/turbines and cavern), which can indeed be purchased in a mature state already today.

A study by Black & Veatch[226] for the National Renewable Energy Laboratory in the USA for a conventional CAES plant showed a lack of improved cost (inflation and deflation cleaned prices) and similarly projected performance characteristics in the study were unchangedfor the period towards 2050.

Technology status in Danish industry and research community

The status for CAES in a Danish context is by and large unchanged as such since 2014. A notable change has happened to the ACAES technology in the sense that High Temperature Thermal Energy Storage has been in focus for increased R&D efforts in Denmark and in several other countries as well.

A number of research projects have been done by different parties involving DONG Energy (now Ørsted), Rambøll, Technical University of Denmark, Aalborg University, Danish Technological Institute in cooperation with experts from other countries. In Denmark there are significant experiences with construction and operation of natural gas underground storage in caverns and aquifers. Similar facilities may be used for compressed air storage. Use of this experience for the optimal operation of a CAES facility for handling intermittency of renewable sources, mainly wind power, has led to a number of research projects. None of these projects have yet reached proposals for economically viable solutions for the current energy system, However, several options for implementation in the future are documented based on conventional and optimized CAES concepts.

---

[225] The Value of Compressed Air Energy Storage in Energy and Reserve Markets, E. Drury, P. Denholm and R. Sioshansi, National Renewable Energy Laboratory, USA, 2009.

[226] COST AND PERFORMANCE DATA FOR POWER GENERATION TECHNOLOGIES, Report prepared for the National Renewable Energy Laboratory, Black & Veatch, 2012. Avaliable on https://www.bv.com/docs/reports-studies/nrel-cost-report.pdf. Accessed November 2018.

Status in other European countries

The most outstanding changed situation within thermo-mechanical energy storage is represented by liquid air thermo-mechanical storage. A demonstration plant is being established in the UK[227],[228], but is not yet operational as mentioned above.

The world's first CAES plant was established in Huntorf, Germany, in 1978 and has been in operation for more than 40 years. In Northern Ireland a new facility has been planned for a couple of years by Gaelectric. Status of the project is that early 2017 the EU has given the project 90 MEUR[229]. The facility could provide generation capacity of 330 MW for periods of up eight hours, according to [229] enough to meet the electricity needs of more than 200,000 homes.

Two large projects have been carried out concerning the Adiabatic CAES technology, which integrates heat storage as well as storage of compressed air. The ADELE project was funded by the German state, whereas AA-CAES was an EU project led by KTH Royal Institute of Technology, Sweden. Several new ideas have been investigated in the United States, but also European development takes place. In Germany, CAEstorage is developing small-scale liquid-piston CAES. Related solutions including liquid air (UK) and reversing heat pump technology (Switzerland) are also considered.

Development needs

The documented long-term operation and the potential for bulk electricity storage make thermo-mechanical electricity storage principles, including CAES, attractive. But the mentioned challenges have generated a momentum concerning innovative ideas.

Recently research and development efforts for CAES have been directed towards improving the relatively low round cycle efficiency by intermediately storing the heat generated in the compression phase and reuse it during the expansion phase (ACAES)[230]. Figure 82 shows how the German utility company RWE envisages how a heat storage facility can be incorporated in a CAES plant. Heat may be stored at temperatures up to 600 °C or even higher in rocks (stone) or other ceramic materials and the technology is being developed for a variety of purposes these years. Within a time perspective of 10-15 years it thus seems fair to anticipate that A-CAES will be commercially available. This development is expected to improve the power-to-power efficiency to around 70 % and bring A-CAES into a much more attractive efficiency class. Another alternative in countries where district heating plays a role is to exchange heat with district heating companies on a commercial basis.

---

[227] https://arstechnica.com/science/2018/06/liquid-air-energy-storage-the-latest-new-battery-on-the-uk-grid/. Accessed November 2018.

[228] Cryogenic Storage Offers Hope for Renewable Energy, Yasmin Ali, BBC News, 2016. http://www.bbc.com/news/science-environment-37902773

[229] https://www.bbc.com/news/uk-northern-ireland-39477262

[230] "ADELE – ADIABATIC COMPRESSED-AIR ENERGY STORAGE FOR ELECTRICITY SUPPLY. RWE Brochure.," RWE Power AG, Cologne, 2010.

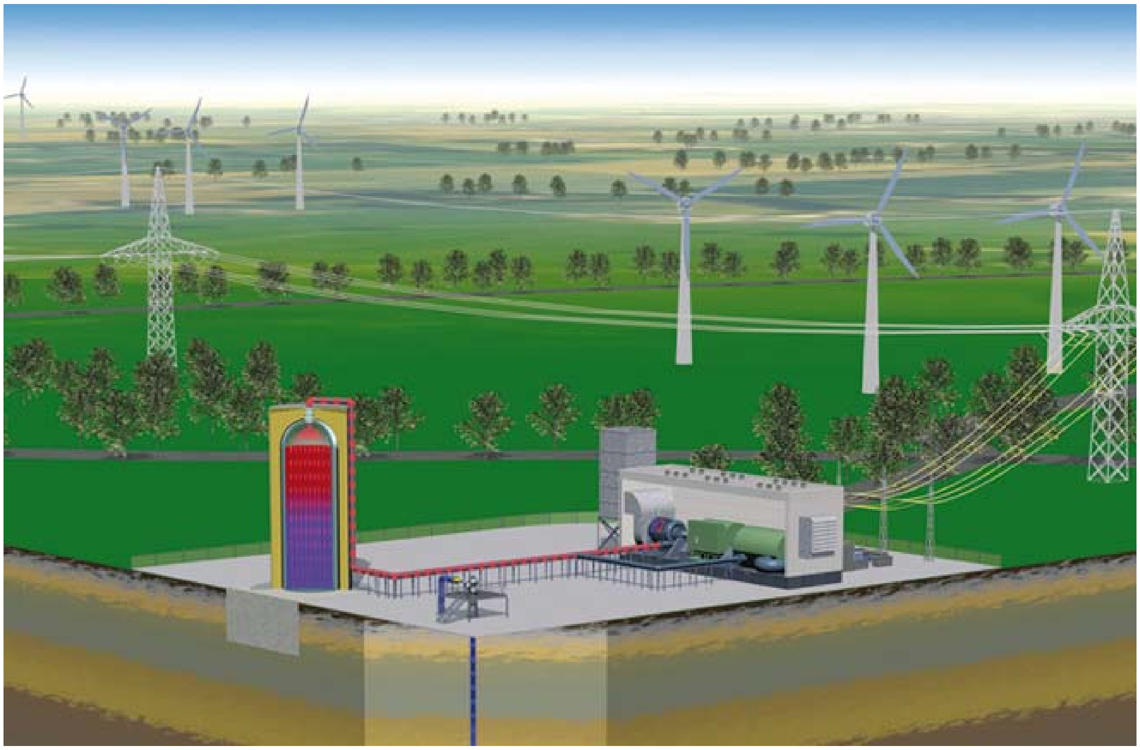


Figure 82. RWE´s vision for an ACAES plant[230].

Danish competition position

Denmark is in focus as demonstration site for several developers. For ALP-CAES possible sites having very large cavern volumes exist. Ideas among several Danish stakeholders may be utilized for practical implementation. Denmark is the leading nation in the field of utilizing CO_2 in refrigeration systems and heat pumps. This combined with in depth knowledge on turbo compressors and expanders is a strong base for industrialization of transcritical Carbon Dioxide Thermo-Mechanical Storage.

Players in Denmark

Ørsted, Rambøll, DTU Technical University of Denmark, Aalborg University and the Danish Technological Institute have worked with thermos-mechanical energy storage technologies and have done techno-economic assessments

AKZO Nobel and Energinet.dk are cavern and aquifer owners in Denmark.

Specific recommendations

Apart for thermal energy storage, conventional methods for large-scale energy storage are not applicable in Denmark (PHS) or have low efficiency and significant consumption of fossil fuel (CAES). ALP-CAES is possible to utilize in Denmark.

Further development of technology class with high efficiency and high flexibility is needed. This will involve development of

- system concepts
    - compressed air or other types

    - high-temperature thermal energy storage
    - storage of compressed fluid and heat at varying temperatures
    - Cavern design including liquid charge/discharge lines
- system integration concepts
    - economic optimization
    - fast start-stop
    - large capacity for energy as well as power input/output
- components
    - compressors/expanders
    - Pumps/turbines
    - reversing units
    - high-temperature and low-temperature heat storage

15. Electric Energy Storage

Most technologies for storage of electrical energy involve conversion of energy from electricity to some other form of energy. Such technologies have been described in the sections preceding the present one and include storage as e.g. chemical or thermal energy. However, electricity may also be stored in electrical form as

- electric current or
- electric charges in a potential difference

Superconducting Magnetic Energy Storage (SMES) and capacitors or supercapacitors represent the two forms and only the latter form plays a role in the energy system.

15.1 Superconducting Magnetic Energy Storage (SMES)

Work on SMES has been going on for quite many years and relies on superconductors to conserve a circular current in a superconducting coil with low Ohmic losses. The energy is stored in the magnetic field induced by the current.

Since SMES relies on superconducters (wether high or low temperature superconducters) they need to be cooled to low temperatures of at least around 50-70 K (-223 ˚C). Thus, when considering SMES for energy storage the energy consumed for keeping the system at low temperature must be taken into account and in any case the cooling expenses must included in the overall economic calculations for such systems.

The principles of SMES can be explained by Figure 83.

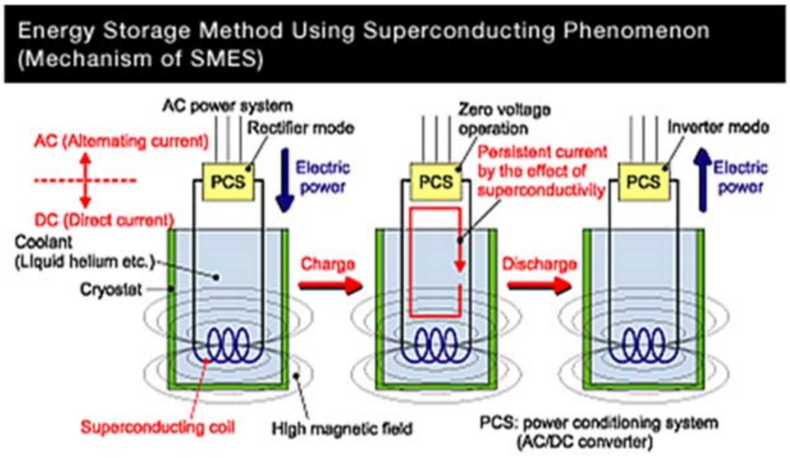


Figure 83. Principles of storing energy in supermagnetic coils[231].

SMES systems are suitable for high power delivery but can only provide the power for short periods. A 10 MW and 20 MJ (10 MW for 2 sec.) equipment has been constructed[232] in

---

[231] http://www.meiji.ac.jp/cip/english/frontline/nomura/index.html Accessed February 2019

[232] T. Katagiri, H. Nakabayashi, Y. Nijo, T. Tamada, T. Noda, N. Hirano, T. Nagata, S. Nagaya, M. Yamane, Y. Ishii, and T. Nitta: Field Test Result of 10 MVA/20 MJ SMES for Load Fluctuation Compensation, IEEE Transactions on Applied Superconductivity, Volume: 19, Issue: 3, pp. 1993-1998, DOI: 10.1109/TASC.2009.2018479, 2009.

Japan in 2009 and since then three commercial SMES units for bridging instantaneous voltage dips are operating in Japan[233].

In general, SMES systems have mainly been constructed at research institutes and they still require substantial R&D to reveal a wider commercial potential. In Europe the main competences within SMES are found at KIT in Germany, CNRS in France and REESA in Spain.

Presently, SMES is currently not considered of substantial academic or industrial interest in Denmark.

15.2 Supercapacitors

Supercapacitors (SCs) are referred to by several names: Ultracapacitors and Electrical Double Layer Capacitors (EDLC). The latter name indicates the electricity storage mechanisms of superconducters.

Supercapacitors store energy electrostatically in an electrical double layer at the interphase between. In the ideal version of SCs, no charge transfer between involved materials take place, but in reality some charge transfer often takes place, thereby leading to a redox reaction. The first mechanism without charge transfer is called EDLC, whereas the second, where some charge transfer is observed, is called pseudocapacitance, because an electrochemical reaction takes place and gives similarities to batteries.

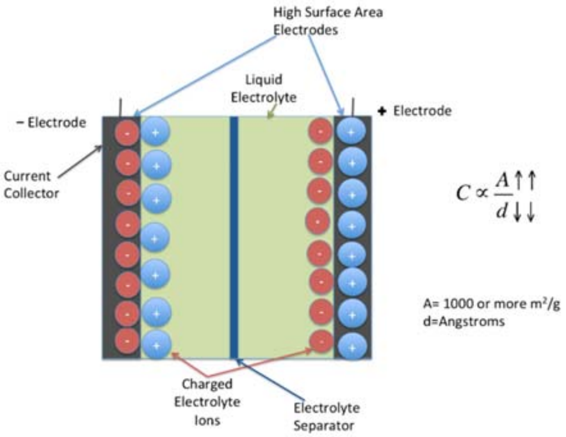


Figure 84. Principles of an electrical double layer capacitor[234]. The charged state is shown. The surface area A of electrodes should preferably be as large as possible to allow maximal adsorption, whereas the thickness of the double layer should be minimal.

Similar to SMES, superconducers are **power storage** devices, meaning that they can release very high power, but only for relatively short time periods. The reason for the high power density is that chemical reactions are not involved in the charging and discharging

---

[233] Shigeo Nagaya, Naoki Hirano, Toshio Katagiri, Tsutomu Tamada, Koji Shikimachi, Yu Iwatani, Fusao Saito, Yusuke Ishii: The State of the Art of the Development of SMES for Bridging Instantaneous Voltage Dips in Japan, Cryogenics, Volume 52, Issue 12, pp. 708-712, 2012

[234] Electrochemical Double Layer Capacitors (Supercapacitors), M. Aslani, Stanford University, 2012

processes, whereas the short discharge times are associated with the low energy density of SCs as reflected in Figure 85.

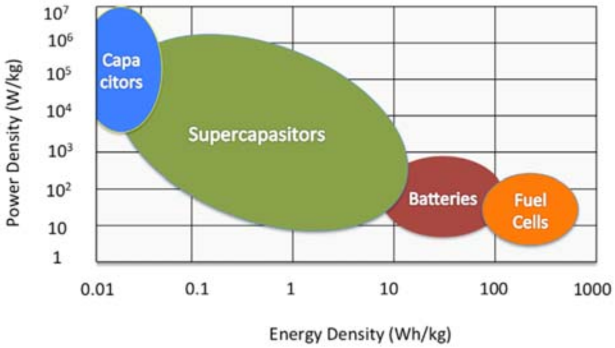


Figure 85. Power and energy densities of capacitors and fuel cells[234]

Because of the lack of chemical reactions, supercapacitors can be cycled (charged and discharged) again and again without degradation - not without losses, though, due to the controlling power electronics.

Applications of supercapacitors are numerous. Examples are: electric vehicles, hand tools, consumer electronics, industrial devices, back-up power supplies and many others.

The current industrial interest in developing superconductors in Denmark is small and in the research community only a scarce interest is found, even though some types of superconductors show similarities to batteries.

16. Virtual energy storage

Virtual energy storage is foreseen as a component of the future technologies to solve the problems about fluctuating or varying electricity supply. Virtual storage is done by controlling electricity demand by moving it from periods of insufficient supply to periods with larger supply than demanded. The technology is more frequently called demand response.

Thus, virtual energy storage does not include operations, which include actual, physical or chemical storage e.g.:

- Heating building envelopes to higher temperatures in periods of excess electricity generation
- Cooling food store houses, freezers and refrigerators to lower temperatures in periods of excess electricity generation

In both of these examples, energy is physically stored as heat in building materials or as cold in food and containment envelope.

Virtual energy storage does include moving energy consumption from periods of high prices and high demand to periods of low prices and low demand (e.g.):

- Operating dish washers at times of excess electricity generation (often night time)

- Reserving energy-intensive industrial production (e.g. electric smelters) to periods of excess electricity generation and stop or downregulate production in periods of insufficient electricity generation

The bullets illustrate the principles, but many other examples suitable and useful for virtual storage applications. Further examples are shown below and still the list is far from exhaustive:

- Operation of electric boilers and large heat pumps (both to be interrupted at high electricity prices or capacity constrains) in district heating systems – possibly in combination with alternative production from gas boilers and CHP
- Operation of water cooling enabling the chillers and heat pumps to interrupt at large electricity prices and increase production at low prices
- Installation of DH&C infrastructure with the above-mentioned facilities as an alternative to individual heat pumps and chillers with little flexibility
- Charging electric cars and load stations in e.g. parking lots in accordance with electricity prices
- Connecting laundry and dish washing machines to hot tap water for heating and thereby taking part in the overall city scale virtual battery
- Operation of any device for use of electricity, which has some flexibility

The driver for application of virtual storage or demand response is at least two-fold:

- Owners of electricity-consuming devices have an opportunity to cut the electricity bill, since electricity prices are lower in periods of excessive generation than in periods of insufficient generation
- Grid operators, including grid balance responsible parties, can save investments in grid capacity expansion (bottlenecks) and have access to important supply-demand balancing tools. They should therefore be able to offer a discount on connection and distribution tariffs, so called smart grid tariffs, which will encourage smart use of electricity.

However, both above-mentioned drivers (naturally) boil down to economic incentives. Thus, the consumer´s cost savings should exceed the costs of installing and operating the required demand response devices plus the effect of inconvenience if any. Therefore, the by far dominating demand response is that which can be established by the large consumer such as district heating companies and some of the large industries with some flexibility in their demand. Provided that smart grid tariffs have been introduced, also electric cars as a whole could play an important role.

Intelligently controlled demand response can provide the same functions as physical (real) energy storage because demand response is able to match demand and supply, which is a basic feature of storage. As an example, controlling loads such as air conditioning systems based on forecasted solar PV generation gives an optimal match: the air-conditioning system is only operating when most needed which coincides with periods of high PV generation.

Many other examples of demand response management/virtual storage providing the same or similar functions as real energy storage can be mentioned and there is no doubt that virtual storage has a role to play in the future energy system. In a workshop on “The Potential of Electricity Demand Response”[235] K. Fiksen gave figures for the Nordic market, where demand response enabled a peak load reduction triggered by demand response of up to 12% (representing 8,300 MW). She added that, at the moment, it is mainly industrial players that provide an impressive amount of demand response to the market, while households still play a minor role.

Advanced development of computer algorithms to control the demand response management is already going on and applied (see also section on “Energy storage in a market perspective”). However, to be successful the development must hold consumers central and secure their acceptance and engagement.

An interesting aspect of virtual storage/demand response is that it can be considered as a support to industry, if a large electricity consumer is paid to reduce their electricity consumption in periods of too low supply, where electricity prices are high and the industrial production might not be profitable. For such cases member states have had to demonstrate the necessity of certain arrangements to the European Commission and in a press release from February 2018[236] Commissioner Margrethe Vestager, has said: "Capacity mechanisms can help to safeguard security of electricity supply, but they must be designed so as to avoid distortions of competition in energy markets. I am glad that our close cooperation with national authorities has enabled us to today approve well-designed capacity mechanisms in six EU countries. They will foster competition among all potential capacity providers to the benefit of consumers and our European energy market."

---

[235] Proceedings of the workshop “The Potential of Electricity Demand Response”, p. Brussels, 30 May 2017

[236] http://europa.eu/rapid/press-release_IP-18-682_en.htm Accessed January 2019.

17. Regulatory frames and market design

Even though the energy systems in Europe and Denmark have been changing dramatically over a couple of decades by now, the regulatory frameworks for how to operate the systems are still characterized by their origin in the fossil, centralized energy system. Today´s energy systems in Europe are increasingly facing integration of variable renewable energy generation, which sets new, decisive conditions and requirements to integration.

Energy storage was indeed a significant component in the fossil energy system – think of piles of coal at central power plants, huge underground storage of fossil natural gas or large containers in harbors and refineries for fuels to drive the transport sector. Without this storage capacity, the fossil-based societies would not have been operational and many regulations were – and still are - valid for this kind of storage. Most regulations concerned environmental issues and to some extent supply security as well.

However, nowadays´ thinking of “energy storage” is very different and the governing regulations have to change accordingly. The value of modern energy storage (ES) can only be understood if its systemic nature is appreciated. ES must be considered for specific applications and it is important to allow for aggregation of different applications for one ES service provider to enjoy its full economic potential.

The existing energy system is designed so, that players cannot profit on all services some ES is able to provide to the whole system. Therefore, a revised market design is important for ES to roll out its virtues in the future.

In terms of updating market design, the following recommendations should be considered:

- Probably most important is to **establish a <u>broadly supported</u> definition of energy storage.** The definition must be prepared at EU level.

- In general, regulations and market design should **as far as possible be made on an EU basis** to be in line with the EU single market for energy.

- Appreciate that **energy storage is a special and important asset** of the complete energy system.

- **Levy structures** (grid fees, taxes or similar**) should not hinder or discriminate** the integration of energy storage.

- **Avoid double tax and fees.** Energy storage is not a consumer nor a generator. Energy can only be generated and consumed once and fees and taxes should accommodate to this fact.

- Storage devices can provide services to regulated as well as non-regulated parts of the energy system, but in all cases **market-based solutions should be preferred** whenever possible.

- **Energy storage adds value to several levels in the energy system**. Thus, operators of ES should be allowed to differ, if it does not lead to market distortion.

- Market design should **allow specialized storage operators to emerge**

- Markets and payments for storage should **allow any storage technology to participate**, if they are able to fulfil the requirements.

- Specific storage technologies provide capabilities to interlink different energy sectors (e.g. fuel for transport, electric power and the heating sector). Therefore an **integrated approach would often be favorable**

18. Conclusions and recommendations

This whitepaper describes dominating energy storage technologies and points out their status, applications, development needs as well as interest and engagement among Danish actors.

As Denmark is rapidly approaching a substantial level of sustainable energy in the energy supply, new means have to be brought into consideration to deal with the fluctuating nature of these types of primary energy input. The same situation is fundamentally found in many other countries in Europe and abroad and an international trend can be seen to put strong emphasis on tools to facilitate the integration of renewable sources.

Energy storage is definitely one important tool to allow sustainable energy take over our future energy foundation without losing the security of supply, the comfort and the convenience we have enjoyed so much while consuming non-sustainable energy in the black energy era.

Luckily, plenty of renewable energy is indeed available all the time, with solar, geothermal and nuclear power (wind power is a derivative of solar power) as the available sources, if nuclear power qualifies to be included in the context. Humankind is only utilizing an ignorable part of the total influx to Earth of solar power and thus, we just need to learn and experience how to exploit the renewable energy and how the new sustainable future can best be organized and realized.

But time is running out! Global climate is changing and disastrous implications for life concerning living conditions and access to land are envisaged by climate models looking into the future. It is urgent to meet these challenges and energy storage is an important link between the abundancy of renewable energy on one hand and availability, comfort and convenience on the other hand.

This whitepaper reviews a wide spectrum of storage technologies at different levels of readiness and discusses energy storage options to facilitate integration of renewables. Based on the studies behind the work a number of recommendations can be given concerning the general situation of energy storage in Denmark.

Overall recommendations for energy storage in Denmark:

- **Take care to involve all relevant, Danish competences in R&D activities on energy storage in Denmark. Some internal competition is fine, but Denmark is too small to allow non-coordinated spending of resources**
- **Revise and adjust rules and regulations governing grid-connected energy storage to encourage an emerging commercial market**
- **Push to design electricity market - including fees and taxes – to incentivize consumers´ purchase energy storage devices**
- **Establish medium to large demonstration projects co-funded between industry, R&D communities and funding authorities**

- **Set up R&D programs to specifically support collaborative coordination of competences in Denmark. Involve public R&D communities as well as industry**
- **Nudge and support Danish participation in European R&D programs**
- **Prepare legislation and regulation to facilitate introduction of energy storage in the energy system on a level playing ground without market distortions**

However, apart from the overall considerations the whitepaper puts special emphasis on selected important technologies in a time perspective of about 5-10 years from now.

Based on maturity, applicability in Denmark and the level of relevant Danish competences, the selected technology classes and associated recommendations are as follows:

Batteries

Since 2014 Denmark has progressed considerably within battery research as well as within use and control of batteries. Major companies in Denmark have installed grid-connected mega-batteries and wind turbine manufacturers have faced the importance of battery operations in electricity systems dominated by non-synchronized wind power. It is an interesting observation that such companies are now engaging in battery research and development much more than 5 years ago and . Moreover, several mega-factories – one I Sweden - are underway in Europe.

Batteries have numerous applications in the modern society ranging from small backup devices to maintain power, while main batteries are exchanged in computers and household appliances, over kWh batteries in the emerging electrical vehicles to large MW grid-connected applications.

Batteries take a prominent position in the present whitepaper. It is amazing how interest in batteries and applications for batteries have evolved over recent years. Even if Asia is still leading and Asian battery products still dominate the market, several countries in Europe, including Denmark, are catching up in terms of R&D activities within industry and research communities.

For Li-ion technology, this is particularly true within battery management systems, but also within better Li-ion chemistries and more appropriate Li-ion designs the EU and Denmark hold promising positions. When it comes to brand new battery chemistries Denmark is indeed at the cutting edge putting emphasis on key properties as higher energy densities and cheaper performance characteristics.

Li-ion technology has limitations and new types of batteries will most probably take over in many applications in a not very distant future. Within those areas, Denmark is in front of the development and an excellent oportunity for new manufacturing companies is likely to emerge, if a fertile soil and tailwind is in place in the first years to come. In any case, much technical and scientific work has to be done within new battery types and chemistries, preferably based on cheap and abundant materials, to trigger the considerable commercial potential within this important topic.

On this basis, the following recommendations are given in addition to the specific recommendations given in the dedicated sections about batteries:

- ➢ Make sure to maintain the outstanding R&D environments within battery technology in Danish universities, technological service institutions and industry
- ➢ Consider more support to basic research in development of new types of batteries with potential for higher energy density
- ➢ Encourage life cycle assessment of batteries including recycling of materials and reuse of batteries
- ➢ Support theoretical methods to develop new materials for batteries and electrochemical energy storage
- ➢ Develop new and better battery management systems for reasons of security and endurance

Electrochemical energy storage

Within electrochemical energy storage (based on electrolysis), Denmark is in the international front as well - perhaps partly because of the long Danish tradition for chemical industry and the parallel competences and activities in the Danish research and technological service communities.

Power-to-fuel technologies (P2G, P2X) have the potential to solve at least three obtrusive challenges in the sustainable energy system:

- The need for mobile energy storage for traction in the transport sector (long distance and heavy duty ground transport, aviation and marine transport)
- The need for large-scale, seasonal energy storage
- The need for hydrogen to compensate for the lack of this gas in conversion of biomass into fuels. The H:C ratio in biomass is about 1.5 (depending slightly on type) as compared to 4 for methane and 2.5 for butane.

Those needs are paramount for an energy system

- ▪ where green mobility is crucial for economy and welfare
- ▪ where energy storage can minimize the need for investments in primary production
- ▪ where biomass should be exploited as well as possible.

Sizeable industries like shipping and aviation have already started the tough transition to renewable fuels and outstanding Danish and Scandinavian sea and air carriers have announced their start on that journey. There are good reasons to support the transition and let Danish actors be among the first movers within the field.

In addition, electrochemical energy storage will at some point be important for manufacturing plastic materials, which are currently used extensively in industrial applications based on fossil sources (gas and oil), which must be substituted.

On this basis, the following recommendations are given in addition to the specific recommendations given in the dedicated sections about electrochemical energy storage:

- ➢ Maintain activities on basic research and development for cheap, efficient electrolysis processes with potential to fit into the Danish electricity system.

  - ➢ Initiate further studies – including small-scale experimental verification – about use of underground formations/structures for storing chemical, synthetic fuels and feedstock gases for such fuels.
  - ➢ Focus on experimental activities and system analyses aiming to optimize synergy between electrolysis and gas from fermentation or gasification of biomass
  - ➢ Initiate projects in support qualified assessment of the potential for utilising electrolysis in combination with existing fuel and gas distribution infrastructure in Denmark.
  - ➢ Study interaction potentials between electrolysis processes and district heating systems

Thermal energy storage

Heating is a large part of the energy system (close to 50%) and thermal energy storage – whether cold or heat storage – is therefore highly important. Thermal energy storage takes many forms and ranges from small equipment in households to large scale thermal energy storage in rocks, molten salt or hot water. Thermal energy storage is already applied extensively in hot water containers in households and in district heating systems. Thermal energy storage deserves more emphasis considering its importance in everyday life and considering the large potential in the strong Danish food industry, where heat is used for processing and for cleaning purposes. Industrial consumption of heat is often done in a daily, cyclic pattern and a significant part of this heat is discarded or wasted after use. At least some of this heat could have been stored from one day to another and thus save consumption of valuable primary energy.

Although storing heat sensibly in water is the dominating technology, other thermal energy storage technologies exist and should be developed based on the work already going on in technological institutions and universities in Denmark. Particularly, latent heat storage and thermo-chemical energy storage are still not used substantially in practical applications, but are catching up as demonstrated by the newly started company Suntherm descried above. Latent and thermos-chemical thermal energy storage have higher energy densities than sensible storage in water and systems can be designed to operate at specific temperatures, whereas heat stored in water gives depleting temperature when releasing the heat.

Nonetheless, all thermal storage technologies should be further developed to support the large heating and the growing cooling sector and to harvest a substantial commercial and export potential.

On this basis, the following recommendations are given in addition to the specific recommendations given in the dedicated sections about thermal energy storage:

- Recommendations and timeline:
  - ➢ Set up R&D support programs for latent heat and thermo-chemical energy storage
  - ➢ Support development of cost efficient, new high-temperature sensible storage technologies for re-electrification by use in combination with (steam) turbines
  - ➢ Subsidize investments in selected thermal energy storage applications

- Update evaluation of the amount of available waste heat in Denmark in terms of energy, power and temperature
- Evaluate commercial potential and export potential for thermal energy storage devices
- Start experimental projects on innovative large-scale thermal energy storage technologies like underground technologies and note that also relatively low-temperature heat storage may be of value.

Mechanical and thermo-mechanical energy storage

Flywheel technology is a new player on the scene for energy storage in Denmark. Five years ago, you could hardly find any European actor on flywheels and now a successful Danish company is marketing flywheels for storage at very competitive prices. The production takes place in Denmark and should be supported and nursed to accelerate its growth.

Mechanical energy storage in general has played a major role in energy systems for about a century in the form of pumped hydro. Some decades ago the compressed air energy storage (CAES) technology was introduced in Germany and later in the USA and since then no other large system has been built. Denmark has fine geological preconditions for establishing huge cavities in underground structures like salt deposits, and in addition, there are strong Danish competence and knowledge within construction and operation of underground pressurized cavities. CAES has attractive storage properties which should be considered for use in the future Danish energy system. Denmark also has competences in industry and research, which can be activated and utilized to assess and establish CAES in Denmark.

On this basis, the following recommendations are given in addition to the specific recommendations given in the dedicated sections about mechanical and thermomechanical energy storage:

- Study new applications for flywheels in the energy system (and beyond)
- Secure more collaboration between industry and research
- Study if the development of large-scale, high-temperature thermal energy storage can have an impact on economy of CAES
- Allow assessment studies of new types of thermo-mechanical technologies
-

Emerging energy storage technologies

The above-mentioned storage technologies must be considered the most important and relevant for Denmark as already mentioned. However, there is no silver bullet and no single solution for the need for energy storage and therefore Danish authorities should be open-minded to new trends within the topic. Historically, some of the most powerful discoveries and developments in history have had roots in completely untraditional thinking, sometimes even unaccepted thinking. Everybody should bear this fact in mind.

- Recommendations:

- Allow room for R&D activities focusing on novel or less mature storage technologies

List of acronyms and abbreviations

AC	Alternating Current
ACAES	Adiabatic Compressed Air Energy Storage
ADELE	Adiabatic Compressed Air Energy Storage for Electricity Supply
AEMO	Australian Energy Market Operator
ALP	Adiabatic Liquid Piston
AU	Aarhus University
BASE	BASE Performance
BMS	Battery Management System
BTES	Borehole Thermal energy Storage
BYG	Civil Engineering (DTU)
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
CASE	Catalysis for Sustainable Energy (DTU)
CEA	French Alternative Energies and Atomic Energy Commission
CEESA	Coherent Energy and Environmental System Analysis (AAU)
CEO	Chief Executive of Organization
CHP	Combined Heat and Power
CNRS	Centre National de la Recherche Scientifique
COP	Coefficient of Performance
CSP	Concentrate Solar Power
DBS	Dansk Batteri Selskab
DC	Direct Current
DFM	Dansk Institut for Fundamental Metrologi
DH	District Heating
DK	Denmark
DME	Di-Methyl Ether
DOE	Department of Energy
DONG	Danish Oil and Natural Gas (now Ørsted)
DSF	Det Strategiske Forskningsråd
DSO	Distribution Service Operator
DTI	Teknologisk Institut
EASE	European Association for Storage of Energy
EDLC	Electrical Double Layer Capacitor
EERA	European Energy Research Alliance
EM	Energy Membrane
EMF	ElectroMotive Force
EMMES	European Market Monitor on Energy Storage
ENTSO	European Network of Transmission Service Operators
EPRI	Electric Power Research Institute
ES	Energy Storage
ESA	European Space Agency
ESIC	Energy Storage Integration Committee
ESS	Energy Storage System
EUDP	Energiteknologisk Udviklings- og Demonstrationsprogram
EUR	Euro
EUROBAT	Association of European Manufacturers of automotive, industrial and energy storage batteries?
EV	Electric Vehicle
FCAS	Frequency Control Ancillary Services
GCA	Global Climate Actions
GEO	GEO Subsurface Expertise
GEUS	De Nationale Geologiske Undersøgelser for Danmark og Grønland
GHG	Green House Gas
GPS	Ground Positioning System
GW	Gigawatt
HDPE	High Density Poly Ethylene
HHV	Higher Heating Value
HIA	Hydrogen Implementing Agreement

HTAS	Haldor Topsøe A/S
IDA	Ingeniører i Danmark
IEA	International Energy Agency
IPU	Institut for ProduktUdvikling
ISO	Independent Service Operator
KIT	Karlsruhe Institute of Technology
KTH	Royal Institute of Technology, Stockholm
KU	Copenhagen University
LAES	Liquid Air Energy Storage
LFP	Lithium Iron Phospfate
LHS	Latent Heat Storage
LIB	Li Ion Battery
LNMO	Lithium Nickel Manganese Oxide
LT	Low Temperature
LTO	Lithium Titanate
MEUR	Mega EUR
MH	Metal Hydride
MJ	Megajoule
MVA	Megawatt
MW	Megawatt
NAS	Sodium Sulfur
NASA	North American Space Agency
NEF	New Energy Finance
NEM	National Electricity Market
NMC	Lithium Nickel Manganese Cobalt Oxide
NRECA	National Rural Electric Cooperative Association
NREL	National Renewable Energy Laboratory
OECD	Organization for Economic Co-operation and Development
PCM	Phase Change Material
PCS	Power Conversion System
PES	Pumped Energy Storage
PHS	Pumped Hydro Storage
PJ	Petajoule
PJM	Pennsylvania-New Jersey-Maryland Interconnection
PTES	Pit Thermal Energy Storage
PV	Photovoltaic
RD	Research, Development
ROTES	Rotary Energy Storage
RWE	Rheinisch-Westfälisches Elektrizitätswerk
SC	Super Capacitor
SDU	University of Southern Denmark
SE	SE Energi & Klima
SEV	Streymoy-Eysturoy-Vágar
SHS	Sensible Heat Storage
SNG	Synthetic Natural Gas
SOC	Solid Oxide Cell
SOEC	Solid Oxide Electrolysis Cell
SOFC	Solid Oxide Fuel Cell
TCP	Technology Collaboration Programmes
TCS	Thermo-Chemical Storage
TES	Thermal Energy Storage
TOFC	Topsøe Fuel Cells
TRL	Technology Readiness Level
TSO	Transmission Service Operator
TUHH	Technische Universität Hamburg-Harburg
TW	Terawatt
UPHS	Underground Pumped Hydro Storage
UPS	Uninterrupted Power Supply
URL	Uniform Resource Locator
USD	US Dollar
USGS	United States Geological Survey
UTES	Underground Thermal Energy Storage
AA	Advanced Adiabatic
AAU	Aalborg University

Annex A - SET Plan targets

Under the European Commission and as a part of the Strategic Energy Technology Plan (SET Plan) economic and technical targets for many energy technologies have been set up. For the convenience of the reader of this document, SET plan targets are given here for several storage technologies. The data is basically from “Commission Staff Working Paper: Materials Roadmap Enabling Low Carbon Energy Technologies, 2011, and are repeated here as compiled by EASE and EERA in “Joint EASE/EERA recommendations for a European Energy Storage Development Roadmap, 2017 Update.

Electrolysis

Table 1: SET-Plan Targets Alkaline Technology.

Property	State-of-the-art	Target 2020-2030	Ultimate goal
Operating current density (A/cm²)	0.2–0.5	0.1–1	0–2
Operating temperature (°C)	ambient – 120	ambient - 150	ambient - >150
Operating pressure (bar)	1-200	1-350	1-700
Durability (h)	10^5	> 10^5	> 10^5
Cyclability	poor	improved	high
Production capacity of electrolysis units (Unit size 1 MW)	1-100 kg/hour (≈ 10-1000 Nm³/hour)	> 100 kg/hour (≈ 1000 Nm³/hour)	> 1000 kg/hour (≈ 10 000 Nm³/hour)
Non-energy cost (€/kg H_2)	<5	2	1

Table 2: SET-Plan Targets PEM Technology.

Property	State-of-the-art	Target 2020-2030	Ultimate goal
Operating current density (A/cm²)	0 – 2	0 – 2	0 – 5
Operating temperature (°C)	50-80	80-120	100-150
Operating pressure (bar)	1-50	1-350	1-700
Durability (h)	10^4	$10^4 – 5·10^4$	> 10^5
Production capacity of electrolysis units	1-30 kg/hour (≈ 10-300 Nm³/hour)	> 30 kg/hour (≈ 300 Nm³/hour)	> 100 kg/hour (≈ 1000 Nm³/hour)
Energy efficiency (kWh/kg H_2 at 80°C, 1 A.cm^{-2})	56	< 50	48
Non-energy cost (KWh/kg H_2)	5	2	1

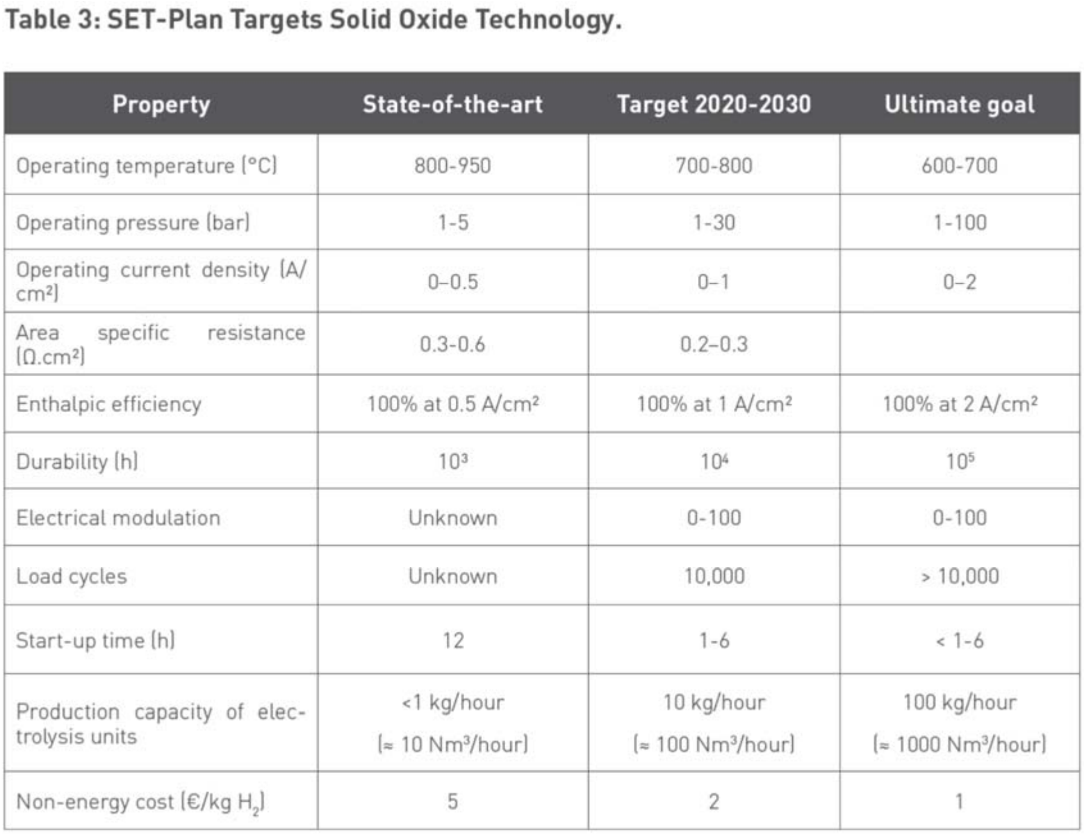


Table 3: SET-Plan Targets Solid Oxide Technology.

Property	State-of-the-art	Target 2020-2030	Ultimate goal
Operating temperature (°C)	800-950	700-800	600-700
Operating pressure (bar)	1-5	1-30	1-100
Operating current density (A/cm²)	0–0.5	0–1	0–2
Area specific resistance (Ω.cm²)	0.3-0.6	0.2–0.3	
Enthalpic efficiency	100% at 0.5 A/cm²	100% at 1 A/cm²	100% at 2 A/cm²
Durability (h)	10^3	10^4	10^5
Electrical modulation	Unknown	0-100	0-100
Load cycles	Unknown	10,000	> 10,000
Start-up time (h)	12	1-6	< 1-6
Production capacity of electrolysis units	<1 kg/hour (≈ 10 Nm³/hour)	10 kg/hour (≈ 100 Nm³/hour)	100 kg/hour (≈ 1000 Nm³/hour)
Non-energy cost (€/kg H_2)	5	2	1

Hydrogen storage

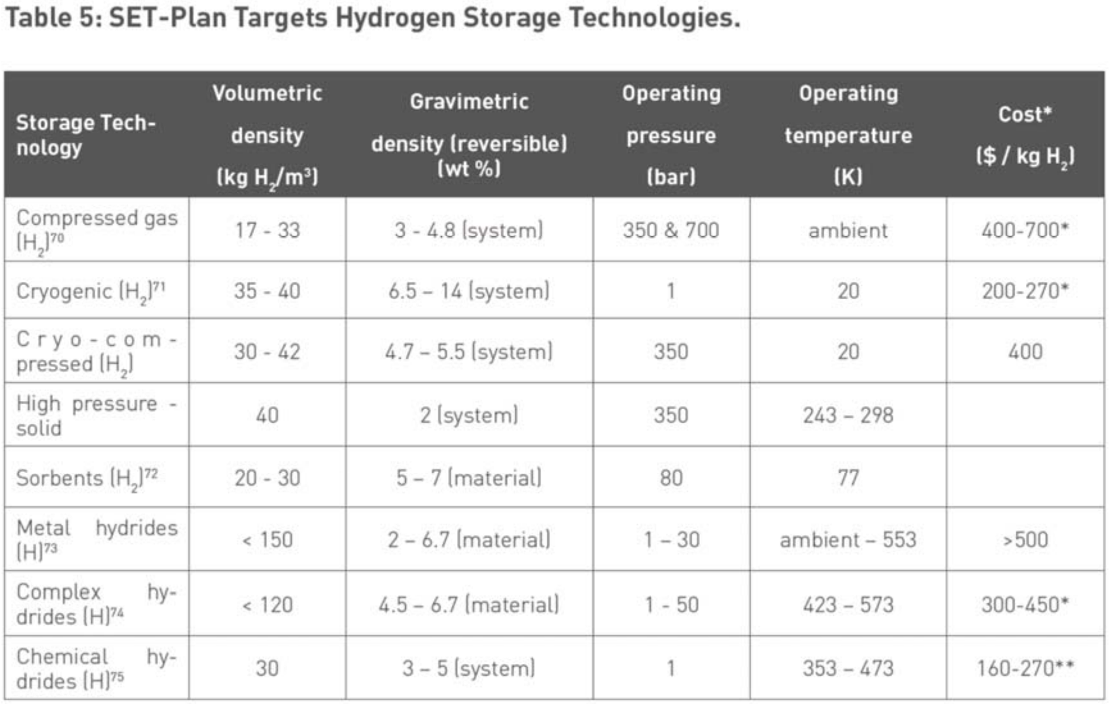
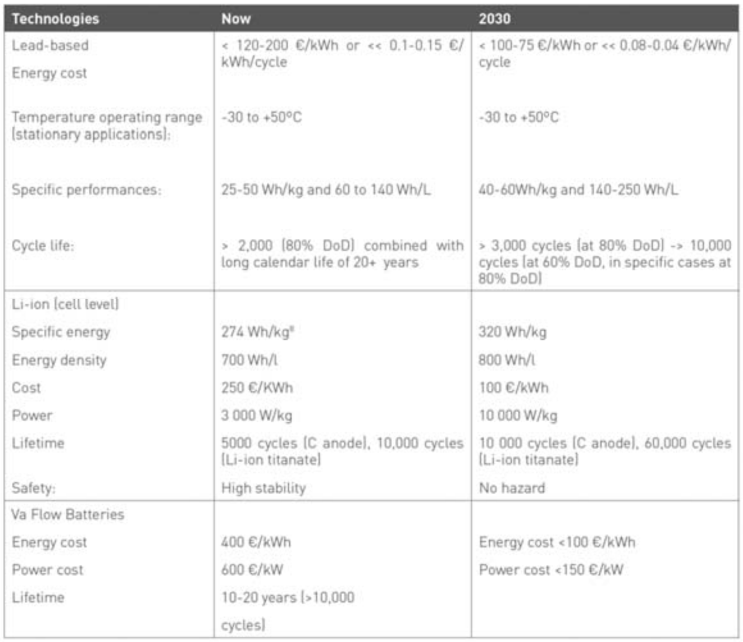


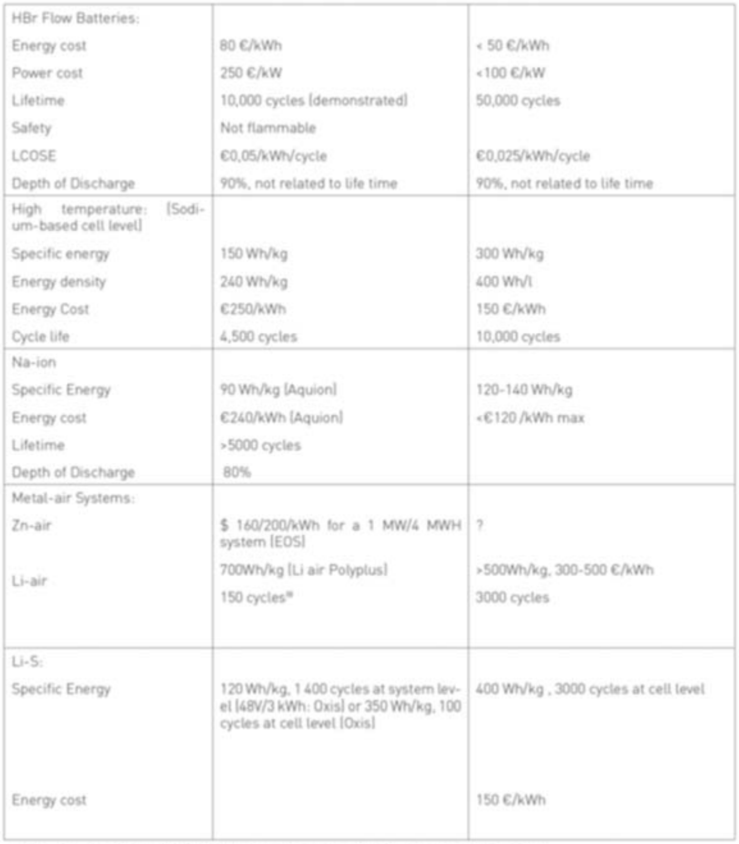
Table 5: SET-Plan Targets Hydrogen Storage Technologies.

Storage Technology	Volumetric density (kg H_2/m³)	Gravimetric density (reversible) (wt %)	Operating pressure (bar)	Operating temperature (K)	Cost* ($ / kg H_2)
Compressed gas (H_2)[70]	17 - 33	3 - 4.8 (system)	350 & 700	ambient	400-700*
Cryogenic (H_2)[71]	35 - 40	6.5 – 14 (system)	1	20	200-270*
Cryo-compressed (H_2)	30 - 42	4.7 – 5.5 (system)	350	20	400
High pressure - solid	40	2 (system)	350	243 – 298	
Sorbents (H_2)[72]	20 - 30	5 – 7 (material)	80	77	
Metal hydrides (H)[73]	< 150	2 – 6.7 (material)	1 – 30	ambient – 553	>500
Complex hydrides (H)[74]	< 120	4.5 – 6.7 (material)	1 - 50	423 – 573	300-450*
Chemical hydrides (H)[75]	30	3 – 5 (system)	1	353 – 473	160-270**

Batteries

Table 8: Targets for electrochemical storage to support the SET-Plan.





Technologies	Now	2030
Lead-based Energy cost	< 120-200 €/kWh or << 0.1-0.15 €/kWh/cycle	< 100-75 €/kWh or << 0.08-0.04 €/kWh/cycle
Temperature operating range (stationary applications):	-30 to +50°C	-30 to +50°C
Specific performances:	25-50 Wh/kg and 60 to 140 Wh/L	40-60Wh/kg and 140-250 Wh/L
Cycle life:	> 2,000 (80% DoD) combined with long calendar life of 20+ years	> 3,000 cycles (at 80% DoD) -> 10,000 cycles (at 60% DoD, in specific cases at 80% DoD)
Li-ion (cell level)		
Specific energy	274 Wh/kg[II]	320 Wh/kg
Energy density	700 Wh/l	800 Wh/l
Cost	250 €/KWh	100 €/kWh
Power	3 000 W/kg	10 000 W/kg
Lifetime	5000 cycles (C anode), 10,000 cycles (Li-ion titanate)	10 000 cycles (C anode), 60,000 cycles (Li-ion titanate)
Safety:	High stability	No hazard
Va Flow Batteries		
Energy cost	400 €/kWh	Energy cost <100 €/kWh
Power cost	600 €/kW	Power cost <150 €/kW
Lifetime	10-20 years (>10,000 cycles)	
HBr Flow Batteries:		
Energy cost	80 €/kWh	< 50 €/kWh
Power cost	250 €/kW	<100 €/kW
Lifetime	10,000 cycles (demonstrated)	50,000 cycles
Safety	Not flammable	
LCOSE	€0,05/kWh/cycle	€0,025/kWh/cycle
Depth of Discharge	90%, not related to life time	90%, not related to life time
High temperature: (Sodium-based cell level)		
Specific energy	150 Wh/kg	300 Wh/kg
Energy density	240 Wh/kg	400 Wh/l
Energy Cost	€250/kWh	150 €/kWh
Cycle life	4,500 cycles	10,000 cycles
Na-ion		
Specific Energy	90 Wh/kg (Aquion)	120-140 Wh/kg
Energy cost	€240/kWh (Aquion)	<€120 /kWh max
Lifetime	>5000 cycles	
Depth of Discharge	80%	
Metal-air Systems:		
Zn-air	$ 160/200/kWh for a 1 MW/4 MWH system (EOS)	?
Li-air	700Wh/kg (Li air Polyplus) 150 cycles[III]	>500Wh/kg, 300-500 €/kWh 3000 cycles
Li-S:		
Specific Energy	120 Wh/kg, 1 400 cycles at system level (48V/3 kWh: Oxis) or 350 Wh/kg, 100 cycles at cell level (Oxis)	400 Wh/kg , 3000 cycles at cell level
Energy cost		150 €/kWh

II: Achieved for consumer cells (18650) with limited cycle life time. Industrial cells achieve about 170 Wh/kg today.

III: In air with 17% humidity. Source: J. Amici et al: O2 Selective Membranes Based on a Dextrin-Nanosponge (NS) in a PVDF-HFP Polymer Matrix for Li-air Cells, Chem. Commun., p 52, 2016.

Liquid Air Energy Storage

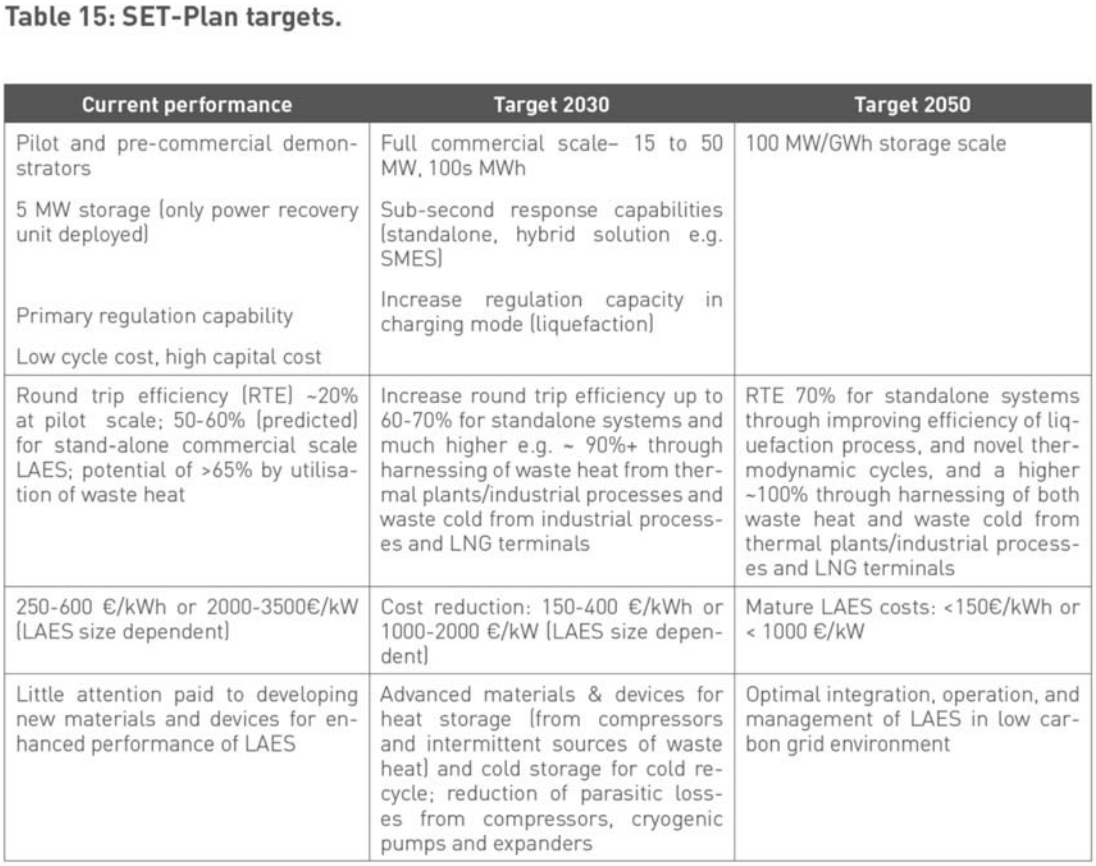


Table 15: SET-Plan targets.

Current performance	Target 2030	Target 2050
Pilot and pre-commercial demonstrators 5 MW storage (only power recovery unit deployed) Primary regulation capability Low cycle cost, high capital cost	Full commercial scale– 15 to 50 MW, 100s MWh Sub-second response capabilities (standalone, hybrid solution e.g. SMES) Increase regulation capacity in charging mode (liquefaction)	100 MW/GWh storage scale
Round trip efficiency (RTE) ~20% at pilot scale; 50-60% (predicted) for stand-alone commercial scale LAES; potential of >65% by utilisation of waste heat	Increase round trip efficiency up to 60-70% for standalone systems and much higher e.g. ~ 90%+ through harnessing of waste heat from thermal plants/industrial processes and waste cold from industrial processes and LNG terminals	RTE 70% for standalone systems through improving efficiency of liquefaction process, and novel thermodynamic cycles, and a higher ~100% through harnessing of both waste heat and waste cold from thermal plants/industrial processes and LNG terminals
250-600 €/kWh or 2000-3500€/kW (LAES size dependent)	Cost reduction: 150-400 €/kWh or 1000-2000 €/kW (LAES size dependent)	Mature LAES costs: <150€/kWh or < 1000 €/kW
Little attention paid to developing new materials and devices for enhanced performance of LAES	Advanced materials & devices for heat storage (from compressors and intermittent sources of waste heat) and cold storage for cold recycle; reduction of parasitic losses from compressors, cryogenic pumps and expanders	Optimal integration, operation, and management of LAES in low carbon grid environment

Supercaps

Table 9: Technical targets.

	Current performance	Target 2030	Target 2050
Voltage	3.0 Volt	4.0 Volt	4.5- 5 Volt
Energy density	4-8 Wh/kg EDLCs	50Wh/kg	75 Wh/kg
	15-30 Wh/kg for LCAPs		
Power density	»10-20kW/kg (1-5s)	»40kW/kg (1-5s)	»60kW/kg (1-5s)
Specific capacitance	6F/g	50 F/g	ca. 600F/g
Cyclability	500k – 1M cycles	1.5M cycles	> 2M cycles
Temp Low	T = -40°C	T = -40°C	T= -40°C
Temp High	T= 65°C	T= 100°C	T= 125°C

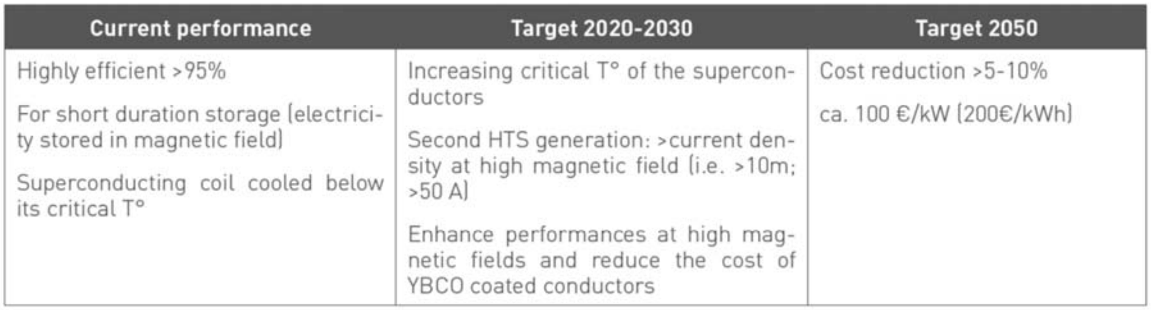
Tabla 10: Economic targets.

	Current	Target 2030	Target 2050
€/W	0,3 €/W (cell basis)	0,2€/W (cell basis)	0,05€/W (cell basis)
€/F	0.015 c€/F	0.005 c€/F	0.002 c€/F

* Supercapacitors (EDLC, Li-ion capacitors, Pseudo capacitors, hybrid, symmetric and asymmetric systems)

Super-Magnetic Energy Storage

Table 11: Targets for SMES materials towards 2030 and beyond[92].



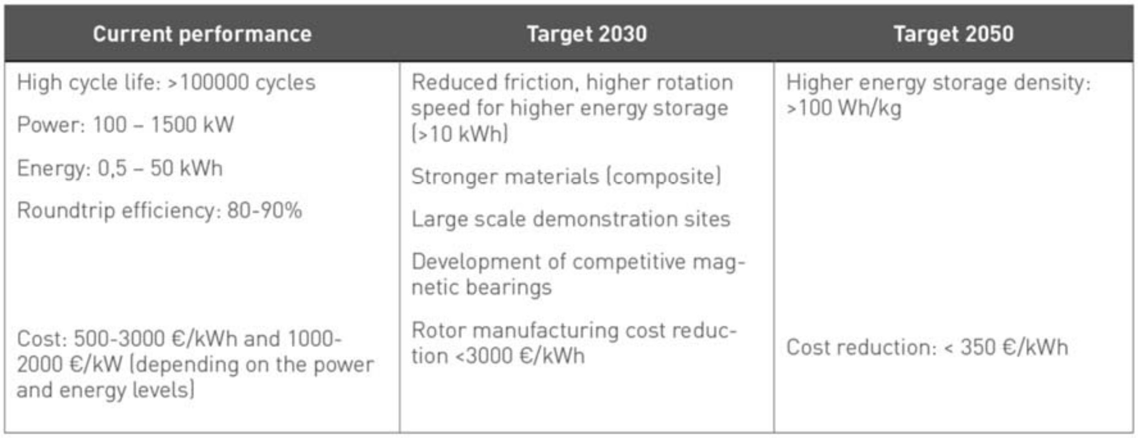
Current performance	Target 2020-2030	Target 2050
Highly efficient >95% For short duration storage (electricity stored in magnetic field) Superconducting coil cooled below its critical T°	Increasing critical T° of the superconductors Second HTS generation: >current density at high magnetic field (i.e. >10m; >50 A) Enhance performances at high magnetic fields and reduce the cost of YBCO coated conductors	Cost reduction >5-10% ca. 100 €/kW (200€/kWh)

Table 12: Targets for SMES materials, technology and systems towards 2030 and beyond.

Current performance	Target 2020-2030	Target 2050
Highly efficient >95% For short duration storage (electricity stored in magnetic field) Superconducting coil cooled below its critical T°	Enhance performance and decrease cost of MgB_2 and 2 G wires and tapes by a factor of five Standardise SMES technology (cryostat, current leads, cooling) Improve the multi-physics designing tools Improve electronic control and coil protection Demonstrate HTS SMES in hybrid or stand-alone applications	Enhance performance and decrease cost of MgB_2 and 2 G wires and tapes by a factor of ten Reduce cost and loss of SMES technology (cryostat, current leads, cooling) by a factor of two Apply SMES in commercial applications

Flywheels

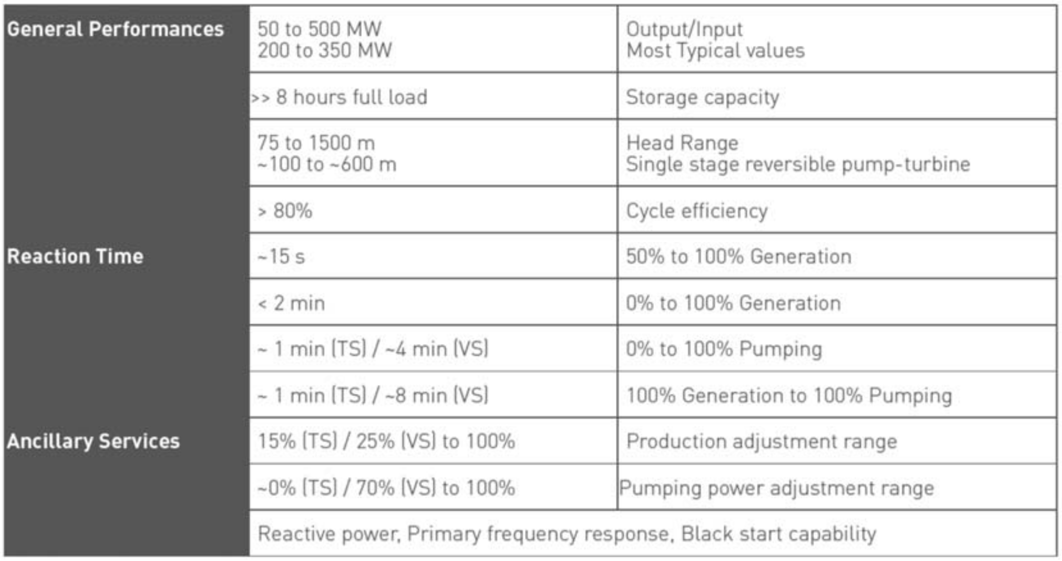
Table 16: SET-Plan targets.



Current performance	Target 2030	Target 2050
High cycle life: >100000 cycles Power: 100 – 1500 kW Energy: 0,5 – 50 kWh Roundtrip efficiency: 80-90%	Reduced friction, higher rotation speed for higher energy storage (>10 kWh) Stronger materials (composite) Large scale demonstration sites Development of competitive magnetic bearings	Higher energy storage density: >100 Wh/kg
Cost: 500-3000 €/kWh and 1000-2000 €/kW (depending on the power and energy levels)	Rotor manufacturing cost reduction <3000 €/kWh	Cost reduction: < 350 €/kWh

Pumped Hydro Energy Storage

Table 17: PHS features (VS = variable-speed, TS = Ternary Set).



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

Hydro Energy Storage

Table 18: SET-Plan targets for hydro energy storage technologies towards 2030 and beyond.

Current performance	Target 2020-2030	Target 2050
GW storage	Materials radical redesign & research on power electronic components	Efficiency improvement
Low cycle cost high capital cost		Cost reduction
$500/kW to $2000/kW (350 to 1500€/kW)	Turbine efficiency improvement	Expand possibilities of PHS installations
Round trip efficiency 70-80%	Increase regulation capacity in pumping mode	Ultrafast regulation
Primary regulation capacity		
	Increase pump-turbine stability in pumping mode	
	New concepts for underground PHS	Studies for first implementation of new underground PHS

Thermal Energy Storage

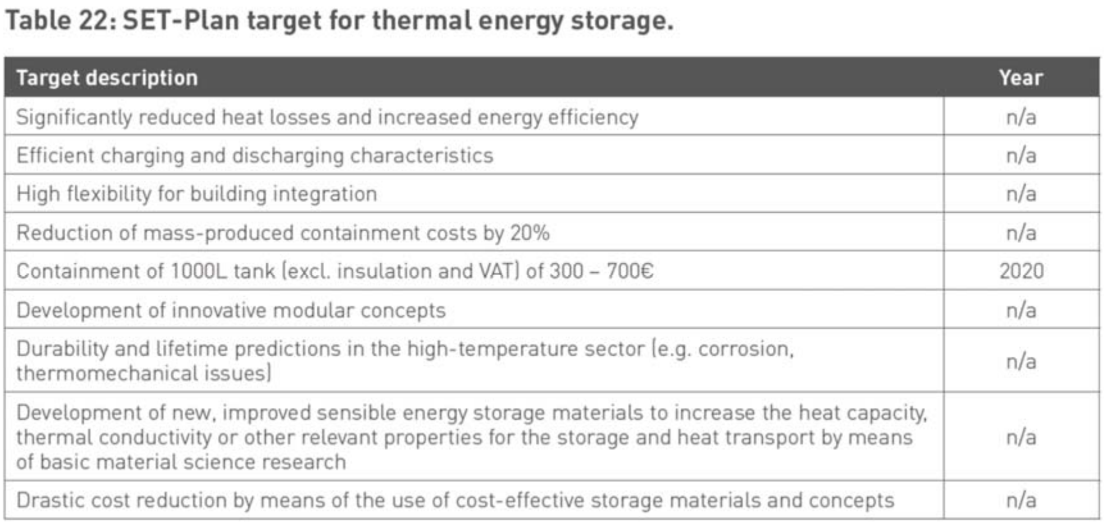
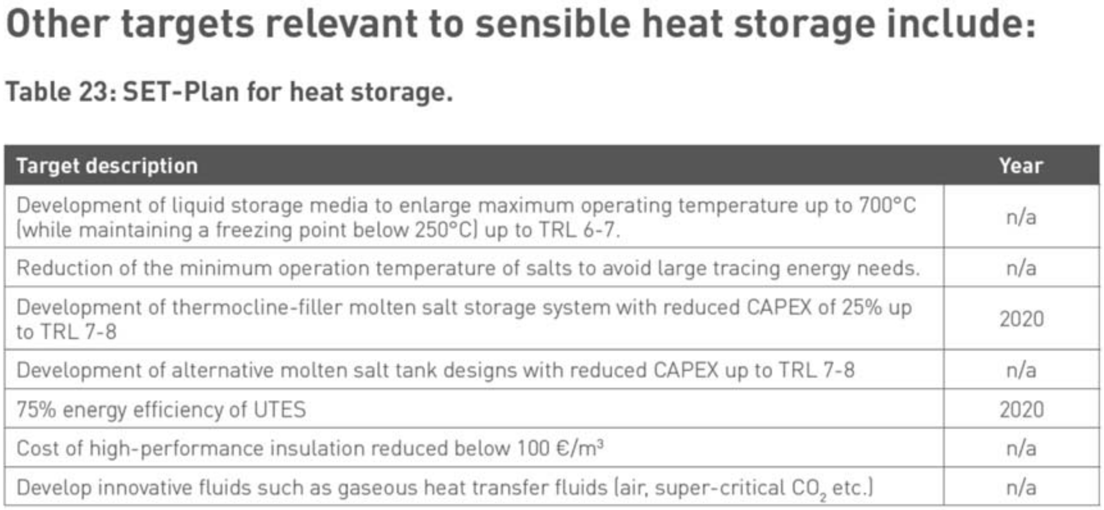


Table 22: SET-Plan target for thermal energy storage.

Target description	Year
Significantly reduced heat losses and increased energy efficiency	n/a
Efficient charging and discharging characteristics	n/a
High flexibility for building integration	n/a
Reduction of mass-produced containment costs by 20%	n/a
Containment of 1000L tank (excl. insulation and VAT) of 300 – 700€	2020
Development of innovative modular concepts	n/a
Durability and lifetime predictions in the high-temperature sector (e.g. corrosion, thermomechanical issues)	n/a
Development of new, improved sensible energy storage materials to increase the heat capacity, thermal conductivity or other relevant properties for the storage and heat transport by means of basic material science research	n/a
Drastic cost reduction by means of the use of cost-effective storage materials and concepts	n/a



Other targets relevant to sensible heat storage include:

Table 23: SET-Plan for heat storage.

Target description	Year
Development of liquid storage media to enlarge maximum operating temperature up to 700°C (while maintaining a freezing point below 250°C) up to TRL 6-7.	n/a
Reduction of the minimum operation temperature of salts to avoid large tracing energy needs.	n/a
Development of thermocline-filler molten salt storage system with reduced CAPEX of 25% up to TRL 7-8	2020
Development of alternative molten salt tank designs with reduced CAPEX up to TRL 7-8	n/a
75% energy efficiency of UTES	2020
Cost of high-performance insulation reduced below 100 €/m³	n/a
Develop innovative fluids such as gaseous heat transfer fluids (air, super-critical CO_2 etc.)	n/a

Phase Change Materials

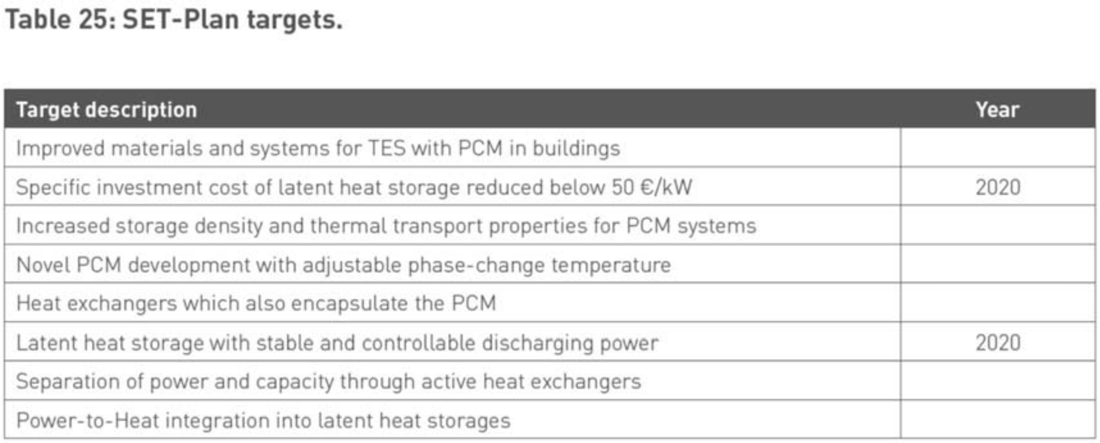
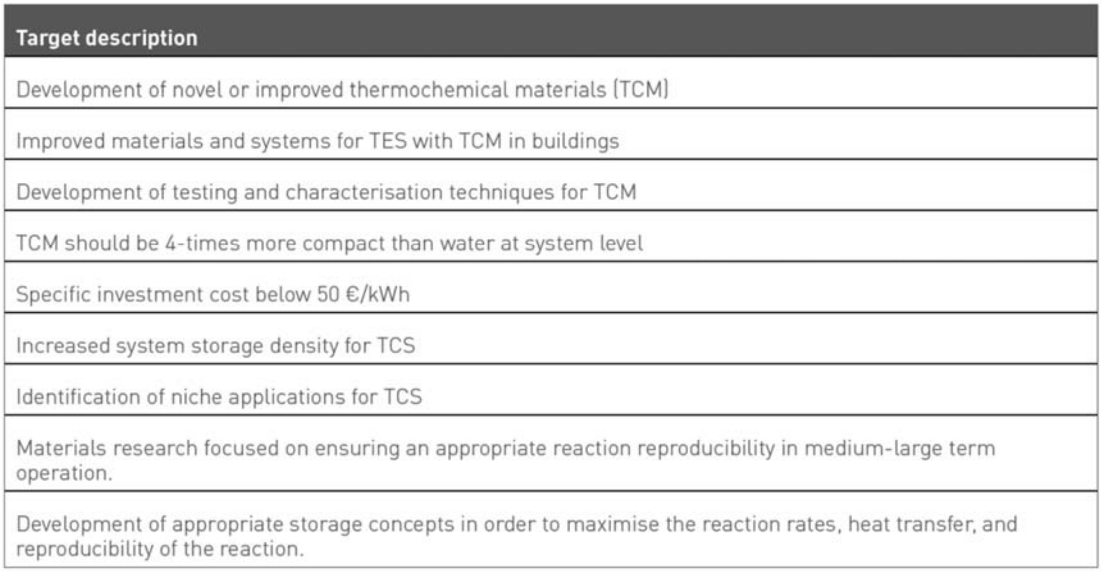


Table 25: SET-Plan targets.

Target description	Year
Improved materials and systems for TES with PCM in buildings	
Specific investment cost of latent heat storage reduced below 50 €/kW	2020
Increased storage density and thermal transport properties for PCM systems	
Novel PCM development with adjustable phase-change temperature	
Heat exchangers which also encapsulate the PCM	
Latent heat storage with stable and controllable discharging power	2020
Separation of power and capacity through active heat exchangers	
Power-to-Heat integration into latent heat storages	

Thermo-Chemical Storage

Table 27: SET-Plan targets.

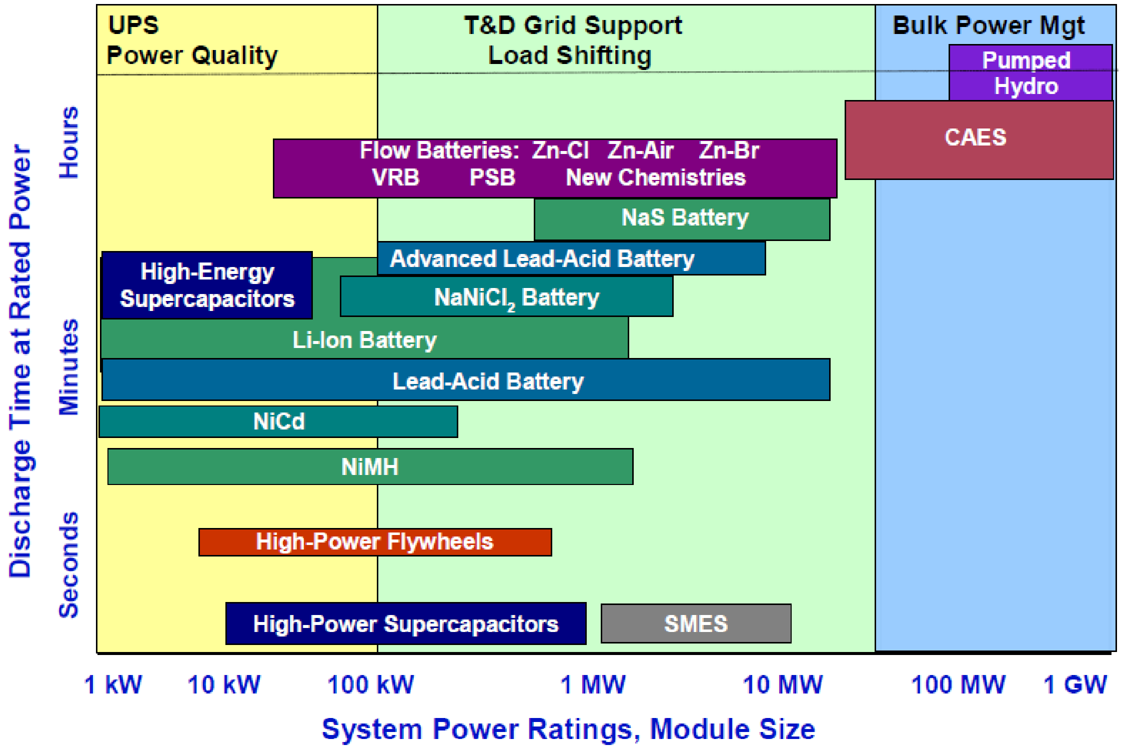


Target description
Development of novel or improved thermochemical materials (TCM)
Improved materials and systems for TES with TCM in buildings
Development of testing and characterisation techniques for TCM
TCM should be 4-times more compact than water at system level
Specific investment cost below 50 €/kWh
Increased system storage density for TCS
Identification of niche applications for TCS
Materials research focused on ensuring an appropriate reaction reproducibility in medium-large term operation.
Development of appropriate storage concepts in order to maximise the reaction rates, heat transfer, and reproducibility of the reaction.

Annex B – Comparison of energy storage technologies

Positioning Energy Storage Technologies; Discharge time (energy capacity) vs. rated power.

Source: DOE/EPRI/NRECA, https://www.sandia.gov/ess-ssl/lab_pubs/doeepri-electricity-storage-handbook/



Annex C – Cost data for energy storage technologies by IRENA

In a report from 2017 (IRENA (2017), Electricity Storage and Renewables: Costs and Markets to 2030, International Renewable Energy Agency, Abu Dhabi) much interesting and valuable information is given about energy storage installation costs for different technologies. Many tables are repeated below and the reader is strongly encouraged to consult the IRENA report for details.

Figure 16: Properties of pumped hydro storage systems, 2016 and 2030

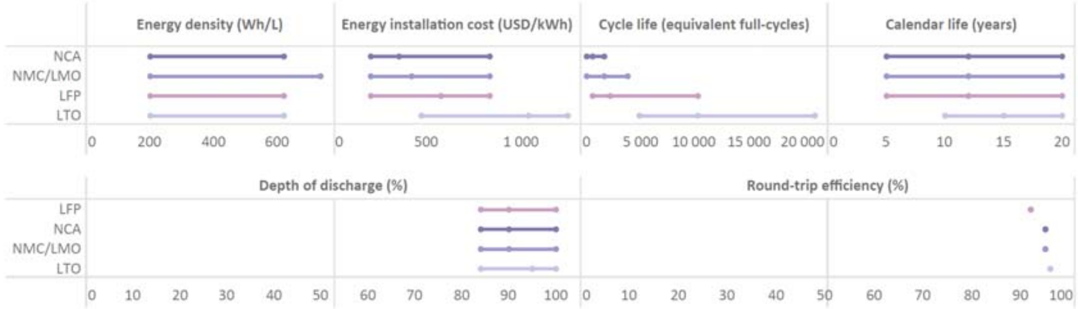
Figure 19: Properties of compressed air energy storage systems in 2016 and 2030

Source: International Renewable Energy Agency.

Figure 22: Properties of flywheel energy storage systems, 2016 and 2030

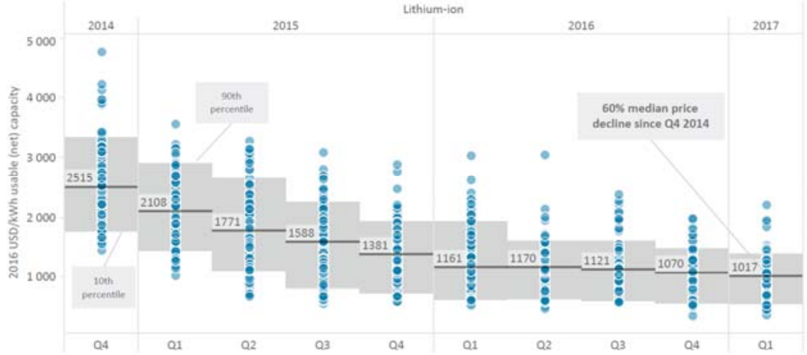
Source: International Renewable Energy Agency.

Figure 26: Properties of selected chemistries of lithium-ion battery electricity storage systems, 2016



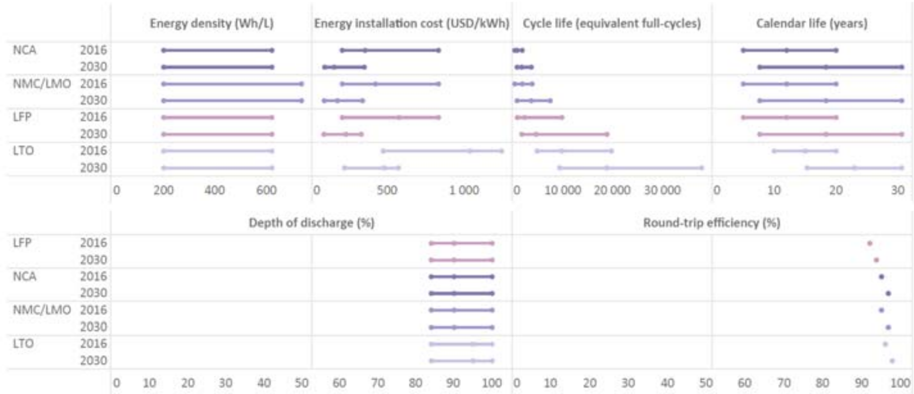
Source: International Renewable Energy Agency.

Figure 29: Home storage lithium-ion system offers in Germany from Q4 2014 to Q1 2017



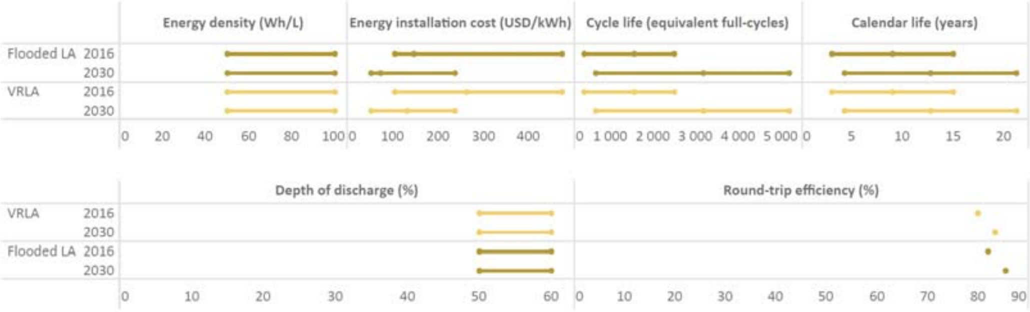
Source: International Renewable Energy Agency, based on EuPD Research, 2017.

Figure 33: Properties of selected chemistries of lithium-ion battery electricity storage systems, 2016 and 2030



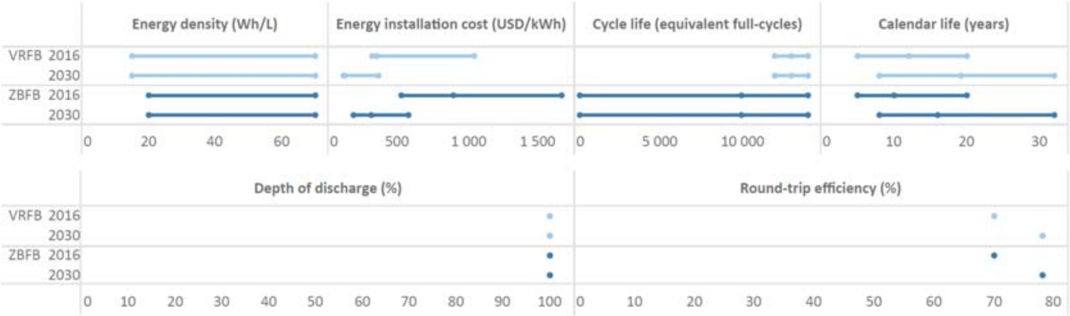
Source: International Renewable Energy Agency.

Figure 36: Properties of lead-acid battery energy storage systems, 2016 and 2030



Source: International Renewable Energy Agency.

Figure 40: Properties of flow battery electricity storage systems in 2016 and 2030

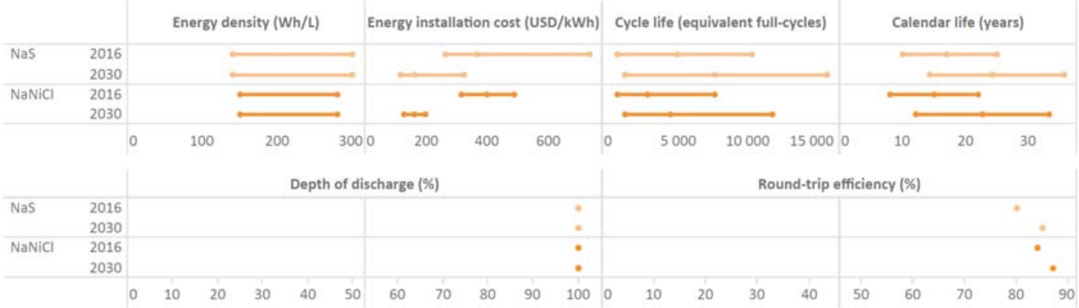


Source: International Renewable Energy Agency.

Figure 45: Properties of high-temperature battery electricity storage systems, 2016

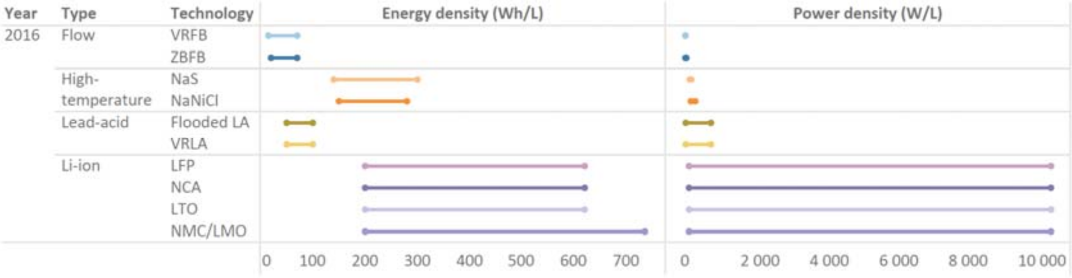
Source: International Renewable Energy Agency.

Figure 46: Properties of high-temperature battery electricity storage systems, 2016 and 2030



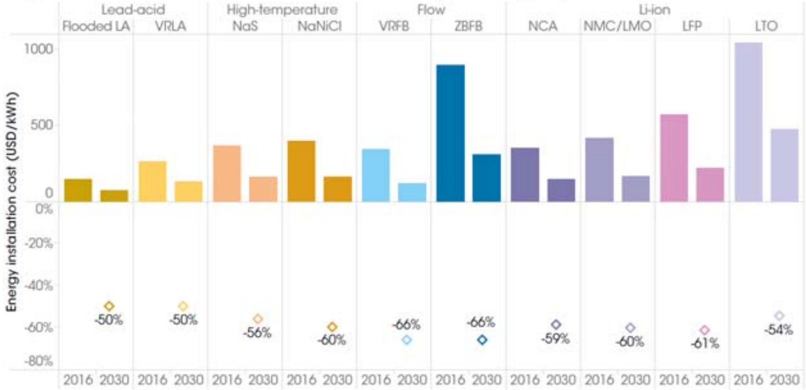
Source: International Renewable Energy Agency.

Figure 47: Energy and power density ranges of selected battery storage technologies, 2016



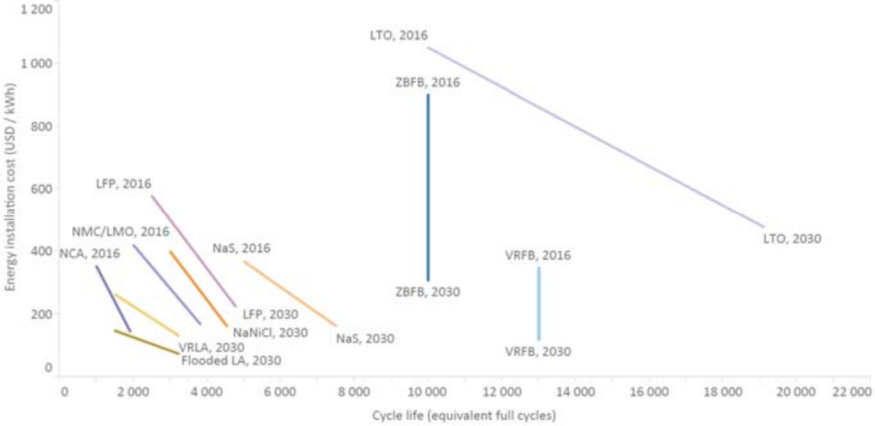
Source: International Renewable Energy Agency.

Figure 49: Energy installation costs central estimate for battery technologies, 2016 and 2030



Source: International Renewable Energy Agency.
Note: LA = lead-acid; VRLA = valve-regulated lead-acid; NaS = sodium sulphur; NaNiCl = sodium nickel chloride; VRFB = vanadium redox flow battery; ZBFB = zinc bromine flow battery; NCA = nickel cobalt aluminium; NMC/LMO = nickel manganese cobalt oxide/lithium manganese oxide; LFP = lithium iron phosphate; LTO = lithium titanate.

Figure 50: Energy installation costs and cycle lifetimes of battery storage technologies, 2016 and 2030



Source: International Renewable Energy Agency.

Energy storage is an important part of the energy transition – for transport and mobility, it is mandatory. To meet the challenges of affordability and responsivity, energy storage technologies must be further developed and refined. Some storage technologies are already mature and on the market. Some need careful attention to reach the market, but will be necessary in the future energy system.

The present whitebook aims to inform the reader about status, needs and perspectives for energy storage technologies, and set out milestones to guide decision makers, industry and research communities on how to trigger storage as an instrument to achieve the climate goals.

Department of Energy Conversion and Storage

Fredeiksborgvej 399
Building 775
DK-4000 Roskilde